TECHNICAL OPINION

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Third Generation and Beyond Wireless Systems

Exploring the capabilities of increased data transmission rates.

Third-generation (3G) mobile and wireless networks target the requirements of multimedia applications and Internet services by offering increased capacities: at least 144Kbps for full mobility applications in all cases; 384Kbps for limited mobility applications in macro- and micro-cellular environments; and 2Mbps for low-mobility applications, particularly in micro- and pico-cellular environments [1].

The International Telecommunication Union Radiocommunication Standardization Sector (ITU-R) issued a call for 3G proposals in 1998. The submissions by various national Standards Development Organizations (SDOs) [1] are shown in the table here. The standardization project resulted in a 3G Time Division Multiple Access (TDMA) standard for Global System for Mobile Communications (GSM)/IS-136 evolution (EDGE/UWC-136) and two 3G Code Division Multiple Access (CDMA) standards: multicarrier cdma2000 and DS-WCDMA.

SDO	Air-interface proposal
ETSI (Europe)	FDD WCDMA, TDD WCDMA
ARIB (Japan)	FDD WCDMA
TIA (USA)	UWC-136, Cdma2000, WIMS (WCDMA)
TIPI (USA)	WCDMA-NA
TTA (Korea)	WCDMA, Cdma2000
China	TD-SCDMA

Radio access proposals of SDOs to the ITU-R.

EDGE. Enhanced Data Rates for GSM Evolution (EDGE) [5] is GSM-compatible and uses the GSM bandwidth and its 200KHz channel structure; however it offers significantly higher data rates. This is because, apart from Gaussian Minimum Shift Keying (GMSK), it is also able to utilize eight-phase shift keying (8-PSK). 8-PSK encodes three bits per-symbol instead of the one bit per-symbol GMSK encoding of GSM. EDGE maintains the burst format of GSM.

Enhanced General Packet Radio Service (EGPRS), the packet-switched transmission mode of EDGE, allows for data rates up to 473Kbps. To support higher speeds than GPRS, Link Adaptation (LA) and Incremental Redundancy (IR) are used. LA estimates link quality and when a poor link quality is experienced the robust GMSK is used for modulation. In cases of links of good quality, the more efficient 8-PSK is selected. IR initially transmits packets with little coding overhead in order to provide high data rates. If decoding fails, packets are retransmitted with additional coding bits. EGPRS supports numerous LA/IR combinations. When decoding of a packet fails, successive retransmissions for that packet use a more noise-tolerant LA/IR combination. This process is repeated until successful decoding of the packet is achieved.

The Enhanced Circuit-Switched Data (ECSD) mode of EDGE maintains the GSM circuit-switched data protocols. The introduction of 8-PSK does not change the offered data rates but does enable a more efficient use of the spectrum. For example, while four time slots in GSM serve a 57.6Kbps circuit-switched connection, the same connection uses only two slots with ECSD.

EDGE Classic and EDGE Compact. EDGE development for IS-136 systems comprises two modes: Compact and Classic. Before explaining their differences we briefly describe the concept of the frequency reuse pattern. We consider hexagonal cells having a Base Station (BS) at their middle. BSs are divided into sectors equally spaced apart. Sectors within a cell use different frequencies. A

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cluster is a set of cells. In a cluster each frequency channel is used only once. For cells having Y sectors each and K available channels, a cluster will comprise K/Y cells, and the frequency reuse pattern is referred to as (K/Y)/K. For example, for K=12, Y=3, we have a 4/12 reuse pattern. This means the 12 available channels are reused every four-cell cluster. Thus, with an appropriate reuse pattern, frequencies are reused at sectors significantly apart from one another, which enables non-interfering operation of the respective data and control channels.

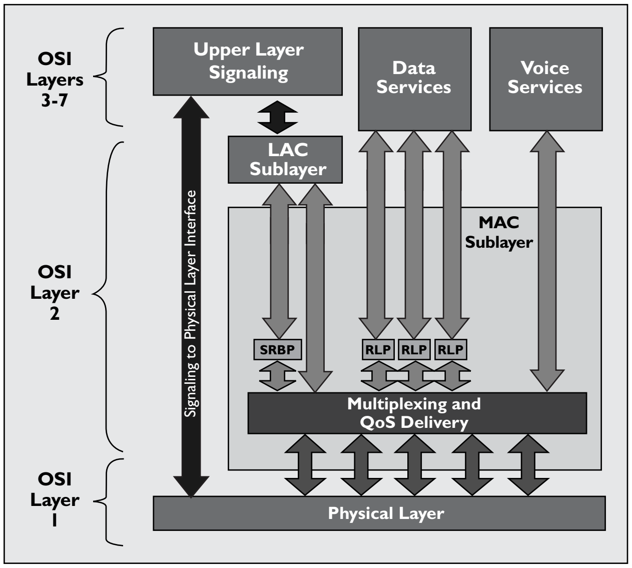

Figure 1. The cdma2000 protocol architecture (Source: 3GPP2).

