Recent Advances in Cellular Wireless Communications

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ABSTRACT Testimonies of “wireless catching up with wireline” have begun. An information superhighway system is envisioned to fulfill the plethora of demand for wireless communications and the need for multimedia networks with multiservice requirements. The revolution in this technology will eventually free us, as communication users, from being tied down to a particular fixed location in a telephone network to person-to-person communications, via pocket-sized terminals, at an affordable price. This article briefly surveys the state of the art, standards, and technological growth experienced in mobile cellular (terrestrial and satellite) communications since the days of the ingenious inventions of Alexander Graham Bell and Guglielmo Marconi, over a century ago. Subsequently, we describe some emerging technological trends that can improve the capacity of third-generation systems and future outlooks for PCSnetworks in the next millennium.

Marconi’s innovative perception of the electromagnetic waves and the air interface in 1897 was the first milestone on the important road to shared use of the radio spectrum. But only after almost a century later did mobile wireless communication[1] start to take off. Despite a series of disappointing false starts, the communication world in the late 1980s was rapidly becoming more mobile for a much broader segment of communication users than ever before. Historically, communication has been restricted primarily to voice traffic between two fixed locations rather than between two people. With the advent of wireless technology, a transition from point-to-point communication toward person-to-person communication (i.e., independent of location) has begun. Testimony to this is the rapidly increasing penetration of cordless and cellular phones, not just in North America but all across the world. In anticipation of the growing consumer demands, the next generation of wireless systems endeavors to provide person-to-person communication of both circuit and packet multimedia data. Henceforth in this article we shall place greater emphasis on the advances in mobile cellular communication and paging, which represents the fastest growing segment of wireless technology.

Initial AM mobile systems used for public safety in the United States since the 1930s were replaced with FM systems after World War II. However, the wireless system configuration remained a single-cell topology (similar to the broadcast model). Later, in the 1950s and 1960s, automatic channel trunking was introduced and implemented under the label Improved Mobile Telephone Service (IMTS) to increase spectrum efficiency. The current cellular configuration was also conceived during this time in response to the chronic problem of spectral congestion (the market gets quickly saturated even with IMTS systems) and poor service in the mobile telephone business. The government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services. Therefore, it became imperative to restructure the radio telephone system to achieve high capacity with limited radio spectrum, while at the same time covering very large areas. However, this novel architecture was only launched in the 1980s when the first commercial mobile telephony was introduced.

The first-generation cellular and cordless telephone networks, which were based on analog technology with FM modulation, have been successfully deployed throughout the world since the early and mid-1980s. A typical example of a first-generation cellular telephone system is the Advanced Mobile Phone Services (AMPS). Second-generation (2G) wireless systems employ digital modulation and advanced call processing capabilities. In view of the processing complexity required for these digital systems, two offered advantages are the possibility of using spectrally efficient radio transmission schemes (e.g., time-division multiple access, TDMA, or code division multiple access, CDMA, in comparison to the analog frequency division multiple

	GSM/DCS-1800	IS-54/136	PDC	1S-95
Region	Europe	North America	Japan	North America
Frequency band (MHz)	900/1800/1900	800/1900	700/1500	800/1900
Multiple access	F/TDMA	F/TDMA	F/TDMA	F/CDMA
Carrier spacing (kHz)	200	30	25	1250
Modulation	GMSK	OQPSK	OQPSK	BPSK/QPSK
Speech coding (kb/s)	VSELP (HR-5.6) RPE-LTP (FR-13) ACELP (EFR-12.2)	VSELP (FR-7.95) ACELP (EFR-7.4)	PSI-CELP (HR-3.45) VSELP (FR-6.7)	QCELP (8, 4, 2, 1) RCELP (EVRC)
Frame size (ms)	4.6	40	20	20
Channel coding (convolution code)	Rate 1/2	Rate 1/2	Rate 1/2	Rate 1/2 or 1/3

HR: half-rate codec; FR: full-rate codec; EFR: enhanced full-rate codec; EVRC: enhanced variable rate codec
An adaptive multitate (AMR) codec for GSM is currently being standardized by ETSI

Table 1. *Air interface characteristics of 2G systems.*

[1] *The line-of-sight (LOS) microwave link is an example of fixed wireless access communication.*

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access, FDMA, schemes previously employed) and the provision for implementation of a wide variety of integrated speech and data services such as facsimile, paging, and low-data-rate network access. Examples of 2G wireless systems include the Global System for Mobile Communications (GSM), TDMA IS-54/IS-136 and CDMA IS-95 digital cellular standards in the United States, Personal Digital Cellular (PDC) in Japan (which is the second largest digital cellular system after GSM), CT2, Digital Enhanced Cordless Telecommunications (DECT), Personal Access Communications System (PACS), and Personal Handyphone System (PHS), to name a few.

Third-generation (3G) wireless systems will evolve from mature 2G networks, with the aim of providing universal access and global roaming. More important, these systems are expected to support multidimensional (multi-information media, multitransmission media, and multilayered networks) high-speed wireless communications — an important milestone toward achieving the grand vision of ubiquitous personal communications. Introduction of wideband packet data services for wireless Internet up to 2 Mb/s will probably be the main attribute of 3G systems.

	CT2	CT2+	DECT	PHS
Region	Europe	Canada	Europe	Japan
Duplexing	TDD	TDD	TDD	TDD
Frequency band (MHz)	864–868	944–948	1880–1900	1895–1918
Carrier spacing (kHz)	100	100	1728	300
Number of carriers	40	40	10	77
Bearer channels/carrier	1	1	12	4
Bit rate (kb/s)	72	72	1152	384
Modulation	GFSK	GFSK	GFSK	$\pi/4$ DQPSK
Speech coding	ADPCM 32 kb/s	ADPCM 32 kb/s	ADPCM 32 kb/s	ADPCM 32 kb/s
Mean TX power (mW)	5	5	10	10
Peak TX power (mW)	10	10	250	80
Frame duration (ms)	2	2	10	5

Table 2. *A comparison of CT2/CT2+, DECT, and PHS.*

SECOND-GENERATION CELLULAR SYSTEMS AND CORDLESS TELEPHONY

A common feature to all 2G systems is that they are digital. Digital cellular has become a true success, with more than 100 million subscribers worldwide since its introduction in the early 1990s. Also, its growth rate is phenomenal. By 2001 it is anticipated that there will be more than 500 million subscribers to digital systems. Table 1 shows the air interface characteristics of some of the 2G systems; Table 2 compares CT2/CT2+, DECT, and PHS.

Standardization has played a crucial role in the development of 2G systems. For instance, the pan-European GSM for was created to replace a large variety of disparate (incompatible) analog cellular systems such as Nordic Mobile Telephone Systems (NMTS), Total Access Communication Systems (TACS), and the German System C, with the most important goal of seamless roaming in all countries. In North America and Japan, however, where unique analog systems existed, the need to standardize IS-54, IS-95, and PDC arose from the lack of spectrum to serve the high traffic density areas. Although the processing complexity of these digital systems are greater than their analog counterparts, they possess three inherent benefits:

- The possibility of using spectrally efficient radio transmission schemes
- Facilitation of the implementation of a wide variety of integrated speech and data services
- Enhanced security features

During the development of IS-54, the major constraints were to provide a substantial increase in system capacity while sustaining backward compatibility with widespread AMPS (e.g., through the dual-mode base station, BS, and mobile station, MS). Although the FCC has decided to open the existing cellular band to any suitable technology, the air interface specifications of the second digital standard in North America, namely IS-95, also meet requirements similar to IS-54 (i.e., significant increase over analog system capacity, ease of transition, and compatibility with the existing analog system), but with completely different technical solutions based on spread-spectrum technology. A detailed description of the various 2G systems may be found in [1].

