Third Generation (3G) Mobile Communications Systems

by
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ABSTRACT
The International Telecommunication Union (ITU) began studies on globalization of personal communications in 1986 and identified long term spectrum needs for future "Third-Generation" mobile wireless telecommunications systems. These 3G mobile telecommunications systems are expected to provide worldwide access and global roaming for a wide range of services. This paper describes the proposed 3G air interfaces of Europe, Japan, and North America. This paper highlights ETSI activities in 3G arena and provides a brief description of the FRAMES Multiple Access (FMA) mode 1 and mode 2 air interfaces. Evolution of GSM and North American TDMA (TIA-IS-136) to Wide-band Code Division Multiple Access (WCDMA) via EDGE system is also presented, as well as a discussion on industry trends.

1.0 Introduction

The studies on globalization of personal communications began in 1986 by ITU to identify the long-term spectrum needs for the future 3G mobile telecommunications systems. In 1992, ITU identified 230 MHz of spectrum in the 2 GHz band to implement the International Mobile Telecommunications - 2000 (IMT-2000) system on a worldwide basis for the satellite and terrestrial components. IMT-2000 capabilities include a wide range of voice, data, and multimedia services with the quality equivalent or better than the fixed telecommunications networks in different RF environments. The aim of IMT-2000 is to provide universal coverage enabling terminals to have seamless roaming across multiple networks.

Standards bodies in Europe, Japan, and North America are trying to achieve harmonization on key interrelated issues including: radio interfaces, system evolution, backward compatibility, user migration, global roaming, and introduction of mobile services and capabilities to support terminals. In Europe, 3G systems are aimed to support a substantially wider and enhanced range of services as compared to the current 2G GSM system. This enhancement includes multimedia and high-speed data services. The enhanced services will impose additional requirements on the fixed network functions. These requirements will be achieved through an evolution path to capitalize on the investment in GSM. In North America, the 3G system, cdma2000 [1] has been proposed by ITU. cdma2000 supports compatibility with the existing CDMA 2G system (TIA-IS-95-B), thus protecting capital investment. In Japan, evolution of the GSM platform is planned for IMT2000 (3G) core network due to its flexibility and widespread use around the world. The service area of the 3G system will be overlaid with the existing 2G (PDC) system. The 3G system will connect and inter-work with a 2G system through an inter-working function (IWF). IMT2000-PDC dual mode terminals as well as IMT2000 single mode terminals will be deployed.

2.0 Evolution of 2G Systems for Higher Data Rate (HDR)

2.1 Evolution of cdmaOne

The TIA-IS-95B upgrade allows for code or channel aggregation to provide data rates of 64-115 kbps, as well as offering improvements in soft handovers and inter-frequency handovers. To achieve 115 kbps rate, up to eight CDMA traffic channels each offering 14.4 kbps need to be aggregated. It is expected that an operator will initially support data rates between 28.8 kbps and 57.6 kbps on the downlink and 14.4 kbps on the uplink since mobile users generally receive more data than they send over the air. Looking further ahead, IS-95C may double the capacity of IS-95A as well as providing a basic data rate of 24.4 kbps. IS-95 HDR will provide ultra-fast data of more than one megabit per second using a dedicated data channel and separate base stations. This step will be closer to third generation data speed.

2.2 Evolution of GSM

The introduction of General Packet Radio Service (GPRS) is one of the key factors in the evolution of GSM networks to 3G capabilities. The next key step in this process is the implementation of Enhanced Data rates for GSM Evolution (EDGE) [2]. EDGE will allow GSM operators to use the existing GSM radio bands to offer wireless multimedia Internet Protocol (IP)-based services and applications at a rate of 384 kbps with a bit-rate of 48 kbps per time-slot and, up to 69.2 kbps per timeslot, under good RF conditions.

