Overview of Wireless Personal Communications

Cellular radio and cordless telephony have demonstrated the demand for wireless communications and provided a foundation for the development of future wireless telecommunications systems and services.

Jay E. Padgett, Christoph G. Günther, and Takeshi Hattori

This century has seen the development of a public wireline network that allows reliable and affordable communication of voice and low-rate data around the globe. There also is a multiplicity of specialized wired networks optimized for purposes such as the local communication of high-speed data. The goal of wireless communication is to allow the user access to the capabilities of the global network at any time without regard to location or mobility. Cellular and cordless telephony, both of which have gained widespread user acceptance during the last ten years, have begun this process but do not yet allow total wireless communication. Cellular systems currently are limited to voice and low-speed data within areas covered by base stations. The basic cordless telephone provides a wireless counterpart to the standard telephone. The handset typically operates within 50 to 100 m of the user's base station, which connects to the public switched telephone network (PSTN). With the advent of digital cordless telephony, cordless "systems" with enhanced functionality (CT2, DECT, PHS) have been developed that can support higher data rates and more sophisticated applications such as wireless private branch exchanges (PBXs) and public-access Telepoint systems.

This article presents an overview of the current state of wireless communications, including relevant ongoing activities in technology development, standards, and spectrum allocation. The next three sections discuss cellular radio, cordless telephony, and wireless data systems, respectively. Following that, ongoing and planned future developments are summarized. The presentation here is oriented toward broad coverage rather than technical depth. However, brief discussions of the air interfaces for existing digital cellular and digital cordless systems are provided, because the air interface bears heavily on system capacity and the environments in which the system can be used, as well as on the cost and complexity of the equipment. More detailed discussions on topics of interest to the reader, including network aspects, can be found in other papers in this issue as well as in the references provided here.

JAY E. PADGETT is a DMTS at AT&T Bell Laboratories and is chair of the TIA Mobile & Personal Communications Consumer Radio Section.

CHRISTOPH G. GÜNTHER is head of the Cellular System Group at Ascom Tech.

TAKESHI HATTORI is executive manager of the Personal Communication Systems Laboratory of the NTT Wireless Systems Laboratories.

A guide to wireless acronyms and abbreviations is on page 40.

Cellular

Cellular radio can be regarded as the earliest form of wireless "personal communications." It allows the subscriber to place and receive telephone calls over the wireline telephone network wherever cellular coverage is provided; "roaming" capabilities extend service to users traveling outside their "home" service areas. Cellular system design was pioneered during the '70s by Bell Laboratories in the United States, and the initial realization was known as AMPS, for Advanced Mobile Phone Service. As detailed below, systems similar to AMPS were soon deployed internationally. All of these "first-generation" cellular systems use analog frequency modulation (FM) for speech transmission and frequency shift keying (FSK) for signaling. Individual calls use different frequencies. This way of sharing spectrum is called frequency division multiple Access (FDMA).

The distinguishing feature of cellular systems compared to previous mobile radio systems is the use of many base stations with relatively small coverage radii (on the order of 10 km or less vs. 50 to 100 km for earlier mobile systems). Each frequency is used simultaneously by multiple base-mobile pairs. This "frequency reuse" allows a much higher subscriber density per MHz of spectrum than previous systems. System capacity can be further increased by reducing the cell size (the coverage area of a single base station), down to radii as small as 0.5 km. In addition to supporting much higher subscriber densities than previous systems, this approach makes possible the use of small, battery-powered portable handsets with lower RF (radio frequency) transmit power than the large vehicular mobile units used in earlier systems. In cellular systems, continuous coverage is achieved by executing a "handoff" (the seamless transfer of the call from one base station to another) as the mobile unit crosses cell "boundaries." This requires the mobile to change frequencies under control of the cellular network. For a more detailed overview of cellular radio, see [1].

0163-6804/95/$04.00 1995 © IEEE

Standard	Mobile TX/Base TX (MHz)	Channel spacing (kHz)	Number of channels	Region
AMPS	**824-849/869-894**	**30**	**832**	**The Americas[1]**
TACS	890-915/935-960[2]	25	1000	Europe
ETACS	**872-905/917-950**	**25**	**1240**	**United Kingdom**
NMT 450	453-457.5/463-467.5	25	180	Europe
NMT 900	**890-915/935-960[2]**	**12.5[3]**	**1999**	**Europe[1]**
C-450	450-455.74/460-465.74	10[3]	573	Germany, Portugal
RTMS	**450-455/460-465**	**25**	**200**	**Italy**
Radiocom 2000[4]	192.5-199.5/200.5-207.5 215.5-233.5/207.5-215.5 165.2-168.4/169.8-173 414.8-418/424.8-428	12.5	560 640 256 256	France
NTT	**925-940/870-885[5]** **915-918.5/860-863.5[6]** **922-925/867-870[6]**	**25/6.25[3]** **6.25[3]** **6.25[3]**	**600/2400** **560** **480**	**Japan**
JTACS/NTACS	915-925/860-870[7] 898-901/843-846[6, 7] 918.5-922/863.5-867[6]	25/12.5[3] 25/12.5[3] 12.5[3]	400/800 120/240 280	Japan

Notes:

[1] AMPS is also used in Australia. AMPS, TACS, and NMT are all used in parts of Africa and Southeast Asia.

[2] The bands 890-915/935-960 MHz were subsequently allocated to GSM in Europe.

[3] Frequency interleaving using overlapping or "interstitial" channels: the channel spacing is half the nominal channel bandwidth.

[4] The latter two band pairs are used to provide coverage throughout the country, and the former ones are used to support high traffic densities in areas like Paris and other major cities.

[5] NTT DoCoMo, nationwide.

[6] IDO, in the Kanto-Tokaido areas.

[7] DDI, outside the Kanto-Tokaido areas.

■ **Table 1**. *Summary of analog cellular systems.*

There are more than 30 million cellular subscribers worldwide.

Analog Cellular Systems

In the United States, a total of 50 MHz in the bands 824-849 MHz and 869-894 MHz is allocated to cellular mobile radio. In a given geographical licensing region, each of two carriers (service providers) controls 25 MHz. The "A" and "B" bands are allocated to "non-wireline" and "wireline" carriers, respectively.[1] Under the AMPS standard, this spectrum is divided into 832 frequency channels, each 30 kHz wide. Frequency modulation (8 kHz deviation) is used for speech, and the signaling channels use binary FSK with a 10-kb/s rate. To meet cochannel interference objectives,[2] the typical frequency reuse plan employs either a 12-group frequency cluster with omnidirectional antennas or a 7-group cluster with three sectors per cell. AMPS cellular service has been available to the public since 1983, and there currently are roughly 20 million subscribers in the United States. AMPS is also used in Canada, Central and South America, and Australia.

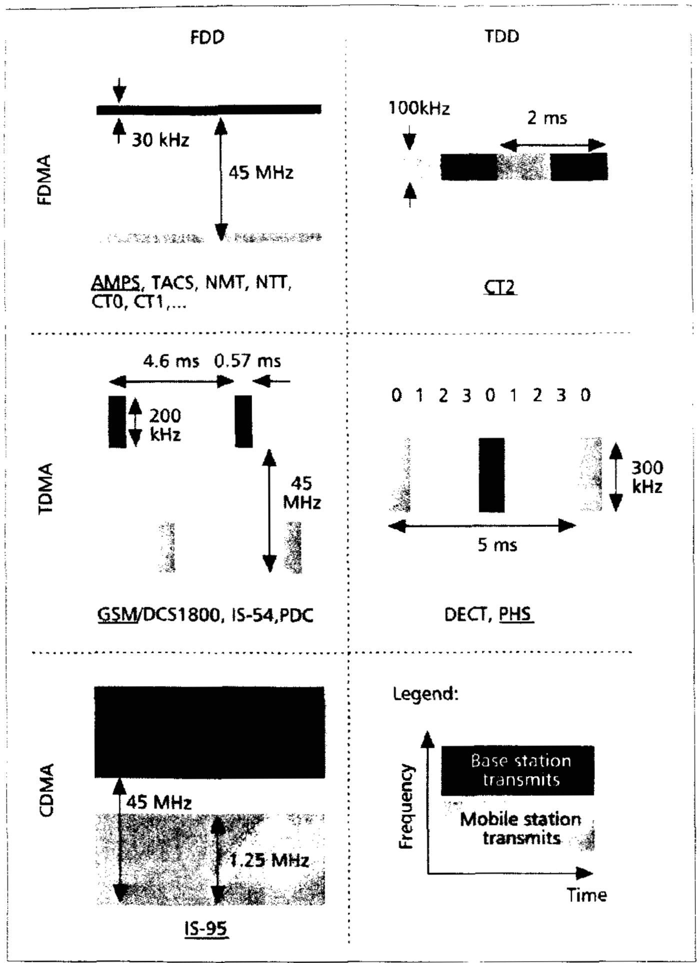
In Europe, several first-generation systems similar to AMPS have been deployed, including: Total Access Communications System (TACS) in the United Kingdom, Italy, Spain, Austria and Ireland; Nordic Mobile Telephone (NMT) in many countries; C-450 in Germany and Portugal; Radiocom 2000 in France; and Radio Telephone Mobile System (RTMS) in Italy. Those systems use frequency modulation for speech, FSK for signaling, and channel spacings of: 25 kHz (TACS, NMT-450, RTMS); 10 kHz (C-450); and 12.5 kHz (NMT-900, Radiocom 2000).[3] Handover decisions are usually based on the power received at the base stations surrounding the mobile. C-450 is an exception, and uses round trip delay measurements. The total number of subscribers to the analog systems is around 8 million (3.7 million for TACS, 2.9 million for NMT, 0.9 million for C-450, and smaller amounts for the remaining systems). A few additional details are found in Table 1.