Cordless technology is essentially a companion to cellular radio (Table 3). It is characterized by low mobility (low range and user speed), low power (i.e., limited coverage), and two-way tetherless toll-quality voice communications. Cordless technology today has evolved from its intended application for private residential to private business environments such as wireless private automatic branch exchange (PABX) and telepoint access in the public domain with two-way calling capability. Therefore, it is capable of providing low-cost multitudinous access points in urban densely populated areas. CT2/CT2+, DCT900, DECT, PHS, and cordless in the industrial, scientific, and medical (ISM) bands are among the popular 2G cordless systems.

Characteristics	Digital cordless	Digital cellular
Cell size	Small (50–500 m)	Large (0.5–30 km)
Antenna elevation	Low (< 15 m)	High (> 15 m)
Mobility speed	Low (< 6 km/hr)	High (< 250 km/hr)
Coverage	Zonal	Wide area
Handset complexity	Low	Moderate
Spectrum access	Shared	Exclusive
Handset TX power	5–10 mW	100–600 mW
Duplexing	TDD	FDD
Speech coding	32 kb/s ADPCM	8–13 kb/s vocoder
Error control	CRC	FEC/interleaving
Detection	Differential	Coherent differential
Multipath mitigation	Antenna diversity (optional)	Diversity/rake/equalizer

Table 3. *A general comparison of digital cordless and cellular.*

THIRD-GENERATION CELLULAR NETWORKS

The third generation of mobile cellular systems are intended to unify the diverse systems we see today into a seamless radio

Proposal	Description	Source
DECT	Digital Enhanced Cordless Telecommunications	ETSI Project DECT
UWC-136	Universal Wireless Communications	USA TIA TR45.3
WIMS W-CDMA	Wireless Multimedia and Messaging Services Wideband CDMA	USA TIA TR46.1
TD-SCDMA	Time-division synchronous CDMA	China CATT
W-CDMA	Wideband CDMA	Japan ARIB
CDMA II	Asynchronous DS-CDMA	S. Korea TTA
UTRA	UMTS Terrestrial Radio Access	ETSI SMG2
NA: W-CDMA	North American: Wideband CDMA	USA T1P1-ATIS
cdma2000	Wideband CDMA (IS-95)	USA TIA TR45.5
CDMA I	Multiband synchronous DS-CDMA	S. Korea TTA

Table 4. *Radio transmission technology proposals for IMT-2000.*

infrastructure capable of offering a wide range of services in many different radio environments, with the quality we have come to expect from wireline telecommunications networks.

Since the mid-'80s, studies on 3G system have been carried out within the International Telecommunication Union (ITU), and particularly within TG8/1, where it was called Future Public Land Mobile Telecommunication Systems (FPLMTS), lately renamed International Mobile Telecommunications — 2000 (IMT-2000)[2, 3]. In Europe, research and development on 3G technology, commonly referred to as the Universal Mobile Communication System (UMTS) and Mobile Broadband System (MBS), have been conducted under the European Community Research into Advanced Communications in Europe (RACE) and Advanced Communications Technologies and Services (ACTS) programs [4]. With support from activities in Europe, the United States, Japan, and developing countries, WARC '92 of ITU identified global bands 1885–2025 MHz and 2110–2200 MHz for IMT-2000, including 1980–2010 MHz and 2170–2200 MHz for the mobile satellite component.[2]

Some major objectives envisioned for IMT-2000 and their key differences from the current 2G mobile system are briefly summarized as follows:

- Use of a common global frequency band for both terrestrial and satellite components, as identified at WARC '92 and WRC '95
- Use of a small pocket terminal with worldwide roaming
- Maximizing the commonality and optimization of radio interfaces for multiple operating environments, such as vehicular, pedestrian, office, and fixed wireless access (FWA) systems
- Significantly high transmission speed capability encompassing circuit- and packet-switched as well as multimedia services
- Support for both symmetric and asymmetric data capabilities in all operating environments
- Compatibility of services within IMT-2000 and with fixed networks
- Spectrum efficiency, quality, flexibility, and overall cost improvement as a result of the utilization of advanced technologies

[2] *The frequency allocation for region 2 of mobile satellite services (MSS) has been modified by WRC '95.*

Radio Transmission Technologies Proposals for IMT-2000

Key elements in the definition of 3G systems are the radio access system and radio transmission technology (RTT). In recent years, standardization activities on IMT-2000 have accelerated toward concrete specifications. A formal request by the ITU — Radiocommunication Standardization Sector (ITU-R) for submission of candidate RTTs for IMT-2000 has been distributed by the ITU, with a closing date of June 1998. Independent evaluations of these proposals, based on Recommendation ITU-R M.1225, will be submitted to ITU-R. The completion of detailed ITU-R standards in time for service is planned at the beginning of the year 2000 [5].

The minimum performance capabilities for user data rate (for both packet and circuit data) specified by IMT-2000 in four different test operating environments are as follows:

- Vehicular environment: 144 kb/s
- Pedestrian environment: 384 kb/s
- Indoor office environment: 2.048 Mb/s
- Satellite environment: 9.6 kb/s

By the end of June 1998, there were 10 proposals submitted to ITU-R for candidate RTTs on the IMT-2000 terrestrial component from the United States, Europe, Japan, China, and Korea, as listed in Table 4 [5]. In all the proposals, except the UWC-136 proposal from TR45.3 and the DECT-based proposal from ETSI DECT, direct-sequence CDMA (DS-CDMA) has been chosen as a leading multiple access technique. The UWC-136 proposal is the 3G evolution of the IS-136 family of standards, which meets IMT-2000 objectives via modulation enhancement to the existing 30 kHz 136 channel (136+) and defines complementary wider-band TDMA carriers (136HS, supporting high-speed data services) to facilitate those services that are not possible on the 30 kHz carrier. The main parameters of the UWC-136 proposal are summarized in Table 5.

	UWC-136	UWC-136+	UWC-136HS (outdoor/Vehicular)	UWC-136HS (indoor)
Multiple access	TDMA	TDMA	TDMA	TDMA
Duplex scheme	FDD	FDD	FDD	FDD and TDD
Channel spacing	30 kHz	30 kHz	200 kHz	1600 kHz
Modulation	π/4 DQPSK	CCH: π/4-DQPSK; TXH: π/4-QPSK and 8-PSK (DTCH)	8-PSK, GMSK	Q-O-QAM, B-O-QAM
Frame length	40 ms	40 ms	4.6 ms	4.615 ms
No. slots/frame	6	6	8	64@72 µs 16@288 µs
Gross bit rate	48.6 kb/s	72.9 kb/s (8PSK) 48.6 kb/s (QPSK/DQPSK)	812.5 kb/s (8-PSK) 270.8 kb/s (GMSK)	5.2 Mb/s (Q-O-QAM) 2.6 Mb/s (B-O-QAM)

Table 5. *Parameters of UWC-136. (Note: The 200 kHz carrier has the same parameters as EDGE.)*