The EDGE system is an extension of GSM with high level modulation (HLM) schemes. It consists of: 200kHz carrier spacing, Quaternary-Offset-QAM (QQQAM) [=16-QAM]; Binary-Offset-QAM (BQAM) [=QPSK]; and GMSK modulation, 8 time-slots per TDMA frame, and a set of convolutional channel codes. The choice of the modulation technique depends upon the data rate. Using HLM schemes, EDGE satisfies the following requirements of IMT-2000:

- 384 kbps capability for pedestrian (microcell) and low speed vehicular (macrocell) environment
- 144 kbps for high speed vehicular environment
- 2 Mbps for indoor office using wide-band 1.6 MHz carrier

2.3 Evolution of IS-136 (DAMP)

The UWC is targeting the TIA-IS-136 evolution to meet IMT-2000 requirements having an initial deployment within 1 MHz spectrum allocation. UWC-136 [3] meets these targets via the existing 30 kHz carrier (IS-136+) and by defining a complementary wider-band TDMA carrier with bandwidths of 200 kHz (IS-136 HS [vehicular/outdoor] - same as EDGE) and 1.6 MHz (IS-136 HS [indoor] - same as FMA) without spreading. IS-136+ will provide data rates up to 64 kbps, and IS-136 HS (indoor) up to 2 Mbps.

3.0 Third-Generation Systems
3.1 European Systems

The Future Radio wideband Multiple Access Systems (FRAMES) defines the radio interface(s) for Universal Mobile Telecommunication Systems (UMTS). Since GSM is the most widely used second-generation system in the world, the frequency grid of FMA is made compatible with GSM. This means that FMA carriers must be located in the frequency band with the same resolution as 200 kHz GSM carriers. Two modes of FMA, FMA1 and FMA2 (W-CDMA), have been proposed to ITU. FRAMES partners who are members of Association of Radio Industries and Business (ARIB) have actively contributed to FMA2 concept for Japanese W-CDMA standardization in ARIB. Two options of FMA1 are: WB-TDMA (FMA1 without spreading) and TD-CDMA (FMA1 with spreading). The WB-TDMA solution is proposed for frequency-division duplex (FDD) operation in paired frequency bands (1920-1980 MHz [uplink] and 2110-2170 MHz [downlink]) for the outside vehicular environment, and TD-CDMA is proposed for time-division duplex (TDD) operation in the single frequency band (2010-2025 MHz) for indoor environment

3.1.1 FMA 1

In FMA 1 [2] users are separated orthogonally into time slots, and within each time slot spreading can provide additional separation. In FDD mode, all time slots of a frame are assigned to either uplink or downlink. In TDD mode, time slot resources are dynamically divided between uplink and downlink (i.e., the position of the switching point can be varied). For FDD and TDD mode, the frame duration is 4.615 ms (same as GSM) and can consist of 1/64, 1/16, and 1/8 slots fitting together in the frame. In TDD mode, the minimum length of uplink and downlink parts is 1/8 of frame duration (577μs). The non-spreading bursts of FMA1 are assigned to the 1/64 and 1/16 slots, whereas the spread bursts are assigned to the 1/8 slots. The 1/8 and 1/64 slots can be used for every service from low-rate speech and data to high-rate data services. The 1/16 slot is used for medium-to-high-rate data services. A basic physical channel is one time slot in the case of FMA1 without spreading, and one time slot and one spreading code in the case of FMA1 with spreading. In FMA1, user bit rates from a few kbps up to 2 Mbps are achieved by allocating different numbers of basic physical channels (i.e., different numbers of time slots and/or spreading codes) to a user.

Synchronization and handover measurements are based on either a slotted discontinuous wideband broadcast control channel (BCCH) or a continuous narrowband (200 kHz) BCCH. For FMA 1 with spreading, a continuous wave pilot signal with high spreading ratio is also considered for BCCH. For slotted wideband BCCH, special bursts are defined including frequency correction burst, synchronization burst, and access burst. The frequency correction burst is of duration 72 μs and contains 171 fixed symbols. Two types of synchronization bursts are defined, one 72 μs duration and another 288 μs duration. Two types of access bursts are defined: one with a 72 μs duration and another a 288 μs duration. The guard periods of the shorter and longer access bursts allow reception of initial random access messages for a maximum cell radii of 5 km and 36 km, respectively.