In Japan, a total of 56 MHz is allocated for analog cellular systems (860-885/915-940 MHz and 843-846/898-901 MHz). The first analog cellular system, the Nippon Telephone and Telegraph (NTT) system, began operation in the Tokyo metropolitan area in 1979. The frequencies were 925-940 MHz (mobile transmit) paired with 870-885 MHz (base transmit), and the channel spacing was 25 kHz, giving a total of 600 duplex channels. The control channel signaling rate was 300 b/s. In 1988, a high capacity system

[1] *A wireline carrier is a fully-separated subsidiary of a Local Exchange Carrier (LEC) in the area where the LEC is a monopoly provider of local wired telephone service.*

[2] *The objective for the carrier-to-interference ratio, averaged over the multipath fading, is 17 dB for at least 90 percent of the covered area [1].*

[3] *NMT-900 and C-450 use frequency interleaving, whereby the "channel separation" is half the separation between adjacent non-overlapping channels (the nominal channel "bandwidth"). The channel spacings given here and in Table 1 refer to the separation between the "interleaved" center frequencies. Overlapping channels cannot be used at the same base station.*



■ **Figure 1.** *Illustration of multiple access and duplexing techniques. The parameters given refer to the systems that are underlined. The widths of the frequency bands and time slots are artificially scaled for illustration purposes.*

was introduced in the same band, with an increased control channel signaling rate of 2.4 kb/s and a reduced channel spacing of 12.5 kHz. The number of channels was further increased by frequency interleaving (channel center frequencies 6.25 kHz apart), resulting in an overall fourfold increase in the number of channels to 2400. In addition, an associated control channel (below the voice band) with a rate of 100 b/s was introduced, which permits signaling without interrupting voice communication. To improve transmission quality and frequency reuse, reception diversity was incorporated into both the base and mobile stations. The mobile terminal of the high capacity system is dual-mode, and can also access the initial (25 kHz) system. The cellular operator NTT DoCoMo currently provides nationwide coverage in the bands 870-885/925-940 MHz.

In 1987, cellular radio was deregulated in Japan and two new operators were introduced. One of these is named "IDO" and began operation of the NTT high capacity system in December 1988, covering the Kanto-Tokaido areas in the bands 860-863.5/915-918.5 MHz. The third cellular carrier is the DDI Cellular Group, which provides coverage outside the metropolitan areas using the JTACS/NTACS systems (based on the European TACS system) in the bands 860-870/915-925 MHz and 843-846/898-901 MHz. Following DDI, IDO has also introduced NTACS in the bands 843-846/898-901 MHz and 863.5-867/918.5-922 MHz. IDO and DDI have formed a partnership to provide nationwide service by introducing roaming capabilities between the two systems. There are currently about 2.6 million subscribers to analog cellular systems in Japan.

[4] *The digital cordless systems CT2, DECT, and PHS noted in Fig. 1 are discussed in the section to follow on cordless telephony.*

Digital Cellular Systems

The development of low-rate digital speech coding techniques and the continuous increase in the device density of integrated circuits (i.e., transistors per unit area), have made completely digital second-generation systems viable. Digitization allows the use of time division multiple access (TDMA) and code division multiple access (CDMA) as alternatives to FDMA. With TDMA, the usage of each radio channel is partitioned into multiple timeslots, and each user is assigned a specific frequency/timeslot combination. Thus, only a single mobile in a given cell is using a given frequency at any particular time. With CDMA (which uses direct sequence spreading), a frequency channel is used simultaneously by multiple mobiles in a given cell, and the signals are distinguished by spreading them with different codes. One obvious advantage of both TDMA and CDMA is the sharing of radio hardware in the base station among multiple users. Figure 1 illustrates the FDMA, TDMA, and CDMA concepts.[4]

Digital systems can support more users per base station per MHz of spectrum, allowing wireless system operators to provide service in high-density areas more economically. The use of TDMA or CDMA digital architectures also offers additional advantages, including:

- A more natural integration with the evolving digital wireline network.
- Flexibility for mixed voice/data communication and the support of new services.
- A potential for further capacity increases as reduced rate speech coders are introduced.
- Reduced RF transmit power (increasing battery life in handsets).
- Encryption for communication privacy.
- Reduced system complexity (mobile-assisted handoffs, fewer radio transceivers).

Second-generation cellular systems based on digital transmission are currently being deployed. These systems are discussed in some detail in this section. Figure 2 shows the associated frequency allocations.

The Pan-European GSM System and DCS 1800 — The large number of different analog systems used in Europe did not represent an ideal situation from a subscriber point of view. This, together with the need to accommodate an increasing number of users and to establish compatibility with the evolution of the fixed network towards digital systems, led the Conférence Européenne des Postes et Télécommunications (CEPT) to establish a "Groupe Spécial Mobile" in 1982. The work of that group became the GSM system (now "Global System for Mobile communications").

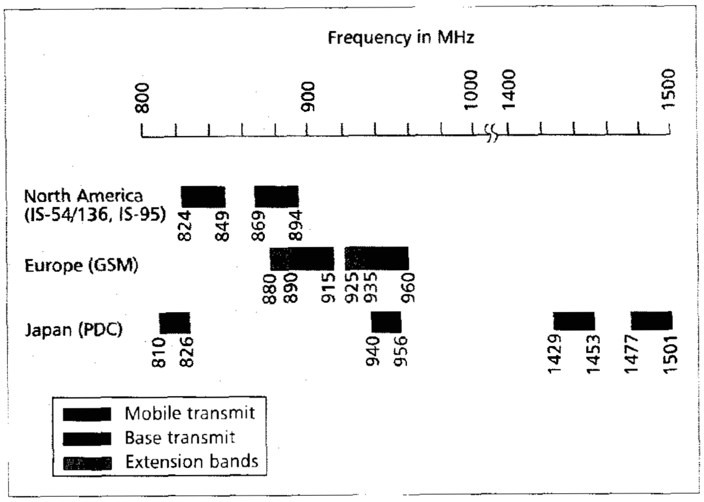
The new system was primarily expected to provide better quality, pan-European roaming, and the transmission of data for fax, e-mail, files, etc. A new design also offered the opportunity to specify a system for lower-cost implementations and the potential for increased spectral efficiency. Finally, a high degree of flexibility and openness to future improvements were recognized as important and taken into account [2].

The decision to use a digital approach was rather obvious because of the advantages already discussed. TDMA was chosen with eight timeslots per radio channel. Each user transmits periodically in every eighth slot (of duration 0.57 ms) and receives in a corresponding slot (Fig. 1). With such an approach, a base station only needs one (faster) transceiver for eight channels. In addition, transmit/receive slot staggering allows a relaxation of the duplex filter requirements for the mobile. The intermittent activity of the mobile transceiver also provides the opportunity (between the transmit and receive bursts at the mobile) to measure the strength of the signals from surrounding base stations. These measurements are reported to the serving base station and used for handover decisions. Note that contrary to the traditional FDMA systems, no additional hardware is needed for finding candidate base stations.

The time-compression of the user data (22.8 kb/s including error correction coding), by a factor of around eight inherent in the TDMA format, implies a bandwidth expansion of the signal by a corresponding factor. This has consequences on the fading of the received signal. The presence of reflectors, like mountains, hills, buildings, and others, leads to a multitude of echoes. In a narrowband system, the resulting signal paths cannot be resolved in time. With a bandwidth of 200 kHz, on the other hand, some degree of resolution becomes possible. In GSM, the staggering of the paths is estimated using a fixed mid-amble (training sequence in the middle of the slot). The intersymbol interference is then resolved with a Viterbi equalizer, for example. The multipath interference is a form of diversity, which, depending on the environment, can significantly reduce fading. With fast-moving mobiles, residual errors are corrected by the rate 1/2 convolutional coding and convolutional interleaving over eight bursts (for class 1 bits).

In some environments, like cities (delays around 1 to 2 μs), 200 kHz of bandwidth is no longer sufficient to resolve the multipath, and slow mobiles can experience long error bursts. This situation can be greatly improved by changing the frequency from slot to slot (frequency hopping). With different hopping patterns used at different base stations, interference diversity can be realized. This is particularly attractive with discontinuous transmission (speech pauses are not transmitted).