Proposal	UTRA	cdma2000	WCDMA/NA	WIMS W-CDMA	W-CDMA	TD-SCDMA	CDMA II	CDMA I
Multiple-access	FDD: DS-CDMA TDD: T/CDMA	FDD: DS-CDMA TDD: T/CDMA	FDD: DS-CDMA TDD: T/CDMA	FDD: DS-CDMA TDD: DS-W-CDMA(FL) DS-S-TDMA (RL)	FDD: DS-CDMA TDD: T/CDMA	TDMA/CDMA	DS-CDMA	DS-CDMA
Duplex scheme	FDD/TDD	FDD/TDD	FDD/TDD	W-CDMA FDD mode: FDD S-TDMA TDD mode: TDD	FDD/TDD	TDD	FDD	FDD
Chip rate (Mc/s)	FDD: 4.096/ 8.192/16.384 TDD: 4.096	1.2288xN Mcps (NX)	FDD: 4.096/8.192/ 16.384 TDD: 4.096	4.096/8.192/ 16.384	1.024/4 096/ 8.192/16 384	1.1136	1.024/4.096/ 8.192/16.384	0.9216/3.6864/ 14.7456
Frame length	10 ms	20/5 ms	10 ms	10 ms	10 ms	5 ms	10 ms	10 ms
Channel coding	Convolutional coding (rate 1/2, 1/3, *K* = 9); optional outer RS coding (rate TBD)	Convolutional coding (R=1/2, 1/3, 1/4, *K* = 9); Turbo code of R=1/2, 1/3, 1/4 and *K* = 4 (preferred for date transmission over 14.4 kb/s on supplemental channel)	Convolutional coding (rate 1/2, 1/3, *K* = 9); optional outer RS coding (*R* = 4/5)	Convolutional coding (FL: *R* = 1/2, *K* = 7, RL: *R* = 1/3, *K* = 9)	Convolutional coding (*R* = 1/2, 1/3, *K* = 9); Turbo code of *R* = 1/3 *K* = 3 (data transmission over 32 kb/s)	Convolutional coding (*R* = 3/4, ***K*** = 9); optional outer RS code; Turbo code of *K* = 4, *R* = 1/2 (preferred for data rate greater than 19.2 kb/s NRT service)	Convolutional coding (*R* = 1/2, 1/3, 1/4, 1/6, *K* = 9), selectable FEC for low rate data; Turbo code of *R* = 1/3 and *K* = 3 for high rate data and packet data	Convolutional coding *R* = 1/2, 1/3, 1/4, 1/6); optional outer (47, 41) RS code
Interleaving	Inter/intraframe	Intraframe	Inter/intraframe	Block interleaving (no details given)	Multistage intra or inter-frame	Interframe,	Intraframe	Intraframe
Data modulation	FDD: FL: QPSK, RL: Dual-channel-QPSK; TDD: QPSK (RL&FL)	QPSK (FL) BPSK (RL)	FDD: FL: QPSK, RL: Dual-channel QPSK; TDD: QPSK (RL&FL)	QPSK	FDD: FL: QPSK, RL: Dual-channel QPSK TDD: QPSK	DQPSK, and 16QAM for high data rate	QPSK (FL) BPSK (RL)	FL: QPSK RL: BPSK
Spreading modulation	FDD: BPSK (FL), QPSK(RL); TDD: QPSK (RL&FL)	QPSK	FDD: BPSK (FL), QPSK(RL); TDD: QPSK (RL&FL)	QPSK	QPSK	BPSK	FL: QPSK RL: OCQPSK(CDTCH, ACCH)/ CQPSK(UPCH)	QPSK (FL) OCQPSK(RL)
Power control	Fast closed loop, open loop, and outer loop Step size: FDD: 0.25–1.5 dB TDD: 1.5–3 dB power control cycles: 1600/s (FDD) 100–800/s (TDD)	FDD: open loop and fast closed loop, FER based outer loop (RL) TDD: open loop step size: 1.0 dB nominal, optional 0.5/2.5 dB Power control cycles: 800/s nominal	FDD: fast closed loop and outer loop (RL&FL) Step size: FDD: 0.25–1.5 dB TDD: 2 dB Power control cycles: 1600/s (FDD) 100–800/s (TDD)	Adaptive power control step size: 1 dB nominal Power control cycles: 1600/s	FDD: RL: closed loop, open loop FL: closed-loop outer loop added TDD: RL&FL: closed loop step size 1 dB power control cycles: FDD: 1600/s TDD: 800/s	RL: open loop and closed loop; step size: 1 dB power control cycles: 200/s	RL: open loop and closed loop; FL: closed loop; FER based outer loop; step size: 1 dB Power control cycles: 1600/s	RL: open loop and closed loop; FL: closed loop; power control cycles: 1600/s
Diversity	RAKE in both BS and MS, antenna diversity in both BS and MS, transmit diversity (TBD)	RAKE in both BS and MS, antenna diversity in BS and optionally MS, delay transmit diversity may be used for both MS and BS	RAKE in both BS and MS, antenna diversity in BS and optionally in MS,	RAKE in both BS and MS, antenna diversity in BS	RAKE, antenna diversity in BS and optional in MS	a smart antenna with 8 elements array at BS	RAKE, antenna diversity, time switched transmission diversity for FL	RAKE, antenna diversity at BS, time switched transmission diversity for FL
Inter-BS synchronization	FDD: no accurate synchronization needed TDD: synchronous	Synchronized	FDD: no accurate synchronization needed TDD: synchronous-	Nonsynchronized	FDD: no accurate synchronization is needed. TDD: synchronous	Synchronized	Asynchronous; synchronous operation is also possible	Synchronous mode; optional asynchronous mode
Detection	MS& BS: pilot symbol based coherent detection	Coherent detection. MS&BS pilot channel based	MS& BS: pilot symbol based coherent detection	Coherent detection	MS&BS: pilot symbol based coherent detection	Coherent detection	Coherent detection. BS: pilot symbol based. MS: pilot channel based	Coherent detection. BS and MS: pilot channel based

Table 6. *Air interface specifications for third-generation CDMA-based proposals.*

Next, we will highlight the similarities and differences of all the CDMA-based RTT proposals. Some important air interface specifications of these proposals are summarized in Table 6. Common to almost all the CDMA-based proposals, the following system specifications/implementations characterize 3G CDMA systems:

- Wideband CDMA
- Pilot-aided coherent reverse link
- Fast closed loop power control in fthe orward link
- Antenna diversity in the BS
- Seamless interfrequency handoff to support hierarchical cells

It is further highlighted that these CDMA-based RTT proposals can be categorized into three classes based on their system specifications:

- UTRA (Europe), W-CDMA (Japan), WCDMA/NA (United States), CDMA II (Korea), WIMS-WCDMA (United States)
- cdma2000 (United States), CDMA I (Korea)
- TD-SCDMA (China)

The key differences between the groups are chip rate, synchronous/asynchronous BS operation and the pilot structures (TDM/CDM, common/dedicated). Although there are small differences in each group, convergence is occurring.[3]

Multiple Access and Duplex — In most of the CDMA-based RTT proposals, wideband CDMA has been proposed for the system with bandwidth 5–20 MHz, due to its inherent advantages in terms of multipath resolution capability, lower transmission power, and support for high-bit-rate service [7]. One exception is the time-division synchronous CDMA (TD-SCDMA) proposal of China CATT, in which narrowband CDMA with a chip rate of 1.1136 Mcps is adopted. Among the wideband CDMA-based proposals, a typical chip rate of 4.096 Mcps is used for 5 MHz band allocation. It is claimed that the choice of the chip rate 4.096 Mchips/s is mainly based on consideration of backward compatibility with GSM and PDC. Differently, the cdma2000 proposal of Telecommunications Industry Association (TIA) TR45.5 and the CDMA I proposal of Korea TTA have specified a chip rate of 3.6864 Mchips/s, which is directly derived from the IS-95 chip rate. In addition, the cdma2000 proposal allows a multicarrier option on the forward link with a fixed chip rate of 1.2288 Mchips/s per carrier. The multicarrier approach can provide flexibility in bandwidth allocation and deployment strategy by allowing multiple bandwidth systems to be overlaid on top of each other.