FMA1 without spreading uses binary offset quadrature amplitude modulation (BOQAM) and quaternary offset QAM (QQQAM) modulations. BOQAM allows near constant envelope signals. The channel spacing of 1.6 MHz and spectral properties of modulated FMA1 carrier allows flexible frequency planning for FMA1 carriers within a UMTS frequency band as well as coexistence with GSM carriers within GSM900/1800 frequency bands. FMA 1 uses hybrid ARQ.

Both real-time (RT) (circuit switched) and non-real-time (NRT) (packet switched) services can be provided by FMA1. The RT services are protected by forward error correction (FEC) codes. Advanced coding techniques such as turbo codes and rate-compatible punctured convolution (RCPC) codes will be used to meet the quality of service (QoS) requirements. Also, concatenated codes (e.g., Reed-Solomon codes concatenated with convolution codes) can be used to achieve very low bit error rates (BER). For RT services, frequency and time hopping together with interleaving can be used to improve frequency diversity, and to average out interference from other users.

3.1.2 FMA 2 (W-CDMA)

FRAMES concept is modeled using a layered approach. The protocol stack for FMA1 and FMA2 are harmonized as far as possible in different layers (Figure 1). In the FMA concept, the goal is to reuse as much of the mode-specific protocols as possible when designing the other mode.

![Figure 1: Layers of FMA1 and FMA2](image)

Although there are basic differences in radio link control (RLC) and media access control (MAC) between FMA1 and FMA2, it is expected that the protocol structure and handling of information exchange can be further harmonized. The logical link control (LLC) provides the same functionality within the protocol stack, and it is assumed to be mode independent apart from some differences for internal parameters. The Radio Network Layer (RNL) is different for two modes. The radio resource control (RRC) provides some fundamental differences between soft handover for FMA2 and mobile assisted hard handover for FMA1, while most functions common to both FMA modes are provided with the Radio Bearer Control (RBC) function. Both RBC and RRC could be presented as a single RRC protocol as well.

W-CDMA [4] is based on 5 MHz with a basic chip rate of 4.096 Mcips/s. The frame duration is 10 ms, allowing for low-delay speech and fast control messages. The logical channels provide services to physical layer and higher layers. In W-CDMA, the following types of logical channels are defined: Broadcast Control Channel (BCCH), Forward Access Channel (FACCH), Common Control Channel (CCCH), and Dedicated Control Channel (DCCCH).
(FACH), Paging Channel (PCH), Random Access Channel (RACH), and Dedicated Channel (DCH). Data arrives on the logical channel in the form of transport blocks. A variable number of transport blocks arrive on each logical channel at each transmission. The size of transport block is different between different logical channel and may also vary in time for a specific logical channel.

Each radio frame is divided into 16 time-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 contains known pilot bits for uplink closed-loop power control, and a transport format indicator (TFI). The number of bits per downlink slot is not fixed but may vary from 20-1280, corresponding to 32-2048 kbps data rate.

![Diagram](image.png)

**Figure 2: Spreading/Modulation for Downlink Dedicated Physical Channel**

For the downlink, data modulation is QPSK in which each pair of two bits are serial-to-parallel converted and mapped to the I and Q branch, respectively (Figure 2). The I and Q branch are then spread to the chip rate with the same channelization code $C_{ch}$ and subsequently scrambled by the same cell specific scrambling code $C_{scramble}$. The channelization codes are orthogonal variable spreading factor (OVSF) codes that preserve the orthogonality between downlink channels of different rates and spreading factors. The OVSF codes are defined using a code tree. The downlink scrambling code $C_{scramble}$ is a 40960 chips (10 ms) segment having a length $2^{18} -1$ Gold Code [5] repeated in each frame. The total number of available scrambling codes is 512, divided into 16 code groups with 32 codes in each group. The grouping of a downlink code is done to facilitate a fast cell search.