In its present version, GSM supports full-rate (22.8 kb/s, eight slots/frame) and half-rate (11.4 kb/s, 16 slots/frame) operation. Speech coders have been specified for both rates, and improved full-rate coders for "radio local loop" (RLL) applications can be accommodated. On the data side, various synchronous and asynchronous services at 9.6, 4.8, and 2.4 kbps are specified for both full-rate and half-rate operation. In particular, these data services interface to audio modems (e.g., V.22bis or V.32) and



■ **Figure 2.** *Digital cellular frequency allocations.*

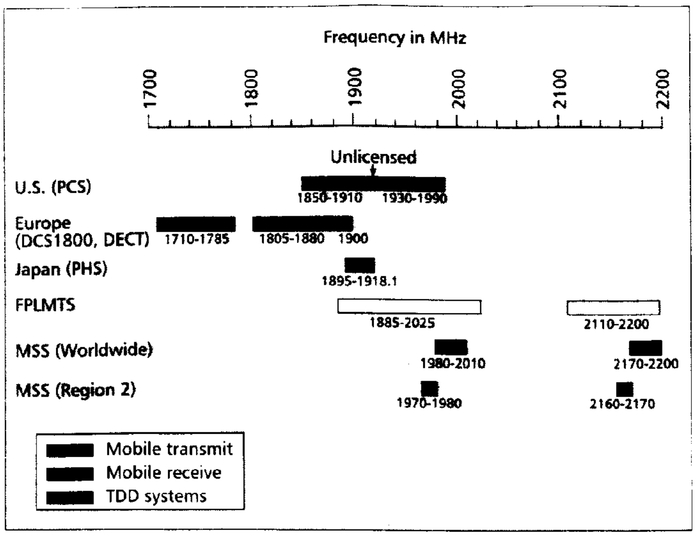
ISDN. Additionally, a connectionless packet service is in preparation, with an emphasis on interworking with X.25 and Internet (see the section on wireless data). Group 3 fax is also supported by the standard.

Originally, GSM was intended to be operated only in bands around 900 MHz. In early 1989, the UK Department of Trade and Industry started an initiative which finally led to the assignment of 150 MHz near 1.8 GHz for Personal Communications Networks (PCN) in Europe, and to the choice of GSM as a standard for that application. This system is called DCS1800, for Digital Cellular System 1800. Its definition meant translating the specifications to the new band and modifying some parts for accommodating overlays of micro- and macrocells. Cellular and PCN are certainly the most prominent applications, but GSM is currently also extended to include "group calls" and "push to talk" for private mobile radio (PMR) applications.

In the cellular area, GSM has experienced tremendous growth since the start of deployment in 1993. As of November 1994, there were two million subscribers throughout Europe, and the system had been adopted by many non-European countries (a total of 26 European and 26 non-European countries). Operators in the United Kingdom and Germany have started DCS1800 networks recently. Coverage is not country-wide at the moment, but ultimately a similar success is expected as for GSM.

For an overview of GSM, see [3], and for an in-depth description, see [4] or the standard [5]. For an overview of DCS 1800, see [6]. Figure 3 shows the frequency allocations for DCS1800, as well as allocations for wireless communications near 2 GHz in the United States and Japan.

IS-54 in North America — To meet the growing need to increase cellular capacity in high-density areas, the Electronic Industries Association (EIA) and the Telecommunications Industry Association (TIA) adopted the IS-54 standard based on TDMA [7]. IS-54 retains the 30-kHz channel spacing of AMPS to facilitate evolution from analog to digital systems. Each frequency channel



■ **Figure 3.** *Regional and international wireless frequency allocations near 2 GHz.*

provides a raw RF bit rate of 48.6 kb/s, achieved using π/4 DQPSK[5] at a 24.3-kbaud channel rate. This capacity is divided among six timeslots, two of which are assigned to each user in the current implementation, which uses a 7.95-kb/s vector sum excited linear prediction (VSELP) speech coder (13 kb/s with error protection). Thus, each 30-kHz frequency pair can serve three users simultaneously, and with the same reuse pattern, IS-54 provides triple the capacity (user channels per cell) of AMPS.[6] When half-rate coders are introduced, each 30-kHz frequency channel will be able to accommodate six user channels, giving another doubling of capacity. The IS-54 standard provides for an adaptive equalizer to mitigate the intersymbol interference caused by large delay spreads, but due to the relatively low channel rate (24.3 kbaud), the equalizer will be unnecessary in many situations.[7]

Since systems using the IS-54 standard must operate in the same spectrum used by the existing AMPS systems, the IS-54 standard is "dual mode," meaning that it provides for both analog (AMPS) and digital operation. This is necessary to accommodate "roaming" subscribers, given the large embedded base of AMPS equipment. Although service providers have already begun to deploy IS-54 equipment in major metropolitan areas in the United States, the conversion to digital will be slower in less dense areas. Consequently, there will be a mix of analog and digital terminals as well as base station equipment for a considerable period of time.

While the initial version of the IS-54 standard used the AMPS control channel specification (10 kb/s Manchester-encoded FSK), IS-136 (formerly IS-54 rev. C) includes a digital control channel (DCC) which uses the 48.6-kb/s modem. In addition to the increased signaling rate, the DCC offers such capabilities as point-to-point short messaging, broadcast messaging, group addressing, private user groups, hierarchical cell structures, and slotted paging channels to support a "sleep" mode in the terminal (to conserve battery power). The companion EIA/TIA standard IS-41 provides network signaling protocols to support inter-system handoff, roaming, and delivery of network-based features and services [8]. IS-54 equipment has already been deployed and is operational in a majority of the top ten cellular markets in the United States, and the rate of customer adoption is increasing.

Personal Digital Cellular in Japan — In Japan, there are two different types of analog cellular systems: (NTT and JTACS), which developed from different backgrounds. From the perspective of the user, a single air interface was desirable for providing roaming capability among different mobile networks. A development study for digital cellular systems with a common air interface was initiated in 1989 under the auspices of the Ministry of Posts and Telecommunications (MPT). The new digital system was established in 1991 and named Personal Digital Cellular (PDC).

The PDC system is also based on TDMA, with three slots multiplexed onto each carrier, similar to IS-54. The channel spacing is 25 kHz with interleaving to facilitate migration from analog to digital. The RF signaling rate is 42 kb/s, and the modulation is π/4 DQPSK. A key feature of PDC is mobile-assisted handoff, which facilitates the use of small cells for efficient frequency usage. The full-rate VSELP speech codec operates at 6.7 kb/s (11.2 kb/s with error correction). Currently, the full-rate codec is available; however, a 5.6-kb/s psi-CELP[8] half-rate codec has already been standardized and will soon be introduced, resulting in a doubling of capacity.

A total of 80 MHz is allocated to PDC; the frequency bands are 810-826 MHz paired with 940-956 MHz and 1429-1453 MHz paired with 1477-1501 MHz. With antenna space diversity, the required C/I is reduced, giving a reuse factor of 4. Group 3 FAX (2.4 kb/s) as well as 4.8-kb/s modem transmission with MNP class 4 are supported using an adaptor to provide the required transmission quality. There are five PDC operators, and are currently 250,000 subscribers to PDC. It is gaining popularity due to high quality, high security, a longer handset battery life, etc. See [9] or the standard [10] for more details.

IS-95 in North America — The EIA/TIA IS-95 standard is based on the CDMA system originally described in [11]. With IS-95, many users share a common channel for transmission. The basic user channel rate is 9.6 kb/s. This is spread to a channel chip rate of 1.2288 Mchip/s (a total spreading factor of 128) using a combination of techniques. The spreading process is different on the forward (base-to-mobile) and reverse links. On the forward link, the user data stream is encoded using a rate 1/2 convolutional code, interleaved, and spread by one of 64 orthogonal spreading sequences (Walsh functions). Each mobile in a given cell is assigned a different spreading sequence, providing perfect separation among the signals from different users, at least for a single-path channel. To reduce interference between mobiles that use the same spreading sequence in different cells and to provide the desired wideband spectral characteristics (not all of the Walsh functions yield a wideband power spectrum), all signals in a particular cell are scrambled using a pseudo-random sequence of length 2^{15} chips.

---

[5] *Differential quadrature phase-shift keying (DQPSK) with a π/4 radian phase shift between successive symbols, to reduce amplitude fluctuations in the signal envelope.*

[6] *The Erlang capacity (offered load at a given blocking rate) actually is increased more than threefold because of improved "trunking efficiency" due to the larger number of available channels.*

[7] *As a rule-of-thumb, an equalizer is needed when the rms delay spread is on the order of 20 percent or more of the symbol duration (for binary and quaternary modulation). The symbol duration is about 40 μs for IS-54. Delay spreads for cellular environments usually are less than 8 μs, except for hilly and mountainous areas.*

[8] *Psi-CELP is pitch synchronous innovation code excited linear prediction, which is a newly established half-rate codec in Japan.*

Orthogonality among users within a cell is preserved because their signals are scrambled identically. A pilot channel (code) is provided on the forward link for channel estimation. This allows coherent detection. The pilot channel is transmitted at higher power than the user channels.

On the reverse link, a different spreading strategy is used because each received signal arrives at the base via a different propagation channel. The user data stream is first convolutionally encoded at rate 1/3. After interleaving, each block of six encoded symbols is mapped to one of the 64 orthogonal Walsh functions (i.e., 64-ary orthogonal signaling). A final fourfold spreading, giving a rate of 1.2288 Mchip/s, is achieved by spreading the resulting 307.2-kchip/s stream by user-specific and base-specific codes of periods 2^{42}-1 and 2^{15} chips, respectively. The rate 1/3 coding and the mapping onto Walsh functions result in a greater tolerance for interference than would be realized from traditional spreading (i.e., a repetition code). This added robustness is important on the reverse link, due to the non-coherent detection and the in-cell interference (no orthogonality among in-cell users).