Frequency-division duplex (FDD) mode is considered the major duplexing technology in almost all proposals except the Chinese TDD-SDCDMA proposal. Nevertheless, time-division duplex (TDD) mode is also supported by proposals such as W-CDMA, UTRA, cdma2000, W-CDMA/NA and WIM W-CDMA. The introduction of a TDD mode is mainly because of the asymmetric frequency bands designated by the ITU. Besides, there are some bandwidths of the spectrum that are planned or being utilized for TDD-TDMA system (e.g., 1900–1920 MHz for TDD-WLL in China, 1850–1990 MHz for PCS in the United States, 1885–1920 MHz for DECT in Europe, and 1895–1918 MHz for PHS in Japan), as illustrated in Fig. 1. Also, the asymmetric nature of the data traffic on the forward and reverse links anticipated in the next-generation wireless systems (e.g., Internet applications) suggests that unpaired TDD mode may sometimes be preferred over paired FDD mode to efficiently utilize the available resources. Thus, an air interface with provision of both FDD and TDD can provide sufficient flexibility of spectrum allotment. Due to this consideration, in the W-CDMA, UTRA, cdma2000, and W-CDMA/NA, TDD mode has been designed as similar to the FDD mode as possible. This will facilitate easy implementation of dual-mode FDD/TDD phones as well as reuse of integrated circuits (ICs) in single-mode TDD phones. In contrast, the WIM W-CDMA applies a different design for its TDD mode, in which DS-S-TDMA is used for the reverse link and wideband CDMA for the forward link.

Physical Channel Configuration — The physical channels are handled within the physical layer. In FDD mode, a physical channel is defined by its code and frequency. It may also be defined by the relative phase (I/Q). In TDD mode, the code, frequency, and timeslot define a physical channel. In general, physical channels can be broadly categorized into two basic classes: dedicated physical channel (DPCH) and common physical channel (CPCH). It is noted that the emphasis for forward and reverse link physical layer designs are different. In the forward link, efficient spectrum utilization and high traffic throughput are the prime concerns. However,

[3] *Various international standards development organizations have agreed to cooperate in the preparation of globally applicable technical specifications for 3G mobile systems under 3GPP and 3GPP2 partnership projects [6].*

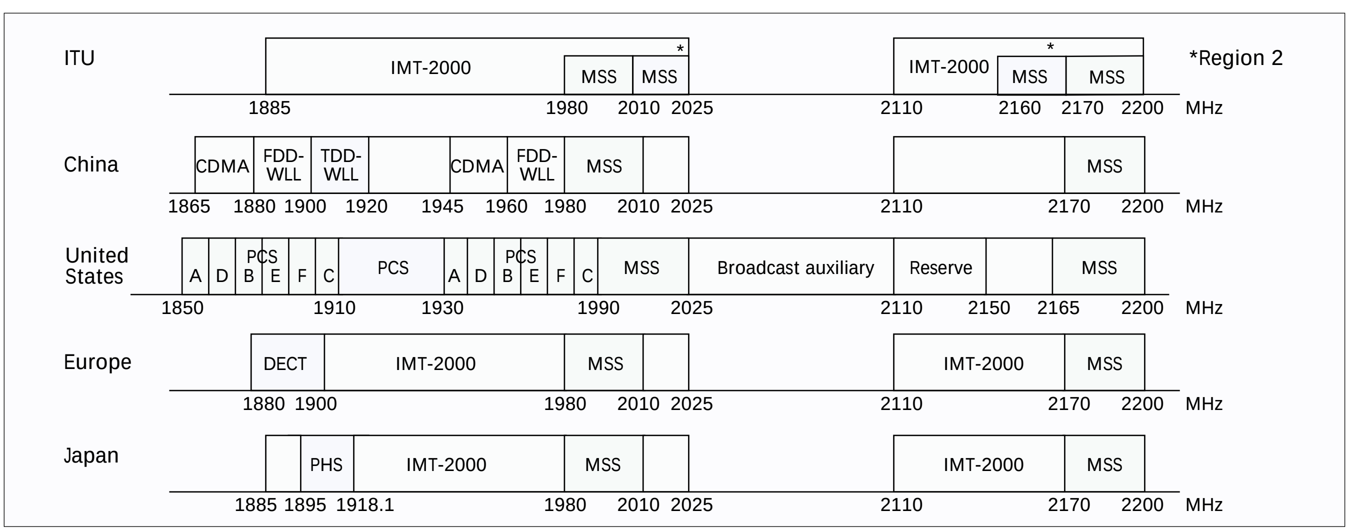


Figure 1. *Frequency allocation around the world.*

Proposal	Forward link			Reverse link	
	CPCH	DPCH	Others	CPCH	DPCH
WIM W-CDMA/FDD	Primary and secondary CCPCH	DPDCH	-	PRACH	DPDCH
TD-SCDMA	Primary and secondary CCPCH	DTCH	-	PRACH	DTCH
W-CDMA	F-CPCH	DPDCH/DPCCH	Perch Channel	R-CPCH	DPDCH,DPCCH
CDMA II	F-CPCH, F-CPCH for packet control	F-DTCH, F-SCH	Index Pilot Channel Cell Pilot Channel	CPCH	DPTCH/DPSCH, DPCCH
UTRA	Primary and secondary CCPCH, SYCH	DPDCH/DPCCH	-	PRACH	DPDCH, DPCCH
NA: W-CDMA	Primary and secondary CCPCH, SYCH	DPDCH/DPCCH	-	PRACH	DPDCH, DPCCH
cdma2000	F-PICH, F-CAPICH, F-SYCH, F-PGCH, F-CCCH	F-DAPICH, F-FCH F-DCCH, F-SCHT	-	R-ACH, R-CCH	R-PICH, R-FCH R-DCCH, R-SCHT
CDMA I	F-PICH, F-SYCH,F-PGCH, F-CPCCH with ACB, F-CTCH/SCH	F-DTCH, F-SCH	-	R-ACH, R-ADCH R-CTCH	R-SCH, R-PICH, R-DTCH

Table 7. *Physical channel configuration in the IMT-2000 proposals. (Note: For convenience of description, some modifications have been made to the abbreviations.*

power consumption for lighter and longer battery life terminals is the most important factor in the reverse link. These considerations impact the configuration of physical channels for the forward and reverse links.

Reverse Link Physical Channels — In the European UTRA proposal, the North American W-CDMA/NA proposal, and the Japanese W-CDMA proposal, two types of DPCH are defined in the reverse link, the dedicated physical data channel (DPDCH) and the dedicated physical control channel (DPCCH). The DPCCH is used to carry control information generated at layer 1, which consists of known pilot bits to support channel estimation for coherent detection, transmit power control (TPC) commands, and an optional part. In the UTRA, the optional part is a transport format indicator (TFI) which is used to inform the receiver about the instantaneous parameters of the different transport channels multiplexed in the reverse link DPDCH. In W-CDMA and W-CDMA/NA, this part consists of the rate information (RI). In the reverse link, the DPDCH and DPCCH are I/Q multiplexed. I/Q multiplexing can avoid bursty transmission which may cause unnecessary problems from electromagnetic compatibility (EMC). Moreover, it allows continuous monitoring of the channel even during periods of no speech activity. Besides the DPCHs, one type of reverse-link CPCH is defined to carry the random access channel (RACH) in all these proposals, namely, the physical RACH (PRACH) in UTRA and W-CDMA/NA, and the common physical channel in W-CDMA, respectively.