EDGE Compact uses a new 200KHz control channel structure. By using BS synchronization and a 1/3 frequency reuse pattern, Compact can be deployed using only 600KHz. EDGE Classic uses the same channel structure as GSM, which typically uses a 4/12 frequency reuse pattern for carriers containing broadcast control channels and a 3/9 reuse pattern for traffic channels. Minor modifications over ETSI EDGE enable Classic to reuse the existing IS-136 30KHz-wide control signaling system. As the channel width of EDGE is 200KHz and 12 different such channels are used for EDGE control carriers due to the 4/12 reuse pattern, operators need 2.4MHz (12 x 200KHz) of bandwidth to deploy EDGE Classic [5]. This is a problem for North American operators, which suffer from spectrum limitations due to the decision of FCC to allocate 3G spectrum to GSM 1900. In those cases operators have to offer EDGE support using only three 200KHz channels in a 1/3 reuse pattern (thus, in 600KHz). However, a 1/3 reuse pattern is too low for control channels to operate reliably; rather, a 4/12 or 3/9 pattern is required.

EDGE Compact solves this problem. By using synchronization between BSs, for each set of four neighboring cells, sectors in those cells that use the same frequenices form four time groups. For control signaling, inside each four-cell cluster different sectors use the same frequency, not concurrently, but in turns. Thus, for control signaling, clusters of four cells are formed and the 1/3 reuse scheme turns into a 4/12 scheme.

Synchronization can be achieved by using GPS receivers. The time group structure does not affect the data traffic channels in Compact, which continue to employ a 1/3 frequency reuse pattern. However, when a data transmission collides with an ongoing control information transmission in neighboring sectors, the data transmission is not performed.

cdma2000. Although cdma2000 [4, 8] can be used as the air-interface of pure 3G network installations, its main advantage is the ability to coexist with cdmaOne (also known as IS-95) systems. This is a very important aspect for North American providers, where significant spectrum is occupied by cdmaOne systems. Figure 1 shows the two lower layers of the protocol architecture of cdma2000.

Cdma2000 uses two spreading modes, 1X and 3X. The 1X mode uses one cdmaOne carrier. Due to protocol enhancements, it approximately doubles the voice capacity of cdmaOne systems and provides average data rates up to 144Kbps. High Data Rate (HDR) is an enhancement of 1X for data services. In cases of low interference, it uses 16-Quadrature Amplitude Modulation (16-QAM), which codes four bits per symbol, thus offering higher speeds than 1X.

The 3X mode offers data rates up to 2Mbps by multicasting traffic over three 1.25MHz cdmaOne carriers. 3X uses direct spreading for uplink transmission, producing a wideband signal matching the rate of three cdmaOne carriers (3 x 1.2288=3.6864Mcps). 3X downlink uses three separate cdmaOne carriers.

Cdma2000 supports both Frequency Division

Duplex (FDD) and Time Division Duplex (TDD) configurations. TDD systems are valuable in environments where unpaired frequency bands are available (as in Europe). The TDD mode introduces minor modifications over FDD regarding guard timing.

The cdma2000 physical layer is an enhancement over that of cdmaOne. It supports a number of physical channels, which are either dedicated to a specific mobile or common among many mobiles. The cdma2000 downlink employs transmit diversity, fast power control, common and auxiliary pilots, and synchronized BS operation. The uplink employs pilot-based coherent detection and power control. Both uplink and downlink use backward-compatible chip rates and frame structures, turbo codes, and independently coded and interleaved data channels.

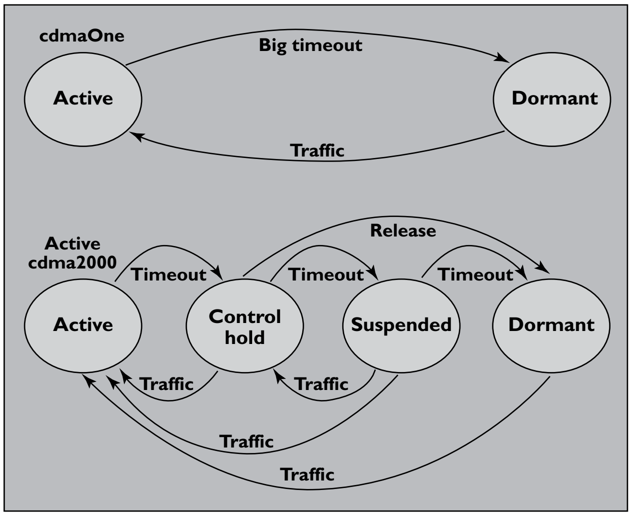

Figure 2. The cdmaOne and cdma2000 MAC sub-layer state machines.