The parameter $k$ determines the number of bits per Dedicated Physical Data Channel (DPDCH) or Dedicated Physical Control Channel (DPCCCH) slot. It is related to spreading factor (SF) of the physical channel as $SF = 256/2^k$. The spreading factor may range from 256 down to 4. Note that the DPDCH and DPCCCH may be of different rates, having different SFs and thus different values of $k$.

DPDCH and DPCCCH are I & Q code multiplexed within each radio frame and transmitted with dual-channel QPSK modulation. Each additional DPDCHs is code multiplexed on either the I- or the Q-branch with this first channel pair.

The channelization code for the BCCH is a predefined code that is the same for all cells within the system. The channelization code(s) used for the Secondary Common Control Physical Channel (CCPCH) is broadcasted on the BCCH. The channelization codes for the downlink Dedicated Physical Channels (DPCHs) are decided by network. The mobile is informed about what downlink channelization codes to receive in the downlink Access Grant message that is a base station response to an uplink Random Access request. The set of channelization codes may be changed during the duration of a connection, typically as a result of change in service or inter-cell handover. A change of downlink channelization codes is negotiated over the DCCH.

![Diagram](image.png)

**Figure 3: Spreading/Modulation for Uplink Dedicated Physical Channel**

A downlink scrambling code is assigned to the cell(sector) at initial deployment. The mobile learns about the downlink scrambling code during the cell search process. Each connection is allocated at least one uplink channelization code to be used for the Dedicated Physical Control Channel (DPCCCH). In most cases, at least one additional uplink channelization code is allocated for a Dedicated Physical Data Channel (DPDCH). Further uplink channelization codes may be allocated if more than one DPDCH is required.

Two types of dedicated physical channels are defined for the uplink: DPDCH and DPCCCH. The DPDCH carries layer 2 dedicated data, and DPCCCH carries layer 1 control information. Layer 2 and layer 1 data is transmitted in parallel on different physical channel. On the uplink, bits/slot may vary from 10 to 640, corresponding to 16-1024 kbps data rate.

As different mobiles use different uplink scrambling codes, the uplink channelization codes may be allocated with no coordination between different connections. The uplink channelization codes are, therefore, always allocated in a predetermined order. The mobile and network only need to agree on the number of uplink channelization codes. The exact codes to be used are then implicitly given. The uplink primary scrambling code is decided by the network. The mobile is informed about what primary scrambling code to use in the downlink Access Grant message. The primary scrambling code may, in rare cases, be changed during the duration of a connection. A change of uplink primary scrambling code is negotiated over the DCCH. The secondary uplink scrambling code is optional, typically used in cells without multician detection in the base station. The mobile is informed if a secondary scrambling code should be used in the Access Grant.
message following a random-access request and a handover message.

The primary scrambling code is a complex code \( C_{\text{scramb}} = C_1 + jC_Q \), where \( C_1 \) and \( C_Q \) are two different codes from the extended very large Kasami set [5] of length 256. The secondary scrambling code is a 40960 chips (10 ms) segment of length \( 2^{41} \)-1 Gold Code.

Data modulation is dual-channel QPSK, in which the DPDCH and DPCCH are mapped to the I and Q branches, respectively (Figure 3). The I and Q branch are spread to a chip rate with two different channelization codes \( C_D \) and \( C_C \) and subsequently complex scrambled by a mobile specific primary scrambling code \( C_{\text{scramb}} \). The scrambled signal may then optionally be further scrambled by a secondary scrambling code \( C''_{\text{scramb}} \).

The primary and secondary CCPCHs are fixed rate downlink physical channels used to carry the BCCH and FACH/PCH, respectively. The CCPCH is modulated and spread in the same way as the downlink dedicated physical channels. In the case of secondary CCPCH, the FACH and PCH are time multiplexed on a frame-by-frame basis within a superframe structure. The set of frames allocated to FACH and PCH, respectively is broadcast on the BCCH.