Differently, the reverse-link DPCH of cdma2000 includes a reverse pilot channel, fundamental channel, supplemental channel, and dedicated control channel. Furthermore, two types of CPCH are defined in the reverse link, the reverse access channel (R-ACH) and common control channel (R-CCCH).

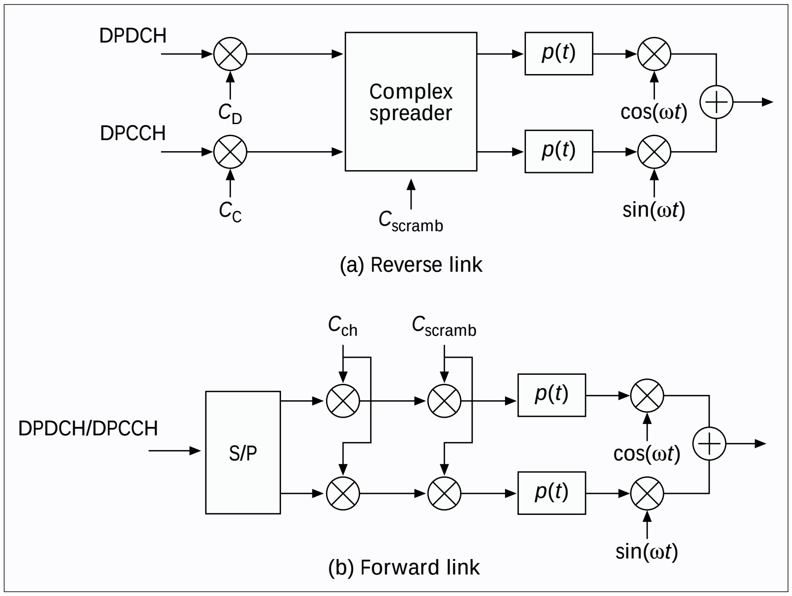
Two Korean proposals have different physical channel configurations. In CDMA I, the reverse dedicated traffic channel, signaling channel, and reverse pilot channel constitute the reverse-link DPCH, and the CPCH includes the reverse access channel, asymmetric dedicated channel, and common traffic channel. Differently, the reverse-link DPCH in CDMA II is composed of a time-multiplexed dedicated physical traffic channel (DPTCH)/dedicated signaling channel (DPSCH) and DPCCH. The DPCCH is used to carry the pilot symbol, TPC symbols, and optional RI, and I/Q multiplexed with DPTCH/DPSCH in the reverse link. There is only one type of CPCH defined by CDMA II for the reverse link.

In WIMS W-CDMA and TD-SCDMA, two types of physical channel are defined for the reverse link, the DPDCH and PRACH. The user information and control information are carried by the DPDCH.

Forward Link Physical Channels — In the UTRA, W-CDMA/NA and W-CDMA proposals, there is only one type of forward-link DPCH, within which dedicated data is transmitted in time multiplexing with control information generated at layer 1 (known pilot bits, TPC, and an optional TFI or RI). Thus, unlike in the reverse link, the forward-link DPCH can be seen as a time multiplex of a forward-link DPDCH and a DPCCH. The time-multiplex pilot structure introduces the simplicity of mobile receiver processing. Furthermore, it has been demonstrated that almost the same bit error rate (BER) performance as a parallel pilot structure can be achieved by using time-multiplex pilot [8]. UTRA and W-CDMA/NA specify three types of forward-link CPCH: primary and secondary common control physical channels (CCPCHs) and a synchronization channel (SYCH). The primary and secondary CCPCHs are used to carry the BCCH and FACH/PCH, respectively. The SYCH is a forward link signal used for cell search, which is only transmitted intermittently and multiplexed after long code scrambling of the DPCH and CCPCH. Differently, W-CDMA defines the forward link common physical channel as the carrier of PCH/FACH, and the BCCH, time-multiplexed with the cell search codes, is carried by the Perch channel.

In cdma2000, the forward-link DPCH is composed of a subset of the forward dedicated auxiliary pilot channel, fundamental channel, supplemental channel, and dedicated control channel. The CPCH includes the forward pilot channel, common auxiliary pilot channel, paging channel, common control channel, and synchronization channel.

In both Korean proposals, the forward DPCH consists of the forward dedicated traffic channel and signaling channel. In CDMA II, the TPC and RI symbols are included in the forward link signaling channel. As for CPCH, the forward pilot channel, sync channel, paging channel, forward common power control channel with an access control bit, and forward common traffic/signaling channel are specified in CDMA I, while only two types of CPCH are defined in CDMA II, the forward link common physical channel and forward link common physical channel for packet control. In addition, an index pilot channel and cell pilot channel are also specified in the CDMA II forward link.



■ **Figure 2.** *The UTRA modulation/spreading scheme.*

In the forward link there are three types of physical channel, the forward DPCH, primary CCPCH, and secondary CCPCH, are specified in both WIMS W-CDMA and TD-SCDM.

Spreading and Modulation — In a CDMA system, modulation consists of data modulation and spreading modulation. The data modulator maps the incoming coded data into possible transmitted symbols and feeds them to the spreading circuit, where the resulting signal is filtered and mixed with the carrier signal (i.e., spreading modulation). In the following discussions on the W-CDMA, UTRA, cdma2000, and W-CDMA/NA RTT proposals, we will restrict our focus on their FDD operation mode since TDD mode shares similar key features.

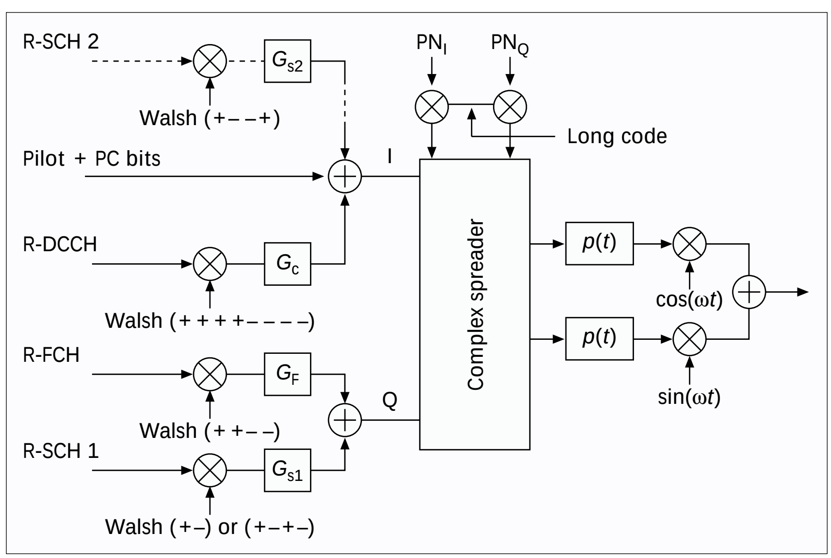
The European Proposal — In the UTRA proposal, dual-channel quadrature phase shift keying (QPSK) modulation is adopted on the reverse link, where the reverse-link DPDCH and DPCCH are mapped to the I and Q channels, respectively. The I and Q channels are then spread to the chip rate with two different channelization codes, and subsequently complex scrambled by an MS-specific complex code. For multicode transmission, each additional reverse link DPDCH may be transmitted on either the I or Q channel. Either short or long scrambling codes should be used on the reverse link. The short scrambling codes are generated from the Extended Very Large Kasami set of length 256. Since this set of codes includes more than one million different codes, no extensive code planning is needed. The long codes are generated from Gold sequences of length 2^{41}-1, and typically used in cells without multi-user detection in the BS to attain better correlation properties. Differently, the forward-link DPDCH and DPCCH are time-multiplexed and then modulated with QPSK. The I and Q channel are spread to the chip rate with the same channelization code and then scrambled by the same real cell-specific long code generated from Gold sequences of $2^{18} - 1$: binary PSK (BPSK) spreading. For both forward and reverse links, the channelization codes are orthogonal variable spreading factor (OVSF) codes which can be defined using a code tree structure. The modulation and spreading scheme of UTRA is depicted in Fig. 2.