The cdma2000 Data Link Control (DLC) layer [4] uses a logical channel structure to enable information exchange. In cdma2000 channel access requests are made using the efficient 5ms frame option rather than the 20ms option of cdmaOne. After submitting a request, a mobile expects an assignment reply from the BS. If it is not received, the mobile executes an exponential backoff procedure and retries. The DLC layer comprises the MAC and Link Access Control (LAC) sublayers. The LAC provides in-sequence reliable frame delivery. The main enhancements of the MAC sublayer of cdma2000 over that of cdmaOne are:

- Quality of Service (QoS) support. QoS negotiation is supported through appropriate prioritization of conflicting requests from contending services. A multiplexing mechanism combines information from various sources according to QoS demands and hands the resulting frames to the physical layer for transmission.
- Additional MAC states. The finite-state machine of cdma2000 MAC sublayer comprises four stages, two more than that of cdmaOne (see Figure 2). Reflecting the status of packet or circuit data transmissions, a different machine is maintained for each transmission. While the MAC of cdmaOne works well for low-rate data, it is inefficient for high-speed data. One reason for this is the excessive interference incurred by traffic channels of idle mobiles in the Active state. In this state cdmaOne mobiles maintain all their channels and go to the Dormant state after a "Big" timeout. Thus, although idle, they maintain their channels for a considerable time period.

The addition of the two extra states alleviates this problem. After a shorter timeout, idle mobiles go from the Active state to the Control Hold state. In the Control Hold state the traffic channel is released; however, a dedicated MAC logical channel is provided to idle mobiles. Over this channel, MAC commands, such as a request for a traffic channel establishment to serve a high-speed data burst, can be transferred almost immediately. In the Suspended state, idle mobiles do not possess a dedicated channel. Nevertheless, state information is stored both in mobiles and in the BS to enable fast assignment of a dedicated channel when packet events for the mobile occur. A second reason for cdmaOne's inefficiency to support high-speed data is its high overhead associated with dormant-to-active stage transition in cdmaOne, where there exists no mechanism for sending user data while in the Dormant state; rather, the mobile must request channel assignment, thus incurring an overhead for infrequent data bursts. Thus, in cdma2000, the Dormant state incorporates a short data burst mode that enables delivery of short data and control messages over logical common traffic channels.

WCDMA. Wideband CDMA (WCDMA) [2, 8] is an asynchronous scheme. It uses a wide (5MHz) carrier to achieve high data rates at the expense of additional spectrum and backward compatibility. The original WCDMA proposals called for a 4.096Mcps chip rate; however, in order to enable easy manufacturing of terminals supporting both WCDMA and cdma2000 this was reduced to 3.84Mcps.

Figure 3 shows the two lower layers of the protocol architecture of WCDMA: the physical and the DLC layers. The latter is split into the MAC, Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), and Broadcast/Multicast Control (BMC) sublayers. The physical layer offers different transport channels to the MAC sublayer. MAC offers different logical channels to RLC.

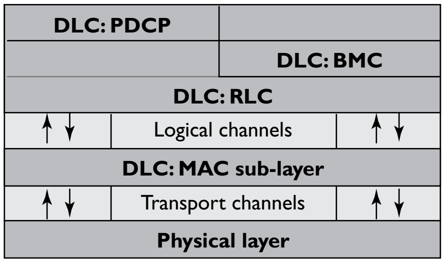

Figure 3. WCDMA protocol architecture.

WCDMA supports a number of uplink/downlink physical channels, to transmit the data carried over logical channels. WCDMA uses 10ms frames and has two operating modes, FDD and TDD, for use with paired and unpaired bands (as in Europe) respectively. WCDMA TDD can support asymmetric traffic, with the ratio of uplink/downlink slots within a frame being able to vary from 15/1 to 1/7.

The WCDMA physical layer provides two types of packet access using random access and dedicated (user) channels. Random access relies on slotted ALOHA and is used only on the uplink for short infrequent bursts. Dedicated access serves more frequent bursts both on the uplink and the downlink. The WCDMA physical layer uses QPSK modulation. It supports adaptive antennas, channel coding and interleaving, downlink/uplink coherent demodulation and fast power control, downlink transmit diversity, and multi-user detection.