The main difference between CCPCH and a downlink dedicated physical channel is that a CCPCH is not power controlled and is of constant rate. The main difference between the primary and secondary CCPCH is that the primary CCPCH has a fixed predefined rate of 32 kbps, whereas the secondary CCPCH has a constant rate that may be different for different cells, depending on the capacity required for FACH and PCH. A primary CCPCH is continuously transmitted over the entire cell while the secondary CCPCH is only transmitted when there is data available and may be transmitted in a narrow lobe in the same way as a dedicated physical channel.

Parallel transport channels (TrCh-1 and TrCh-M) are separately channel-coded and interleaved. The coded transport channels are then time-multiplexed into a coded composite transport channel (CC-Tr-Ch). Interframe (10ms) interleaving is carried out after transport-channel multiplexing. 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:

- Rate 1/3 convolutional coding is typically applied for low delay services such as voice with moderate error rate requirements (BER \( \approx 10^{-3} \))
- A concatenation of rate 1/3 convolutional coding and Reed-Solomon coding plus interleaving can be applied for high-quality service (BER \( \approx 10^{-5} \))
- Turbo codes are also being considered and will most likely be used for high-rate-quality services.

Rate matching is applied to match the bit rate of the CC-Tr-Ch to one of the limited set of bit rates of the uplink or downlink physical channel. Two different rate-matching steps are carried out: Static Rate Matching and Dynamic Rate Matching. Static rate matching is carried out with 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-Tr-Ch is matched to the bit rate of the physical channel. Static rate matching is applied on both uplink and downlink. 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-Tr-Ch is exactly matched to the bit rate of the physical channel. Dynamic rate matching is only applied to the uplink.

FCH indicates transmission rate for the current rate on the DPDCH. The coding for the 6 bit FCH is mapped to biorthogonal Walsh functions of length 2 that represent the 64 different values for FCH. The FCH data is interleaved and multiplexed over the entire DPCCH frame.

An access attempt corresponds to a random-access burst that consists of two main parts: the preamble part and the message part. The preamble consists of a length-16 complex symbol sequence, the random access signature, spread by cell-specific preamble code of length 256 chips. The message part is divided 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 TFI to indicate the bit rate of the data part of the random access burst. The random access burst 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.

3.2 North American cdma2000 System

The cdma2000 system provides a wide range of implementation options to support data rates (for circuit and packet data services) from 9.6 kbps up to greater than 2 Mbps. It provides maximum flexibility by allowing service providers to make engineering tradeoffs between channel sizes in multiples of 1.25 MHz equal to 1, 3, 6, 9, and 12. It incorporates advanced antenna technologies, and supports advanced services that are not practical in other systems (e.g., high speed circuit data B-ISDN or H.224/223 (telecommunications). It is claimed that the cdma2000 system can be operated economically in wide range of environments including outdoor megacell (>35 km radius), outdoor macrocells (1-35 km radius), indoor/indoor microcells (up to 1 km radius), and indoor/outdoor picocell (<50 m radius), and deployed in indoor office environment, wireless local loop, vehicular, and mixed vehicular and indoor/outdoor environments.

The main differences between W-CDMA and cdma2000 systems are chip rate, downlink channel structure, and network synchronization [1],[6]. Cdma2000 uses a chip rate of 3.6864 Mcchip/s for 5 MHz bandwidth with a direct spread downlink (forward link), and a 1.2288 Mcchip/s chip rate for a multicarrier downlink. The multicarrier approach partitions the downlink spectrum into multiple 125 MHz carriers. This option is useful for overlaying a cdma2000 system over an existing cdmaOne network. Moreover, the multicarrier approach provides transmit diversity on the downlink. The uplink (reverse link) only
supports the direct spread approach. As with IS-95B, the spreading code of cdma2000 is generated using different phase shifts of the same PN-sequence. This is possible due to the synchronous network operation. A bandwidth of 5 MHz can resolve a greater degree of multipath propagation than a narrower bandwidth, increasing diversity and improving system performance. Larger bandwidths of 10, 15, and 20 MHz have been proposed to support the highest data rates more efficiently.