North American Proposals — cdma2000 uses QPSK for data modulation in each physical channel on the forward link. The modulation symbols are spread with a Walsh code to provide orthogonal channelization among different channels and different users, and then scrambled by a cell-specific complex pseudo-noise (PN) sequence. The length of the Walsh codes varies according to the data rate. Quasi-orthogonal functions may be used when a Walsh code limit occurs. On the reverse link, as depicted in Fig. 3, each physical channel is first spread with a Walsh code to provide orthogonal channelization. Then the spread pilot and dedicated control channel are mapped into the I channel, and the spread fundamental channel and supplement channel are mapped into the Q channel.[4] The additional supplement channels can be accommodated by increasing the Walsh code for supplemental channel to 8 bits and mapping additional R-SCHs to either the I or Q channel. The I and Q channels are spread by a complex PN sequence. The complex PN sequence is generated by TIA/Electronics Industry Association (EIA)-95B I/Q channel PN sequences with a period of 2^{15} chips and an MS-specific long code with a period of $2^{41} - 1$ chips.

The proposed RTT in the North American W-CDMA/NA proposal is based on the ETSI RTT under development between T1P1, ETSI, and ARIB. It has almost the same modulation and spreading configuration as UTRA. The only difference is that on the reverse link a secondary scrambling code (generated from Gold sequences) may be used optionally for further scrambling, besides the primary scrambling code which is generated from the extended Very Large Kasami set.

In the FDD mode of the North American WIMS W-CDMA proposal, QPSK/QPSK is adopted for data/spreading modulation on both the forward and reverse links. Orthogonal

[4] *Optionally, two supplemental channels (SCHs) can be accommodated to support bearer service profiles where more than one SCH is needed In that case both SCHs are spread using a 4-bit Walsh code and then mapped to the I and Q channels, respectively.*



■ **Figure 3.** *cdma2000 reverse dedicated channel structure.*

Modified Quadratic Residue codes are used for channelization and long PN codes for complex scrambling.

The Japanese Proposal — In the W-CDMA proposal of ARIB, the configuration of reverse link spreading and modulation is similar to the UTRA proposal, except that only the long scrambling codes are used. However, certain modification has been made for forward link configuration. Since the BPSK spreading leads to performance degradation due to I/Q crosstalk (because of the phase error in the receiver), the cell-specific complex long codes generated from Gold sequences are used for scrambling on the forward link. The complex spreading also helps reduce peak-to-average power and thus improves power efficiency.

The Korean Proposals — The CDMA I and II proposals adopt QPSK for data modulation in each physical channel on the forward link. The modulation symbols are then spread by a channelization code and complex scrambled by a complex cell-specific PN code. In CDMA II, the index pilot channel is independently scrambled by a complex PN code with a shorter period. On the reverse link, both proposals use BPSK for data modulation and orthogonal code QPSK (OCQPSK) for spreading modulation. OCQPSK provides the significant benefit of reduced linear requirements for the power amplifier and thus improved power efficiency. In this scheme, each physical channel is spread by a short channelization code and added to either the I or Q branch, respectively. Then the I and Q channels are multiplied by a complex short code which uses a pair of short orthogonal codes as its real and imaginary parts, and subsequently scrambled by a real mobile-specific long PN code (BPSK scrambling). Walsh codes and layered orthogonal codes are used for channelization in CDMA I and CDMA II, respectively.

Additionally, CDMA II employs one-chip multipath resistant spreading (OMRS) for the reverse link user packet channel (UPCH) (logical channel) to reduce intracell co-channel interference in a multipath environment. Figure 4 illustrates the reverse link UPCH structure for user *K* with the OMRS scheme.

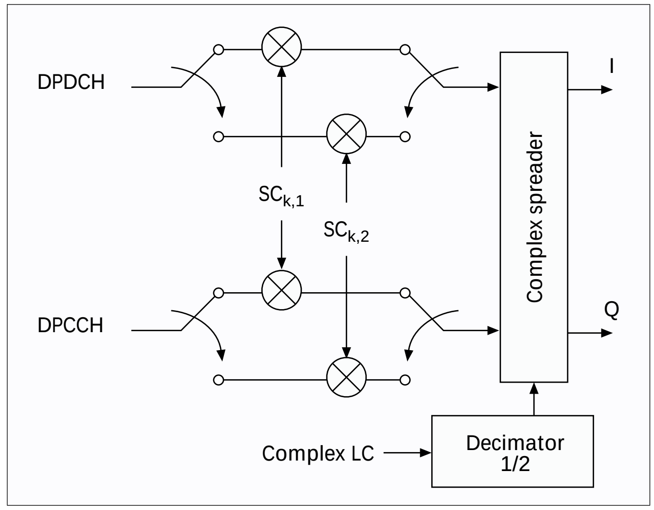


Figure 4. *One-chip multipath resistant spreading for the reverse link UPCH of CDMA II.*

The Chinese Proposal — In the TD-SCDMA proposal, the basic data modulation scheme is differential QPSK (DQPSK). However, for high-rate data, 16-quadrature amplitude modulation (QAM) is employed. Spreading modulation simply uses BPSK. Walsh codes of length 16 are used for channelization, and PN codes of length 256 chips for scrambling.

***Intercell Operation* —** Similar to IS-95B, cdma2000 and CDMA I adopt an intercell synchronous network. The Global Positioning System (GPS) will be utilized for synchronization to a common time reference as in cdmaOne deployments. In these systems, different cell BSs use different time shifts of the same PN sequence in the forward link. In general, synchronized operation can yield superior performance with less MS complexity. In contrast, intercell asynchronous operation is stipulated in the UTRA, W-CDMA, W-CDMA/NA, and CDMA II systems to avoid GPS-based synchronization techniques as well as to circumvent the difficulty in providing an external synchronization source for micro- and picocell BSs in the buildings (however, it is noted that intercell synchronous[5] operation is also possible for these RTT proposals). Since the asynchronous technique does not require any external timing source such as GPS, it makes system deployment from outdoors to indoors very flexible. However, it makes cell search and code synchronization more complex, and may require much longer cell search time because a large number of long codes must be assigned to each cell site in the forward link. To overcome this disadvantage, a fast cell search algorithm has been developed for the W-CDMA system. A special synchronization signal, which consists of two search codes transmitted in parallel within each slot, is designed to facilitate the fast cell search procedure. The primary search code is an unmodulated orthogonal Gold code of length 256 chips with a period of one slot which is used to acquire slot/symbol synchronization. The secondary search code, with a period of one frame, is chosen from a set of 17 different Gold codes of length 256 which is used to acquire frame timing of the target base station and to identify the scrambling code group. After the detection of the scrambling code group, the scrambling code can be identified through symbol-by-symbol correlation with all the scrambling codes within the identified code group. Although the synchronization signal causes interference on data channels due to the periodic destruction of orthogonality, the performance degradation is negligible when channel coding and bit interleaving are employed [9]. This cell search function is also adopted in the UTRA and W-CDMA/NA proposals. Differently, the CDMA II proposal uses two pilots in the forward link, an index pilot and a cell pilot, to achieve fast cell search. The index pilot, with a shorter period PN code, is transmitted time-aligned to the cell pilot. Each index pilot is mapped to a different group of cell pilots, and thus code planing and cell planing must be carried out.