Another essential element of the reverse link is tight control of the mobile's transmit power, to avoid the "near-far" problem that arises from the different fading, shadowing, and path loss situations experienced by the different signals. A combination of open-loop and fast closed-loop control is used, with the commands for the closed-loop control being transmitted at a rate of 800 b/s. These bits are stolen from the speech frames.

At both the base station and the mobile, RAKE receivers are used to resolve and combine multipath components, significantly reducing the fading amplitude. This receiver architecture also is used to provide base station diversity during "soft" handoffs, whereby a mobile making the transition between cells maintains links with both base stations during the transition. The mobile's receiver combines the signals from the two base stations in the same manner as it would combine signals associated with different multipath components.

The IS-95 CDMA approach offers a number of benefits, including increased capacity, elimination of the need for planning frequency assignments to cells, and flexibility for accommodating different transmission rates (a higher-quality 13 kb/s speech coder, for example). Moreover, the variable-rate speech coding, power control, reduced fade margin, and forward error correction (FEC) all contribute to the reduction of the required RF transmit power.

Like IS-54, IS-95 is compatible with the IS-41 signaling protocol, and is a dual-mode standard designed for the existing North American cellular bands; IS-95 terminals can operate either in the CDMA mode or the AMPS mode. Deployment of IS-95 systems in the Los Angeles, California area is expected this year. For a more detailed overview of IS-95, see [11, 12] and for a focus on the reverse link, see [13].

Cordless Telephony

First-Generation Analog Cordless

Since 1984, analog cordless telephones in the United States have operated on ten frequency pairs in the bands 46.6-47.0 MHz (base transmit) and 49.6-50.0 MHz (handset transmit). Prior to 1984, five of the 49 MHz frequencies were paired with five frequencies near 1.6 MHz, an arrangement that proved less than satisfactory due to the imbalance in the performance of the two links and the limited number of channels.

The allowed emission bandwidth is 20 kHz, and the effective radiated power (ERP) is very low, roughly 20 μW (compared to 10 mW for most other cordless telephone systems). Analog FM is used for the voice signal, and the U.S. Federal Communications Commission (FCC) rules require digital coding of the signaling functions for security. There are an estimated 60 million 46/49 MHz cordless telephones in use in the United States, and total sales are roughly 15 million units per year. Despite the recent availability of higher-power digital cordless telephones operating in the 915 MHz Industrial, Scientific, and Medical (ISM) band (discussed below), the popularity of 49 MHz analog cordless telephones is expected to continue for a considerable time due to their low cost (U.S. $50 to $100 is typical for a basic unit).

Because of the large embedded base of these devices, the existing ten channel pairs have become inadequate, particularly in high-density areas. In August 1992, the TIA petitioned the FCC to make 15 additional frequency pairs near 44 MHz (base transmit) and 49 MHz (handset transmit) available for cordless telephones. In August 1993, the FCC adopted a Notice of Proposed Rule Making (NPRM) in response to TIA's petition, proposing specific provisions to be added to the FCC Rules [14]. A final ruling on the new frequencies by the FCC is expected this year.

The first cordless telephones were imported to Europe from the Far East and the United States. In most of Europe, such equipment was illegal but was sold in large quantities "for export only." In the United Kingdom, a standard very similar to the one originally used in the United States was introduced (MPT 1322) to offer an alternative to the illegal imports [15]. This standard (sometimes referred to as "CT0"), allowed for eight channel pairs near 1.7 MHz (base unit transmit) and 47.5 MHz (handset transmit), and most units could access only one or two channel pairs. A similar standardization approach was adopted in France. There are an estimated 4.7 million illegal units in operation; 1994 sales of legal and illegal units are estimated at 2.4 and 1 million, respectively.

In the rest of Europe, the reaction to the demand for cordless communication was to develop the analog cordless standard known as CEPT/CT1 [16]. This cordless standard provides for forty 25-kHz duplex channel pairs in the bands 914-915/959-960 MHz (80 pairs are allocated for CT1+ in the bands 885-887/930-932 MHz, which do not overlap the GSM allocation) and for a form of Dynamic Channel Assignment (DCA), whereby one of the 40 (or 80) duplex frequency pairs is selected at the beginning of each call. With this large number of channels and DCA, the blocking probability is low, even in densely populated areas. CT1 historically is a coexistence standard rather than an interoperability standard, which has the consequence that equipment from different manufacturers is typically incompatible. This situation also has advantages, however; it provides opportunities for new features such as scrambling to provide speech privacy, and cordless PBX applications. Such enhancements

There are an estimated 60 million 46/49 MHz cordless telephones in use in the United States, and total sales are roughly 15 million units per year.

CT2 is an FDMA/TDD air interface optimized for low-cost implementation of digital cordless and Telepoint systems.

would have been impossible to implement under a tightly-specified standard. Total annual sales for CT1/CT1+ are estimated at 2.2 million units and are expected to increase to 2.5 million and 2.7 million in 1995 and 1996, respectively. The current embedded base is estimated at 5.4 million units.

In Japan, there are 89 duplex channels near 254 MHz (handset transmit) and 380 MHz (base transmit) allocated to analog cordless telephones using FM [17]. The channel spacing is 12.5 kHz and the allowed transmit power is 10 mW. Unlike CEPT/CT1, there are two dedicated control channels, to facilitate fast connections and conserve battery life, at the price of somewhat reduced robustness against interference. Typical battery life in the "standby" mode between charges is 150 to 190 hours. The total market penetration is roughly 20 million units, with retail sales of 3 to 4 million units annually.

In addition, very low-power (500 μV/m at 3 meters, or roughly 50 nW ERP) cordless telephones are allowed in Japan below 350 MHz and above 1 GHz. However, the demand for these devices is fairly small due to their very limited operating range (on the order of 10 m).

Digital Cordless

The CT2 Common Air Interface — The deficiencies of the analog MPT1322 cordless systems in the United Kingdom (most notably the limited number of channels and resulting high blocking probability) stimulated the development of an alternative that later became the CT2/Common Air Interface (CAI). The most salient features of that standard are the digital transmission format and the use of time division duplexing (TDD). With CT2, speech is first digitized using a 32 kb/s adaptive differential pulse code modulation (ADPCM) encoder (CCITT G.721). The time-compressed digitized speech and control data are modulated onto a carrier at a rate of 72 kb/s using Gaussian filtered FSK (GFSK) and are transmitted in 2-ms frames. Each frame includes one base-to-handset and one handset-to-base burst (Fig. 1). This mode of duplexing (TDD) has significant advantages: the expensive duplex filter required with frequency duplexing is replaced by a switch; both transmission and reception antenna diversity can be used (due to propagation path reciprocity); and rather arbitrary frequency bands can be allocated (frequency-duplexed systems need symmetric pairs of bands separated by several MHz).[9]

The CT2 spectrum allocation consists of 40 FDMA channels with 100-kHz spacing in the range 864-868 MHz. The 100-kHz spacing reduces the bandwidth efficiency to half its value for CT1 (50 kHz per duplex channel). The maximum transmit power is 10 mW, and two-level power control helps to prevent the desensitization of base station receivers, and as a by-product, contributes to improved frequency reuse. A call re-establishment procedure on another carrier after three seconds of handshake failure gives robustness against the usual impairments of radio channels. The control data bits are protected against errors.

CT2 also supports the transmission of data, up to 2.4 kb/s through the speech codec (4.8 kb/s with an increased error rate), and higher rates by accessing the 32 kb/s bearer channel directly.

CT2 was promoted as a Telepoint standard. Telepoint networks use cordless base stations to provide wireless pay phone services. Incoming calls are not supported with the basic service. They require additional functionality such as manual registration and paging. User acceptance of CT2-Telepoint varies widely over the continents. No breakthrough was achieved in Europe; in the United Kingdom, for example, the last operator terminated service in 1993. In Hong Kong, however, there are 150 000 subscribers to CT2 Telepoint service, and systems are being deployed in other parts of Southeast Asia, including China, Malaysia, Singapore, and Thailand. European sales of CT2 handsets for 1994 are estimated to be 0.4 million, with projected increases to 0.5 and 0.6 million in 1995 and 1996, respectively. The current embedded base is estimated at 0.6 million units.

A Canadian enhancement of the CT2 CAI, called CT2+, is designed to provide some of the missing mobility management functions. For that purpose, 5 of the 40 carriers are reserved for signaling. Each carrier provides 12 Common Signaling Channels (CSC) using TDMA. These channels support location registration, location updating, and paging, thereby enabling the Telepoint subscriber to receive calls. CT2+ operates in the frequency band 944-948 MHz.

In summary, the family of CT2 standards is an attractive option for cordless and Telepoint systems optimized with respect to cost. A more detailed description of CT2 can be found in [18].

DECT — Digital European Cordless Telecommunications — DECT is designed as a flexible interface to provide cost-effective communication services to high user densities in picocells, even with colocated systems that are not coordinated. The standard is intended for applications such as domestic cordless telephony, Telepoint, cordless PBXs, and RLL. It supports multiple bearer channels for speech and data transmission (which can be set up and released during a call), handover, location registration, and paging. Functionally, DECT is closer to a cellular system than to a classical cordless telephone. However, the interface to the PSTN or ISDN network remains the same as for a PBX or corded telephone.