A complex spreading is used to reduce peak-to-average power and improve power efficiency. The spreading modulation can be either balanced or dual-channel QPSK. In the balanced QPSK spreading, the same data signal is divided into I and Q channels. In dual-channel QPSK spreading, the symbol streams on the I and Q channels are independent of each other. On the downlink, QPSK data modulation is used to save code channels. QPSK data modulation allows the use of the same orthogonal sequence for both I and Q channels.

Cdma2000 incorporates coherent detection on the uplink to improve its performance compared to noncoherent reception used by IS-95. A pilot signal on the uplink will be used to facilitate coherent detection. The cdma2000 uses fast closed loop power control on the downlink-dedicated channels with 800 updates per second. The closed loop power control compensates for medium to fast fading and for inaccuracies in open loop power control. Also, fast power control is effective for adaptation of dynamically changing interference conditions due to the activation and deactivation of high power, high data rate users. The power of the uplink channels for a specific user is adjusted at a rate of 800 bits per second. The uplink power control bits are punctured onto a dedicated downlink channel. Additionally, the uplink utilizes turbo codes, which outperform convolutional codes for data rates greater than 9.6 kbps. Since the capacity of a CDMA system is very dependent on the operating $E_b/N_0$ of the receiver, this improvement increases the capacity of the uplink.

The cdma2000 system supports 5 and 20 ms frames for control information on the fundamental, and dedicated channels, and uses 20 ms frames for other types of data (including voice). Interleaving and sequence repetition are over the entire frame interval. This provides improved time diversity over systems that use shorter frames. A 20 ms frame is used for voice. A shorter frame would reduce one component of the total voice delay, but degrade the demodulation performance due to the shorter interleaving span. The cdma2000 uses several approaches to match the data rates to the Walsh spreader input rates including adjusting the code rate, using symbol repetition with or without symbol puncturing, and sequence repetition.

Similar to W-CDMA, cdma2000 also uses a layered structure. The link layer offers the protocol support and control mechanisms to provide data transport services. It supports varying levels of reliability and QoS characteristics as per needs of the specific upper layer service. It performs all of the functions that are necessary to map data transport needs of the upper layers into the specific capabilities and characteristics of the physical layer. Link layer maps logical data and signaling channels into code channels that are specifically supported by coding and modulation function of the physical layer. The link layer is subdivided into two sublayers: link access control (LAC), and media access control (MAC). The LAC manages the point to point communication channels between peer upper layer entities.

![Figure 4: Future Cellular/PCS Network Architecture](image)

**4.0 Industry Trends**

Because of the explosive growth of mobile wireless usage and the need for high-speed data services, the efficiency of allocated spectrum must be significantly improved. Moreover, globalization requires world-wide harmonization. Consequently, several 3G proposals, which have been discussed in this paper, are being considered by the ITU. One or more of these proposals will be adopted. The essence is that 3G air interfaces will provide the user required services in a seamless manner for a competitive price during the next decade.

Figure 4 shows a typical network architecture that may be used for deploying 3G services. In Europe and Asia where GSM has been deployed extensively, higher data rate services will be offered via EDGE which ultimately will evolve to W-CDMA. In North America, IS-95A systems will be upgraded to IS-95B to offer circuit and packet data services up to 64 kbps. It is expected that ITU will approve multiple air interfaces including cdma2000, W-CDMA (FMA2), W-TDMA (FMA1 without spreading), and TD-CDMA (FMA1 with spreading). The IS-136 based TDMA systems will offer higher data rate services via IS-136+ and W-TDMA and finally be evolved to W-CDMA. To achieve international roaming interworking functions will be provided between cdma2000 and W-CDMA.

**5.0 References**

3. TR-45 Proposed RTT Submission (UWC-136),” TR-45.3/98.03.03.19, March, 1998