***Performance Enhancement Techniques* —** A number of attractive techniques have been proposed, as additional features of the systems, to further enhance system performance, capacity, and coverage. Most of these features are expected to be incorporated in the system design at a later stage. Some of the key techniques are briefly outlined below.

The Adaptive Antenna — The adaptive antenna has been recognized in most inproposals as a way to enhance capacity and coverage of the system. Solutions employing adaptive antennas can be supported through the use of connection-dedicated pilots on both the forward and reverse links.

Advanced Receiver Structures — Multi-user detection has been proposed for the reverse link in UTRA and W-CDMA/NA due to its potential capacity gains. In general, it is easier to

[5] *For instance, W-CDMA uses a specific code as the secondary search code and a common scrambling code for all BSs in intercell synchronous operation mode.*

apply multiuser detection in a system with short spreading codes since cross-correlation does not change every symbol as with long spreading codes. To facilitate more advanced receiver structures with reasonable complexity, the possibility of using only short codes has been considered in UTRA and W-CDMA/NA. In addition to multi-user detection, interference cancellation has also been proposed in the W-CDMA proposal from Japan and the CDMA I proposal from Korea.

Transmit Diversity — A number of transmit diversity techniques have been proposed for the forward link. It has been recognized that transmit diversity on the forward link can provide a means to achieve similar diversity gain as for MS receiver diversity without the complexity of an extra receiver. The major transmit diversity techniques proposed by different schemes are orthogonal transmit diversity, time switch transmit diversity, and selection diversity. In addition, multicarrier transmit diversity is also suggested in cdma2000 based on its forward link configuration.

EVOLUTION TO 3G CAPABILITIES

Besides 3G activities, IS-95, GSM, and IS-136 continue evolving toward IMT-2000/UMTS requirements [10–12]. This evolution will make it possible to already introduce a subset of IMT-2000 services into current 2G systems. A revolutionary/evolutionary 3G wideband access then provides the full set of IMT-2000 services with increased spectrum efficiency and flexibility. In the following, we will briefly describe the evolution trends for these systems.

***IS-95 Evolution* —** The next phase of data speed improvements for IS-95 (cdmaOne) systems is part of the TIA-IS-95B specifications. The new high-speed data feature in IS-95B allows the CDMA system to facilitate medium-data-rate (MDR) services up to 115.2 kb/s by aggregating eight CDMA traffic channels (maximum) for packet data transmission. It is anticipated that an operator will initially support data rates between 28.8 and 57.6 kb/s on the forward link, and 14.4 kb/s on the reverse link (in the context of browsing the Web or downloading e-mail). Soft handover and mobile-assisted interfrequency hard handoff (MAHO) improvements as part of IS-95B will translate into increased system capacity. Looking further ahead, IS-95C (cdma2000 Phase 1) is expected to facilitate IMT-2000 MDR, double the cdmaOne system capacity, and increase standby time. Standardization for IS-95C is rapidly progressing for the single-carrier and three multicarrier versions for the cdma2000 standard. The multicarrier option in the forward link is the most attractive for existing IS-95 operators since it allows a smooth migration to 3G systems on the existing spectrum [12].

***GSM Evolution* —** The evolution of GSM in Phase 2+ is currently underway. Key enhancements include the high-speed circuit-switched data (HSCSD) service facilitating data rates up to 57.6 kb/s using four time slots, advanced speech call items (ASCI), intelligent network (IN) technologies introduced via Customized Application for Mobile Enhanced Logic (CAMEL), enhanced short message service (SMS), and high-speed General Packet Radio Service (GPRS). GPRS is an important data service for GSM which allows full mobility and wide area coverage with data rates up to 115.2 kb/s, and supports both the Internet Protocol (IP) and X.25. Beyond Phase 2+ of the GSM, ETSI has decided to develop Enhanced Data Rates for Global Evolution (EDGE) as a future evolution of GSM using the same spectrum allocation (existing radio bands) as today. The commonalities between EDGE and GSM in terms of carrier bandwidth (200 kHz), symbol rate (270.833 ksymbols/s), and frame format (8 TDMA slots/4.6 ms frame) are beneficial when designing multimode terminals.

***IS-136 Evolution* —** The future outlook for IS-136 is specified in IS-136 Revision B. The enhancement features in comparison to the current IS-136 Revision A include the use of higher-level modulation(8-PSK) for higher payload capacity to the existing 30 kHz carrier, support of GPRS-based packet data, enhanced voice quality using the US1 vocoder, and IN functionality. In January 1998 the members of the Universal Wireless Consortium (UWC) voted to select EDGE as the 3G system for IS-136 evolution, representing the global IS-136 community. It is also highlighted that EDGE represents the convergence of GSM and IS-136 for vehicular/outdoor environments, and provides an evolutionary path for these existing cellular systems to approach the IMT-2000 requirements. This migration path is illustrated in Fig. 5 [11].