DECT uses TDMA and TDD, with 12 slots per carrier in each direction (Fig. 1). A DECT base station therefore can support multiple handsets simultaneously with a single transceiver. Furthermore, it can allocate several slots to a single call to provide higher data rates. In addition to the advantages of TDD discussed above, the flexible allocation of slots to one or the other direction allows DECT to adjust for traffic asymmetries such as can occur during data base retrieval. To meet the expected traffic density, 10 carriers in the band 1880-1900 MHz are allocated in the initial implementation. The basic speech teleservice uses the same 32 kb/s ADPCM coding as CT2.

A key element of DECT is its "interference confinement" and "interference avoidance" strategy. The former involves the concentration of interference to a small time-frequency element even at the price of a reduced robustness, and the latter implies the avoidance of time-frequency slots with a significant level of interference by a handover to another slot at the same or another base station. This is a powerful approach for the uncoordinated

[9] TDD is not used more widely (e.g., in cellular systems) because it has disadvantages that are significant for some applications. TDD requires systemwide frame synchronization to avoid base-to-base and mobile-to-mobile interference, doubles the RF symbol rate (or halves the utilization of the front-end radio hardware in the base station), and requires additional guard time (which imposes substantial overhead for large cells).

	CT2	CT2+	DECT	PHS	PACS
Region	Europe	Canada	Europe	Japan	United States
Duplexing	TDD		TDD	TDD	FDD
Frequency band (MHz)	864-868	944-948	1880-1900	1895-1918	1850-1910/1930-1990*
Carrier spacing (kHz)	100		1728	300	300/300
Number of carriers	40		10	77	16 pairs/10 MHz
Bearer channels/carrier	1		12	4	8/pair
Channel bit rate (kb/s)	72		1152	384	384
Modulation	GFSK		GFSK	π/4 DQPSK	π/4 QPSK
Speech Coding	32 kb/s		32 kb/s	32 kb/s	32 kb/s
Average handset TX power (mW)	5		10	10	25
Peak handset TX power (mW)	10		250	80	200
Frame duration (millisec)	2		10	5	2.5

*General allocation to PCS (see Figs. 3 and 4); licensees may use PACS.

■ **Table 2.** *Summary of digital cordless air interface parameters.*

operation of base stations, since the interference caused by a foreign mobile station approaching a base station may reach a level at which no practical amount of baseband processing can recover the desired signal. In a cellular system, a handover to the closer base station takes place under such circumstances. With DECT, this is only possible if the foreign mobile station has the required access rights.

DECT is designed for low cost, flexibility, and operation in an uncoordinated environment. Among other things, this means that the base stations need not be synchronized. Various mechanisms, including fields for synchronization and parity, allow the detection of sliding collisions and the initiation of corrective actions such as handover. The information about access rights, base station capabilities, paging messages, etc., is multiplexed onto the control channel of each active transmission to optimize the utilization of the base station transmitter and to obtain robustness; a dummy bearer is used when there is no active call. The problem of inadequate frequency-switching speed in the base station synthesizer is taken into account by the provision of a list of "blind" slots. Due to the high signaling rate (1152 kb/s) and the correspondingly large bandwidth, either equalization or antenna diversity typically is needed for using DECT in the more dispersive microcells (Telepoint or RLL applications). This issue is currently under study, and field tests are being performed. Finally, a multiframe structure, which allows for a sleep mode of the handset, contributes to the conservation of battery life. Clearly, this short summary of DECT characteristics is only a representative selection to convey the spirit of the design.

For flexibility and broad applicability, DECT closely follows the Open Systems Interconnect (OSI) reference model, and it allows for a series of escape routes to proprietary additions and alternatives, which in particular include the possibility of specifying alternative Medium Access Control (MAC), Data Link Control (DLC) and network-layer protocols. This possibility is key to the future evolution.

In Europe, the first DECT systems are currently being shipped, primarily for business and domestic applications. DECT unit sales for 1994 are estimated at about 0.1 million. DECT and possible variants of it are the potential basis for low cost, picocell based systems in the near future.

In summary, DECT is a flexible standard for providing a wide range of services in small cells. An overview of basic design considerations is given in [19]. Detailed specifications are included in [20].

Personal Handyphone System — A study for the next generation portable telephone systems in Japan was initiated in January 1989 under the auspices of MPT. Following the report, the concept of the Personal Handyphone System (PHS, formerly PHP) was launched, on the basis of a digital cordless telephone and a digital network. The system objectives of PHS are to provide for not only home and office use, but also for public access capability [21]. The air interface protocol for PHS was determined by the Research & Development Center for Radio Systems (RCR), and the network interface was determined by the Telecommunications Technical Committee (TTC) [22].

Like DECT, the PHS standard uses TDMA and TDD, but each frequency carries 4 duplex bearer channels rather than 12. The RF channel rate of 384 kb/s was chosen based on the tradeoff between maximizing the multiplexing number and minimizing the effects of frequency-selective fading, particularly in outdoor environments (250-ns delay spread).

The PHS allocation consists of 77 channels, 300 kHz in width, in the band 1895-1918.1 MHz. The band 1906.1-1918.1 MHz (40 frequencies) is designated for public systems, and the band 1895-1906.1 MHz (37 frequencies) is used for home/office applications. The channel is autonomously selected by measuring the field strength and selecting a channel on which it is below a prescribed level, i.e., fully dynamic channel assignment is used. The modulation is π/4 DQPSK, and the average

DECT is a flexible standard for providing a wide range of services in small cells. Like DECT, PHS uses TDMA and TDD, but has four duplex bearer channels per frequency rather than twelve.

Direct sequence and frequency hopping digital cordless telephones operate in the 902-928 MHz band in the United States.

transmit power per direction is 10 mW (80 mW peak power) for the handset and no greater than 500 mW (4W peak) for the cell site. The frame duration is 5 ms. Like DECT and CT2, PHS uses 32 kb/s ADPCM speech coding, and error detection in the form of a cyclic redundancy check (CRC) is provided, but there is no error correction. Unlike DECT, however, PHS provides dedicated control channels. The typical talk and standby time are 5 hours and 150 hours, respectively. PHS supports handoffs (as an option), although it is confined to walking speed. Taking advantage of the channel reciprocity inherent with TDD and low-speed mobility, transmission diversity is provided on the forward link. Reception diversity at the base station can be used on the reverse link. Moreover, muting of the audio speech signal improves voice quality on both links in fading channels. As for data transmission capability, PHS currently can support G3 fax at 4.2 to 7.8 kb/s and full-duplex modem transmission at 2.4 to 9.6 kb/s through the speech codec. A new standard will be established to support 32- or 64-kb/s data by direct access to one or two bearer channels, respectively.

The home/office application for PHS has already been introduced in Japan, and the public application will be introduced this year. For purposes of providing service, Japan is divided into 11 regions, with at most three operators per region licensed to offer public access systems using the 12 MHz of available spectrum. The potential subscriber base for PHS is estimated to be 5.5 million in 1998 and 39 million in 2010. PHS also is expected to be introduced soon to provide cost-effective local wireless access (i.e., RLL). See [23] for a discussion of PHS network aspects and anticipated services.

WACS and PACS — In the United States, Bell Communications Research (Bellcore) developed an air interface for Wireless Access Communications Systems (WACS) [24]. This interface is intended to provide wireless connectivity to the local exchange carrier (LEC), and is designed with low-speed portable applications and small-cell systems in mind. Base stations are envisioned as shoebox-sized enclosures mounted on telephone poles, separated by about 600 m. The WACS air interface is similar to the digital cordless interfaces, with two notable exceptions: frequency-division duplexing (FDD) is used rather than TDD, and greater effort has been made to optimize the link budget and frequency reuse.

In the original design, each frequency carried ten user timeslots. Speech coding was 32 kb/s, with a superframe structure to allow for lower rate speech codecs. The frame duration was 2 milliseconds to minimize the delay added to the speech path. The modulation was QPSK (Quaternary Phase-Shift Keying) with coherent detection, which provides substantially better performance than the discriminator-based receivers used in most digital cordless systems. Two-branch polarization diversity at both the handset and base with feedback gives an advantage approaching that of four-branch reception diversity. Like the digital cordless air interfaces, the WACS design provides for error detection but not for FEC or adaptive equalization. Potential applications envisioned for WACS include RLL, portable public service, and wireless PBX.

As part of the standards process in the United States related to the recently-allocated spectrum near 2 GHz for Personal Communications Services (PCS) discussed below, attributes of WACS and PHS have been combined to create an industry standard proposal for Personal Access Communications Services (PACS). PACS is intended as a "low-tier" air interface for the licensed portion of the new 2-GHz spectrum. PACS retains many of the attributes of the original WACS design. The main changes include a reduction of the number of timeslots from ten to eight, and a corresponding reduction in the channel bit rate and bandwidth, as well as a slight increase in the frame duration. The modulation has been changed to $\pi/4$ QPSK, and coherent detection is used.

Table 2 shows the key physical layer parameters for CT2/CT2+, DECT, PHS, and PACS.