The MAC sublayer provides services to upper layers via logical channels. In the other way, the MAC sublayer accesses services offered by the physical layer through the use of transport channels. MAC sublayer services to upper layers include unacknowledged transfer of MAC frames, resource reallocation and changing of MAC parameters, and measurement reports regarding traffic volume and channel quality. RLC services to upper layers include connection establishment/release between RLC peer entities, transfer of higher-layer Protocol Data Units (PDUs) without the overhead of adding RLC protocol information (transparent transfer), unacknowledged transfer of higher-layer PDUs, QoS setting, and notification of upper layers on unrecoverable errors. PDCP and BMC services to upper layers are network-layer PDU transmission/reception and broadcasting/multicasting services, respectively.

Fixed Network Evolution

While the migration from 2G to 3G systems entails a revolutionary path for the air-interface, fixed network evolution will be more conservative [1]. The goal is to maximize reuse of existing fixed network infrastructure, in order to provide seamless migration from 2G to 3G systems and lower the accompanying costs. As reference architecture for our discussion, we use a simplified version of the Universal Mobile Telecommunications System (UMTS) Release '99. In this architecture, the UMTS terrestrial Radio Access Network (UTRAN) corresponds to the BS Subsystem (BSS) of GSM. The UTRAN comprises 3G-capable BSs and Radio Network Controllers (RNCs, which in GSM terminology correspond to the BS Controllers (BSCs)). Studies indicate four possibilities for the evolution of the fixed part of the cellular network [9]:

Use of ATM in the UTRAN and of TDM/frame relay in the Core Network (CN). In this option, ATM technology is used in the UTRAN to meet the requirements for QoS, high-speed soft-handoff, and scalability, while GSM technology continues to dominate the CN. This option targets smooth evolution toward 3G networks while retaining existing investments.

Use of ATM both in the UTRAN and the CN. This choice offers seamless integration of wireless and wireline networks.

Use of ATM in the UTRAN and of Internet Protocol (IP) in the CN. This option will exploit the ATM QoS capabilities in order to provide support for time-critical services in the UTRAN. The use of IP in the CN will support the growth of packet-data services in wireless networks.

Use of IP both in the UTRAN and the CN. This option leads to an all-IP-based infrastructure. However, solutions to IP QoS issues need to be found.

Beyond 3G Systems: Fourth-Generation (4G) Systems

4G mobile and wireless networks target the more demanding market of 2010 and beyond with capacities of approximately 100Mbps. In the course of 4G network development, many technical issues [6] (such as access, handoff, location coordination, multicasting, and QoS support), as well as economical ones (pricing and billing), must be studied and resolved. Current reports on 4G research [6] outline the following emerging technologies for use in 4G networks:

Adaptive Modulation and Coding (AMC). The goal of this technology is to modify modulation and coding over a wireless link based on link quality.

Adaptive Hybrid ARQ. Similar to AMC, it targets optimization of link capacity by adaptive ARQ techniques.

Multiple Antennas and OFDM. Multiple antenna technology enables higher capacities and spectral efficiency. Orthogonal Frequency Division Multiplexing splits the message to be transmitted into a number of parts that are sent in parallel over different low-rate frequency channels, resulting in an overall high-capacity, multipath-resistant link.

Ad hoc networks. Research is under way to determine whether low-power, ad hoc mesh architectures utilizing efficient routing schemes will offer spectrally efficient solutions for 4G networks.

One of the primary goals of 4G wireless networks will be to provide backward compatibility and interoperability with the different new and legacy mobile and wireless networks. The mixing and internetworking of different wireless networks will provide a set of, possibly overlapping, layers with different access technologies complementing one another [3]. Depending on their geographical location, users will be served by different layers and enjoy different qualities of wireless access in terms of bandwidth. Possible layers will be [7]:

Distribution layer. It will support digital video and broadcasting services at moderate speeds over relatively large cells. It will also support full coverage and mobility and cover sparsely-populated rural areas.

Cellular layer. It will comprise 2G and 3G systems, providing high capacities in terms of users and data rates inside densely populated areas such as cities. The cell size will obviously be smaller than that used in the distribution layer. It will also support full coverage and mobility.

Hot-spot layer. It will support also high-rate services over short ranges, such as in offices and buildings. It will comprise WLAN systems, such as IEEE 802.11 and HIPERLAN. This layer is not expected to provide full coverage, due to its short range, although roaming should be provided.

Personal network layer. It will comprise very short-range wireless connections, such as those of Bluetooth. Due to the very short range, mobility will be limited, however, roaming should be provided in this layer too.

Fixed layer. This will comprise the fixed access systems, which will also be part of the 4G network of the future. **C**

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