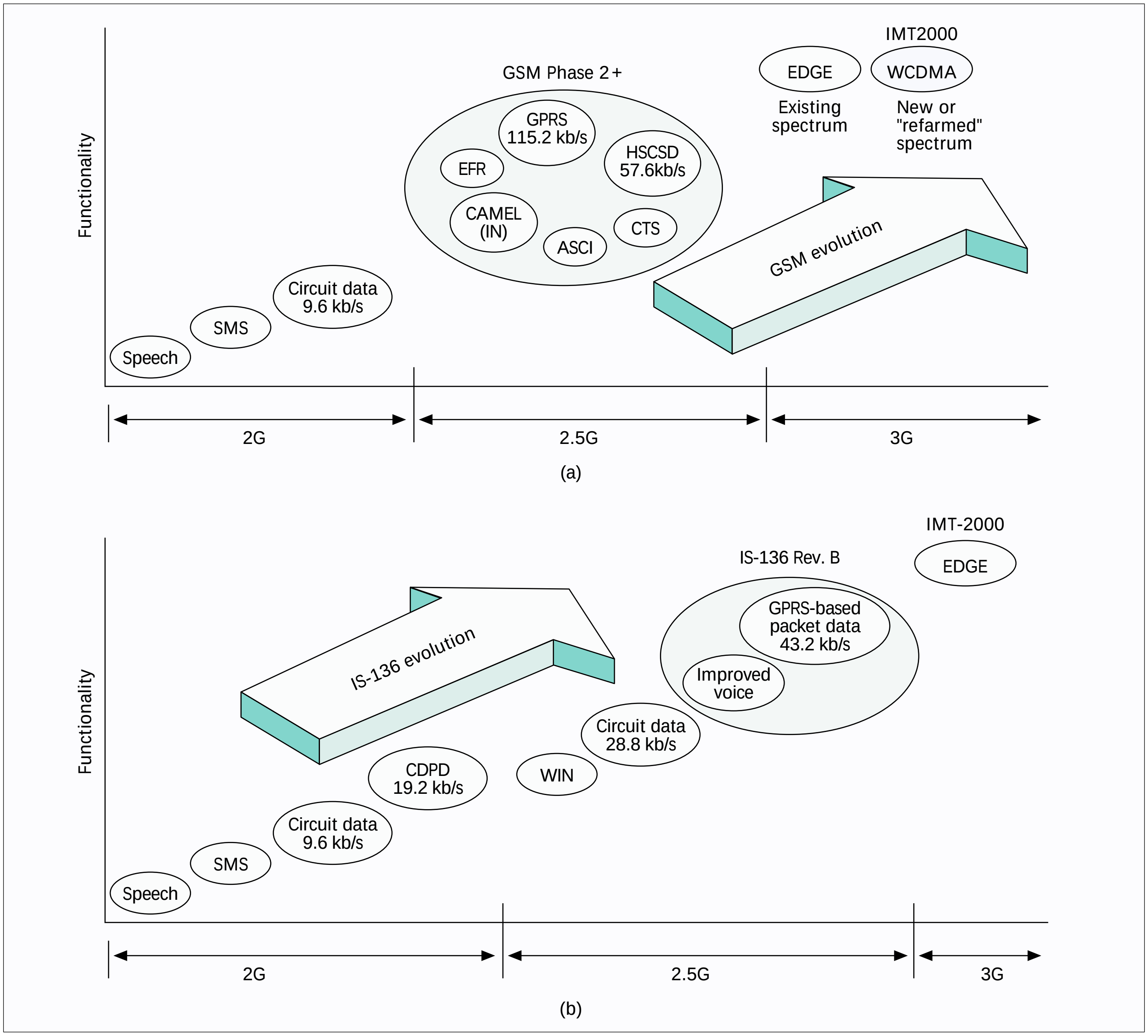
FIXED WIRELESS SERVICES

Fixed wireless services are also experiencing a tremendous growth in both developing and developed countries, but for different reasons. In developing countries, the “fixed cellular system” (usually referred to as *wireless local loop*, WLL) is utilized for providing reliable, flexible, and economical local telephone service in place of traditional copper wireline. Therefore, radio technology allows developing countries to upgrade their existing public switched telephone network (PSTN) infrastructure into the next millennium. The attractive features or key benefits of WLL include low capital costs, fast network deployment, low maintenance costs, and high flexibility in planning and deployment.

In developed countries, fixed wireless technology is gaining popularity because it provides a cost-effective solution for broadband access in the last mile of connection to homes or businesses (i.e., from the high-speed backbone to the end user). The need for broadband access has already been established, and compelling applications (e.g., Internet access) are gradually being introduced. There are many options for providing this vital connection including fiber to the curb (FTTC), two-way hybrid fiber coax (HFC), digital subscriber line (xDSL), and wireless access. FTTC would seem an ideal solution, but the deployment time and infrastructure costs are prohibitive for a short-term solution. HFC and xDSL are promising candidates, providing data rates on the order of 2–30 Mb/s downstream and 1–2 Mb/s upstream. These alternatives suffer from high costs to upgrade existing networks and/or slow market rollout because of lack of competition. Due to these facts, wireless access seems a viable and attractive proposition since it involves lower startup cost, faster rollout, and the ability to add users once the network is operational at marginal cost, rather than pay for every possible user at deployment. In general, broadband access systems can be categorized into two classes:

- Broadcast of television via terrestrial radio transmission or satellite systems
- Wireless local area networks

Currently there are two regulated services providing fixed point-to-multipoint broadcast media, namely multipoint multichannel distribution service (MMDS) and local multipoint distribution systems (LMDS), also known as local multipoint communication systems (LMCS). MMDS is an old technology and has existed since the mid-1970s, primarily to provide wireless TV distribution to remote areas within a 35-mi radius of the hub site (in the 2 GHz RF spectrum). MMDS has a small



■ **Figure 5.** *The evolution path for GSM and IS-136.*

market, and the bulk of customers are concentrated in countries without significant coaxial cable infrastructure. Similar to MMDS, LMDS is used to provide wireless cable TV distribution. However, it can easily be distinguished from the former since its typical operating frequency is in the 26–32 GHz range, smaller cell size (radius less than 5 km), and larger bandwidths (approximately 1 GHz). Since LMDS can handle enough traffic to replicate the PSTN or existing HFC networks, it is gaining a lot of interest around the world except in Europe, where microwave video distribution service (MVDS) at 38–42 GHz is the primary new broadband access technology.

In Europe, specifications and standards for service-independent high-quality fixed radio access networks (HIPERACCESS) are currently being developed within the Broadband Radio Access Networks (BRAN) project sponsored by ETSI. This long-range variant is intended for point-to-multipoint high-speed access (25 Mb/s typical data rate) by residential and small business users to a wide variety of networks, including the UMTS core networks, asynchronous transfer mode (ATM) networks, and IP-based networks (HIPERLAN/2 might be used for distribution within premises).

SATELLITE COMMUNICATIONS

Communications satellites today are utilized for fixed wireless access, broadcast, and mobile services. The evolution of affordable, digital very small aperture terminal (VSAT) satellite terminals is rapidly changing the role of satellites. Examples of fixed satellite services include video conferencing, data communications, and distance learning (i.e., *virtual classrooms*), to name a few. Satellite direct-to-home TV is a typical example of broadcast satellite service, operating in the Ku band. Modern mobile satellite services (MSS) constitute an integral part of the PCS network, which will enable global connectivity. A geostationary earth orbit (GEO) satellite constellation is not very suitable for MSS because it suffers from several inherent limitations for providing true global personal communications:

- Restricted coverage — high latitude and polar regions are not covered.
- A long time delay due to propagation delay may prohibit true duplex telephone conversation.
- In view of the high altitude, the link budget does not allow for a small handheld terminal.

Proposal	Source	Orbit constellation	Multiple access
SAT-CDMA	S. Korea TTA	LEO (49)	DS-CDMA
SW-CDMA	European Space Agency	LEO/MEO	DS-CDMA
SW-CTDMA	European Space Agency	HEO/GEO	W-QS-C/TDMA
ICO RTT	ICO Global Communications	MEO (10)	F/TDMA
Horizons	Inmarsat	GEO	TDMA
INX*	Iridium	LEO/MEO	TDMA, CDMA
* An additional proposal received by September 30, 1998			

Table 8. *Proposals for the IMT-2000 satellite component.*

Hence, it is anticipated that the first-generation nongeostationary earth orbit (NGEO) family of orbits will be integrated with terrestrial PCS networks, at least during the initial phase.

The first-generation NGEO is currently being commissioned. Intermediate Circular Orbit (ICO) Global Communications can deliver services on a global basis from mid-earth orbit (MEO), and Iridium and Globalstar offer mobile cellular services from low earth orbit (LEO) satellite constellations.

IMT-2000 envisions integrated terrestrial and satellite components covering a wide range of user densities, service types, and available service sets making up IMT-2000. Satellite-based mobile systems are intended to be used in a complementary mode to terrestrial systems. By June 1998 five proposals had been submitted to ITU-R for candidate RTTs on the IMT-2000 satellite component [5]. Some major attributes of these proposals are summarized in Table 8.

CONCLUSIONS

In this article we briefly survey the evolution of wireless communications since the deployment of initial AM mobile systems until the current deployment of 2G wireless systems, and the future directions of this marvelous technology toward the envisioned personal communications network. Similarities and key differences between the various 3G proposals submitted to the ITU are reviewed. In order to have a common standard worldwide for the RTT, it is imperative to carry out harmonization at an international level. With recent technological breakthroughs in digital signal processing, RF, and battery technologies as well as developments in modern VLSI chip-set designs, the dream of ubiquitous communication between anyone, anywhere, at anytime is becoming a reality. Indeed:

It is dangerous to put limits on wireless.

Guglielmo Marconi (1932)

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