Digital Cordless in the North American ISM Bands — There are a number of frequency bands reserved for Industrial, Scientific, and Medical (ISM) devices. These devices generally use RF energy for heating rather than communication, and include applications such as microwave ovens, RF welders, and plywood heaters. In the United States and Canada, these bands include 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz. Unlicensed devices such as cordless telephones that use either frequency hopping or direct sequence spreading[10] are allowed to operate in these ISM bands with up to 1 watt of transmit power. Devices not using frequency hopping or direct sequence spreading are limited to a field strength of 50 mV/m at 3 meters, or about 0.5 mW ERP.

There currently are digital cordless telephones using both frequency hopping and direct sequence spreading, operating in the 902-928 MHz band. There are no detailed standards specifically governing ISM band cordless telephones. Manufacturers therefore have considerable design freedom for innovation and application of advances in technology without being constrained by channelization plans and operational restrictions based on older technologies. However, the interference environment tends to be undisciplined and difficult to predict. This situation places a premium on designs that are sufficiently robust and flexible to operate in the presence of unpredictable interference or to avoid it.

Digital Cordless Compared to Digital Cellular

From the foregoing summaries of the various digital cordless air interfaces, it is clear that while there are significant differences among them, they have a number of characteristics in common which distinguish them from the digital cellular technologies discussed earlier. In general, the digital cordless systems are optimized for low-complexity equipment and high-quality speech in a quasi-static environment (with respect to user mobility). Conversely, the digital cellular air interfaces are geared toward maximizing bandwidth efficiency and frequency reuse in a macrocellular, high-speed fading environment. This is achieved at the price of increased complexity in the terminal and base station. As summarized in Table 3, the physical layer parameters for digital cordless and digital cellular technologies reflect these respective design objectives.

[10] Frequency hopping systems are required to use pseudo- random hopping patterns of at least 50 frequencies in the 902-928 MHz band, and at least 75 frequencies in the other bands. Direct sequence systems must have a processing gain of at least 10 dB and a 6 dB bandwidth of at least 500 kHz.

Wireless Data

Wireless data systems are designed for packet-switched ("asynchronous") rather than circuit-switched ("isochronous") operation. Operators of wide-area messaging systems use licensed spectrum, and sell service to customers. Conversely, wireless local area networks (LANs) are usually privately owned and operated, and provide high-rate data communication over a small area. With the exception of the Altair system, wireless LANs are unlicensed and typically operate in the ISM bands (except for the infrared systems). A brief summary of wireless data systems is provided here; see [25] for a detailed discussion and an extensive reference list.

Wide Area Data Service

Advanced Radio Data Information Service (ARDIS) and RAM Mobile Data (RMD) offer wireless packet data messaging service over their dedicated networks using the specialized mobile radio (SMR) frequencies near 800/900 MHz. Both are available to 90 percent of the urban business population in the United States, and have a combined total of roughly 52,000 subscribers. ARDIS offers service in over 400 metropolitan areas. The data rate is 4.8 kb/s, with upgrades underway to 19.2 kb/s in some areas. RMD offers service over its Mobitex network, providing coverage in 216 metropolitan areas, with 10 to 30 duplex channels available in each area. The data rate is 8 kb/s. The Mobitex architecture was originally developed by Telia, the Swedish national operator. To encourage the development of multiple equipment sources, Mobitex software and hardware specifications are made available without any license or fee. The specifications are published by the Mobitex Operators' Association (MOA). As a result, there are a number of terminal suppliers. Mobitex networks are operational in 10 countries besides the United States.

Cellular Digital Packet Data (CDPD) does not require a specialized network but rather uses the existing analog cellular network. CDPD takes advantage of the idle time on the analog AMPS channels to transmit packet data at a rate of 19.2 kb/s. It is designed to operate as a "transparent" overlay on the AMPS system.

The General Packet Radio Service (GPRS) standard is being developed to provide packet data service over the GSM infrastructure. Two alternative approaches are being considered: 1) the allocation of specific GSM channels for packet transmission, which are shared by all active packet subscribers; and 2) the fast establishment of a GSM traffic channel on any radio resource available. The high grade service aims at a packet error rate of 10^{-4} and a delay less than 1 s. Particular attention is given to the interworking with Public Switched Packet Data Networks and Internet.

There also are wireless data services emerging in the United States that operate on an unlicensed basis in ISM spectrum. The recently-announced Ricochet™ wireless packet data system uses a microcell architecture with small, inexpensive, easily-installed base stations mounted on the tops of lamp posts, utility poles, and buildings. The customer accesses the network via a wireless modem that connects to the serial port of a laptop or notebook computer.

	Digtial Cordless	Digital Cellular
Characteristics		
Cell size	small (50 to 500 m)	large (0.5 to 30 km)
Antenna elevation	low (15m or less)	high (15m or more)
Mobility speed	low (6 kph or less)	high (up to 250 kph)
Coverage	zonal	wide-area continuous
Handset complexity	low	moderate
Base complexity	low	high
Spectrum access	shared	exclusive
Design attributes		
Handset TX power (average)	5 to 10 mW	100 to 600 mW
Duplexing	TDD*	FDD
Speech coding	32 kb/s ADPCM	8 to 13 kb/s vocoder
Error control	CRC	FEC/interleaving
Detection	discrim/differential*	coherent/differential
Multipath mitigation	antenna diversity (opt.)	diversity/equalizer/Rake

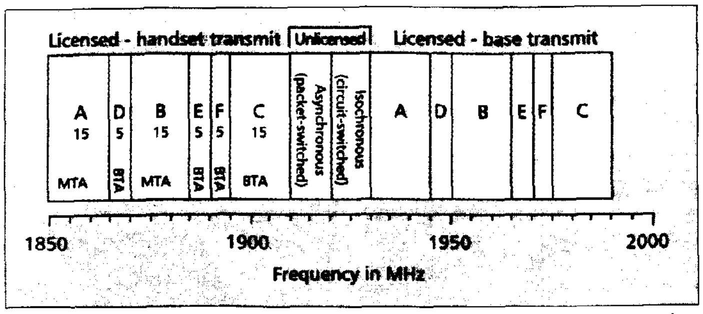
*PACS uses frequency duplexing and coherent detection.

■ **Table 3.** *General comparison of digital cordless and digital cellular air interfaces.*

Wireless Local Area Networks (LANs)

Wireless LANs are targeted primarily for high data rates (generally ≥ 1 Mb/s) and in-building applications, and may be preferable to their wired counterparts for situations in which wiring is difficult or impractical, or some degree of mobility is needed. There currently are a number of products available that operate on an unlicensed basis in the ISM bands, such as FreePort™ and WaveLAN.® FreePort provides a wireless Ethernet® (IEEE 802.3) hub and operates in the 2400-2483.5 MHz (hub receive) and 5725-5850 MHz (hub transmit) ISM bands, using direct sequence spreading. WaveLAN [26] provides peer-to-peer communication in the 902-928 MHz band in the United States and in the 2.4-2.48 GHz band in most other countries (it is available in 39 countries outside the United States). WaveLAN uses direct sequence spreading with a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol. Altair uses the Ethernet protocol and operates in the terrestrial microwave spectrum near 18 GHz; a site-specific U.S. FCC license is required.

Standards are being developed for wireless LANs, under IEEE 802.11 in the United States and ETSI/RES10 in Europe (known as HIPERLAN, for High Performance Radio LAN). There are a number of similarities between the IEEE 802.11 and the HIPERLAN work. Both standards are intended for rates exceeding 1Mb/s, and will support architectures with an infrastructure as well as "ad hoc" architectures, whereby terminals communicate directly with each other (peer-to-peer) without the mediation of a fixed base station. Point-to-point, point-to-multipoint, and broadcast services will be available. While asynchronous packet transmission will be



■ **Figure 4.** *The U.S. PCS frequency plan. MTA is "major trading area" and BTA is "basic trading area."*

the dominant mode, distributed time-bounded services (DTBS) will also be supported. Finally, since it is anticipated that many terminals will be battery-powered, the standards will incorporate a sleep mode for power management.

There also are some differences between IEEE 802.11 and HIPERLAN. The initial focus of IEEE 802.11 is the development of a single standard for the MAC layer,[11] and multiple physical-layer standards compatible with the single MAC. Initial work on physical-layer standards is focused on both direct sequence and frequency hopping for the 2.4-GHz ISM band. Other physical layer standards, including one for the 1.9 GHz unlicensed PCS band (discussed below), are anticipated. In addition, a standard for a baseband infrared (IR) physical layer is under development.

HIPERLAN is focusing on higher data rates than IEEE 802.11. This is made possible by the allocation of large dedicated bands: 5150-5300 MHz plus another 200 MHz near 17 GHz. Furthermore, the HIPERLAN standard is planned to include provisions for a flexible forwarding mechanism for ad-hoc (non-infrastructure) networks, to extend the effective range of the terminals. The nodes are subdivided into forwarding and non-forwarding nodes, and a self-adapting wireless LAN is created. Finally, HIPERLAN is placing more emphasis on DTBS.

In Japan, two types of wireless LANs have been standardized. One is for medium rates in the range of 256 kb/s to 2 Mb/s using spread spectrum in the 2.4 GHz ISM band. The other is for high rates ($\geq$ 10 Mb/s) using Quadrature Amplitude Modulation (QAM), QPSK, or 4-level FSK, and operating near 18 GHz.

Ongoing Work and the Future

The future of wireless personal communications offers many possibilities. Continuous improvements in microelectronics technology and radio link techniques coupled with advances in network signaling and control capabilities will support increasingly sophisticated features and services. Part of the challenge in planning future wireless systems is to determine the services that they will be required to support. This has been the major thrust of TG8/1 of the ITU-R (the International Telecommunication Union-Radiocommunication sector, formerly CCIR), which is defining Future Public Land Mobile Telecommunication Systems (FPLMTS). Spectrum was allocated on an international basis to FPLMTS at the 1992 World Administrative Radio Conference (WARC '92), as shown in Fig. 3. For more detail on the WARC '92 allocations, refer to reference [27].

Universal Mobile Telecommunications Systems (UMTS) in Europe

In Europe, the long term goal is a Universal Mobile Telecommunications System (UMTS), which unifies the worlds of cellular, cordless, RLL, low-end wireless LAN, private mobile radio (PMR), and paging. The idea is to provide the same type of services everywhere, with the only limitation being that the available data rate may depend on the location (environment) and the load of the system. The scope is a multi-operator system with mixed cell architectures and multimedia capabilities. These requirements are difficult to meet. They have implications on both the radio interface and the protocol structure.

GSM and DCS1800 are actively being pushed towards a UMTS and get rather close to it. Radio local loop service to the home and business, as well as PBX functionality in the public switches, could take over cordless functions if service is provided at an adequate price. A major unsolved issue is the provision of higher data rates. Under rather optimistic conditions, an alternative modulation scheme and the use of asymmetric slot allocations could boost the rate perhaps up to 64 kb/s, but certainly not to 2 Mb/s. Spectrum efficiency and costs for the low end are issues also.

DECT could grow beyond its present application areas of cordless phone, PBX and Telepoint. Studies and field trials currently are being performed for local loop replacement. The extension of the range by more advanced antenna systems and some form of equalization, as well as repeaters, are important issues in this context. DECT could support the low-cost mass-market in densely populated areas, leaving wide area coverage to cellular systems (partial UMTS). Dynamic channel allocation and the high degree of flexibility in providing new services, by combining channels to achieve higher data rates (without modification of the standard perhaps up to 200 kb/s/transceiver) are other assets. Finally, the use of a DECT air interface in conjunction with the GSM infrastructure also is being studied.

The projects Advanced TDMA (ATDMA) and Code Division Testbed (CODIT) from the R & D in Advanced Communications Technologies in Europe (RACE) program follow more revolutionary approaches to UMTS. The former project uses TDMA, and the latter one, CDMA as the principal access technique. Both projects seek higher data rates. In the testbeds, rates up to 64 and 128 kb/s are being considered, and the concept work includes burst rates up to 2 Mb/s. Low delay connectionless packet transmissions and access to the Internet also are being addressed. A type of multimedia capability with the parallel transmission of speech and fax or a concurrent retrieval of data from a data base is possible in CODIT, for example. Many aspects of the TDMA and CDMA approaches have been introduced in the previous sections. A few properties that have received particular attention in view of the UMTS objectives are as follows. With CDMA, a bandwidth that is in excess of the optimum bandwidth for a given environment can be tolerated

[11] *The MAC layer manages the access to the radio channel(s). In terms of the OSI reference model, the MAC is the lower part of the data link layer, directly above the physical layer. The upper part of the data link layer is the logical link control (LLC) layer.*

and cells of widely varying size can be accommodated with almost no penalty on spectrum efficiency. With TDMA, different operators (smaller bandwidth) and uncoordinated environments (see DECT) can be supported more easily. Both projects have tried to solve some of the inconveniences of the respective approaches. In ATDMA, a type of soft performance degradation is achieved by trading the rate of the speech coding against the rate of the error correction coding. In order to take advantage of speech activity, the combination of talkspurt detection and a Packet Reservation Multiple Access (PRMA) scheme has been studied. In CODIT, interfrequency handover is included to switch from embedded microcells to overlaying macrocells or from a cellular environment to an uncoordinated one. In uncoordinated environments, interference from neighbor systems is detected by the mobile station. The presence of the latter interference, which is an indication of a close base station that could be blocked, triggers a handover to another frequency or to a cellular operator. As is to be expected, both projects try to develop the specific strengths of their own approach, but try also to find mechanisms for including the advantages of the competing approach. The soft degradation introduced in TDMA or the interfrequency handover introduced in CDMA, in order to support interoperability between collocated operators, are examples. Both approaches look promising, with some advantage for CDMA in cellular environments and for TDMA in uncoordinated environments.

Additional concepts are considered outside ETSI and RACE also. "Page and answer" is an idea being investigated at Ascom, for example. In its simplest form, an incoming call is put on hold at a server, which issues a page. The called party responds on the most suitable terminal (wired, cordless, or cellular) and answers using a wrist pager sending dual-tone multifrequency (DTMF) tones to connect (toll-free) and authenticate to the server. The server then completes the connection. More advanced implementations are also being conceived. Advantages of such approaches are that they save investment, do not require heavy handsets with rather limited operation times, avoid unnecessary restrictions on data rates (in the office, at home), and maintain the traditional charging of the calling side.

In summary, the mainstream in Europe is currently exploiting the potential of GSM and DECT, including further evolutions and the interworking of these standards. Other standards are being finalized, for wireless LAN (HIPERLAN) and PMR (TETRA, for Trans European Trunked Radio System), for example. Concurrently, the definition and specification of a UMTS is being attempted within ETSI and supported by RACE. The design of ISM band and other non-standardized systems also is being pursued but with a lesser emphasis.

PCS in the Emerging Technologies Bands in the United States

The path being taken toward future wireless systems in the United States is very different from that in Europe. In support of a free-market approach, the FCC has recently allocated 140 MHz of spectrum near 2 GHz to PCS. Figure 4 shows the exact frequencies. Note that the A and B blocks are designated for major trading areas (MTAs), while blocks C through F are to be licensed on the basis of BTAs (basic trading areas). There are 51 MTAs and 492 BTAs in the United States (which suggests a rough comparison of MTAs to states and BTAs to counties). In addition to the allocations for licensed terrestrial systems, a total of 20 MHz was allocated for unlicensed applications (and more is expected in the near future). Of this, 10 MHz is designated for "isochronous" (i.e., circuit-switched) applications such as voice, and 10 MHz for "asynchronous" applications like wireless packet data. Equipment operating in the 2-GHz unlicensed band will be required to comply with a "spectral etiquette" incorporated into Part 15 of the FCC rules. This etiquette was developed by the technical subcommittee WINTech of the industry body WINForum, and is intended to promote harmonious coexistence of diverse systems in the unlicensed band while allowing designers considerable flexibility with respect to system architecture (modulation, coding, signaling protocols, frame structure, etc.). Two of the essential ingredients in the etiquette are 1) a "listen before talk" (LBT) requirement, intended to prevent a transmitter from interrupting communication already in progress on a frequency; and 2) a transmit power limit that varies as the square root of the signal bandwidth, intended to put wideband and narrowband systems on a relatively even footing with respect to interference and use of the spectrum.

The FCC is awarding licenses in the PCS spectrum via "competitive bidding" (i.e., auctions). The winner of each license is free to use any desired air interface and system architecture, provided it complies with the FCC rules governing transmit power levels, etc. Hence, there are no predetermined standards for systems that will be operating in the 2-GHz PCS spectrum. This has led the TIA and Committee T1 of the Alliance for Telecommunications Industry Solutions (ATIS, formerly the Exchange Carrier Standards Association) to form a Joint Technical Committee (JTC) to review potential PCS standards submitted by contributors, and to make recommendations. The JTC has recognized that PCS standards fall naturally into two categories: "high tier," supporting macrocells and high-speed mobility; and "low tier," optimized for low power and low complexity. These two tiers essentially correspond to the "digital cellular" and "digital cordless" categories, respectively, discussed earlier. At this point, the JTC has narrowed the initial list of 16 possible standards down to seven. Five of these are variations of existing air interfaces: PACS (low-tier) and proposals based on GSM, IS-54, and IS-95 (high-tier) as well as DECT (low-tier). The other two are based on a hybrid TDMA/CDMA approach, and wideband CDMA (W-CDMA), respectively. In addition, the TIA has initiated an activity under its TR41 technical committee to develop standards for wireless user premises equipment (WUPE) operating in the unlicensed PCS band.

The 2-GHz PCS spectrum currently is occupied by operating point-to-point microwave radio systems. For the most part, these incumbent transmission links must be relocated to other frequencies (e.g., 6 GHz) or converted to optical fiber facilities before PCS systems can be deployed.[12] The PCS licensee is required to compensate the incumbent for the cost of relocating. For the unli-

The mainstream in Europe is currently exploiting the potential of GSM and DECT, including further evolutions and the interworking of these standards.

[12] *In some cases, it may be possible to frequency-coordinate between the PCS operator and an incumbent to avoid interference.*

censed band, financing the cost of relocating the incumbents is less straightforward, since an equitable mechanism must be developed for sharing the cost of relocation among the purveyors of unlicensed equipment. In addition, during the transition period, the usage of specific frequencies in specific areas must be limited to those which have been cleared. The industry forum UTAM, Inc. (for Unlicensed PCS Ad Hoc Committee for 2 GHz Microwave Transition And Management) was formed to deal with these issues.

FPLMTS Work in Japan

Japan has estaablished a new standardization committee and related working groups in connection with FPLMTS work. CDMA as well as advanced TDMA technologies are being studied, including progagation and access tests, to contribute to ITU-R standardization activities.

Global:Mobile Satellite Services

There are some situations in which providing radio coverage with cellular-like terrestrial wireless networks is either not economically viable (such as in remote, sparsely-populated areas), or physically impractical (such as over large bodies of water). In these cases, mobile satellite services (MSS) could fill the gap, allowing complete global coverage. Spectrum has been designated by the ITU for MSS (as shown in Fig. 3), and there are many MSS systems in various stages of concept, design, and operation. Some support only data services while others accommodate voice as well. Some are designed for special purposes and/or private user groups while others are intended for general (public) use and interconnection to the PSTN. The latter could support universal wireless communications.

One way to broadly categorize MSS systems is according to the orbital altitude of the satellites: geostationary satellites (GEOS), at an altitude of 35,786 km; low earth orbit satellites (LEOS), at altitudes on the order of 1,000 km; medium earth orbit satellites (MEOS), at altitudes on the order of 10,000 km; and highly elliptical orbit satellites (HEOS), with widely varying altitudes. GEOS systems for public use include INMARSAT-M, MSAT, ACTS, MOBILESAT, and NSTAR. LEOS systems include Iridium [28] (66 satellites at roughly 770 km), Globalstar (48 satellites at 1400 km), and Teledesic (840 satellites at 700 km). Odyssey is a MEOS proposal with 12 satellites at about 10,600 km, and the ELMSAT proposal specifies a HEOS approach with two or three satellites.

Guide to Wireless Acronyms and Abbreviations

ADPCM	Adaptive differential pulse code modulation
AMPS	Advanced Mobile Phone Service
CDMA	Code division multiple access
CDPD	Cellular Digital Packet Data (U.S.)
CEPT	Conférence Européenne des Postes et Télécommunications
CRC	Cyclic redundancy check
CT	Cordless Telephone (interim ETSI standards, e.g., CT1)
DCA	Dynamic channel assignment
DCS1800	Digital Cellular System 1800 (Europe)
DECT	Digital European Cordless Telecommunications
DLC	Data link control (layer)
DQPSK	Differential quaternary phase shift keying
EIA	Electronic Industries Association (U.S.)
ERP	Effective radiated power
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission (U.S.)
FDD	Frequency division duplexing
FDMA	Frequency division multiple access
FEC	Forward error correction (channel coding; e.g., convolutional coding)
FM	Frequency modulation
FPLMTS	Future Public Land Mobile Telecommunication Systems
FSK	Frequency shift keying
GFSK	Gaussian filtered FSK
GMSK	Gaussian minimum shift keying
GPRS	General Packet Radio Service (GSM connectionless packet service, ETSI, Europe)
GSM	Groupe Spécial Mobile (originally) currently Global System for Mobile Communication (ETSI, Europe)
HIPERLAN	High Performance Radio Local Area Network (ETSI, Europe)
INMARSAT	International Maritime Satellite Organization
IR	Infrared
IS-41	Interim Standard 41 (TIA/EIA cellular network signaling standard, U.S.)
IS-54	Interim Standard 54 (TIA/EIA TDMA cellular standard, U.S.)
IS-95	Interim Standard 95 (TIA/EIA CDMA cellular standard, U.S.)
ISDN	Integrated Services Digital Network
ISM	Industrial, Scientific, and Medical (bands, devices)
ITU-R	International Telecommunication Union-radio communication sector
LEOS	Low earth orbit satellite
MAC	Medium access control (layer)
MNP	Microcom Networking Protocol
MPT	Ministry of Posts and Telecommunications (Japan)
MSS	Mobile satellite services (or systems)
NMT	Nordic Mobile Telephone (Europe)
PACS	Personal Access Communications Services
PBX	Private branch exchange
PCN	Personal Communications Network (Europe)
PCS	Personal Communications Services (U.S.)
PDC	Personal Digital Cellular (Japan)
PHS	Personal Handyphone System (Japan, formerly PHP)
PMR	Private mobile radio
PRMA	Packet Reservation Multiple Access
PSTN	Public Switched Telephone Network
QPSK	Quaternary Phase Shift Keying
RACE	R & D in Advanced Communications Technologies in Europe
RCR	Research & development Center for Radio systems (Japan)
RF	Radio frequency
RLL	Radio local loop
RTMS	Radio Telephone Mobile System (Italy)
RX	Receive or reception
SMR	Specialized mobile radio
TACS	Total Access Communication System (Europe)
TDD	Time division duplexing
TDMA	Time division multiple access
TETRA	Trans European Trunked Radio System
TIA	Telecommunications Industry Association (U.S.)
TTC	Telecommunication Technical Committee (Japan)
TX	Transmit or transmission
UMTS	Universal Mobile Telecommunications System
VSELP	Vector sum excited linear prediction (speech coding)
WACS	Wireless Access Communications Systems
WARC	World Administrative Radio Conference

A major advantage of using GEOS is that continuous global coverage up to 75° latitude can be provided with only 3 satellites. Drawbacks include the 240-to-270-ms round trip propagation delay and the high RF power required. Although the LEOS approach minimizes the required transmit power (making small portable handsets viable) as well as the delay, there are also disadvantages. Due to the large number of satellites required to provide global coverage and their limited lifetime (five to ten years due to orbital decay), replacement satellites will have to be launched frequently. Moreover, the rapid movement of the LEOS "cells" relative to the earth (about 7.4 km/s for Iridium) requires frequent handoffs.

A detailed discussion of mobile satellite communications is beyond the scope of this article (see [29] and [30] for details), but it should be noted that there are some economic viability issues. The network operating and maintenance costs must be balanced against the willingness-to-pay of a sufficiently large market to support the service. Despite the technical and economic hurdles, however, MSS may become an important component in the future wireless global network.

Conclusion

Wireless personal communications is in the process of revolutionizing telecommunications services and the way in which people use them. Overall growth in the cordless and cellular markets during recent years has exceeded expectations. There is widespread anticipation that customer demand for wireless telecommunications will continue to expand for the foreseeable future. This is reflected by the high level of engineering activity and standards development worldwide. There are many different views on what the future will bring in terms of wireless capabilities and designs. However, one thing is clear: wireless personal communications has achieved "mainstream" status and will be a major force in driving the development of telecommunications systems and services.

References

[1] V. H. McDonald, "The Cellular Concept," *BSTJ*, vol. 58, no. 1, part 3, pp. 15-41, Jan. 1979.

[2] M. Mouly and M.-B. Pautet, "The Evolution of GSM," in Mobile Communications - Advanced Systems and Components, Proc. 1994 Int. Zurich Sem. on Dig. Commun., (Springer-Verlag, LNCS, vol. 783).

[3] M. R. L. Hodges, "The GSM Radio Interface," *Br. Telecom Tech. J.*, vol. 8, pp. 31-43, Jan. 1990.

[4] M. Mouly and M.-B. Pautet, *The GSM System for Mobile Communications*, (Paris, 1992, ISBN 2-9507190-0-7).

[5] ETSI GSM Specifications, Series 01-12.

[6] P. A. Ramsdale, "Personal Communications in the UK — Implementation of PCN Using DCS 1800," *Internat. J. Wireless Info. Networks*, pp. 29-36, vol. 1, no. 1, Jan. 1994.

[7] TIA/EIA IS-54, "Cellular System Dual-Mode Mobile Station-Base Station Compatibility Standard," Telecommunications Industry Association, April, 1992.

[8] TIA/EIA IS-41, "Cellular Radio Telecommunications Intersystem Operations," Telecommunications Industry Association, December, 1991.

[9] K. Kinoshita, M. Kuramoto, and N. Nakajima, "Development of a TDMA Digital Cellular System Based on Japanese Standard," Proc. 41st IEEE Veh. Technol. Conf., pp. 642-645, 1991.

[10] Research & Development Center for Radio Systems (RCR), "Digital Cellular Telecommunication Systems," RCR STD-27, Apr. 1991.

[11] A. Salmasi and K. S. Gilhousen, "On the System Design Aspects of Code Division Multiple Access (CDMA) Applied to Digital Cellular and Personal Communications Networks," Proc. 41st IEEE Veh. Technol. Conf., pp. 57-62, 1991.

[12] TIA/EIA IS-95, "Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread-Spectrum Cellular Systems," Telecommunications Industry Association, July, 1993.

[13] R. Padovani, "Reverse Link Performance of IS-95 Based Cellular Systems," *IEEE Pers. Commun.*, vol. 1, no. 3, pp. 28-34, 3Q 1994.

[14] Federal Communications Commission, Notice of Proposed Rule Making in the matter of Amendment of Parts 15 and 90 of the Commission's Rules to Provide Additional Frequencies for Cordless Telephones, ET Docket 93-235, adopted Aug. 20, 1993.

[15] R. S. Swain, "Cordless Communication in the UK," *British Telecom Technol. J.*, vol. 3, no. 2, pp. 32-38, April 1985.

[16] ETSI, "Radio Equipment and Systems - Technical characteristics, test conditions and methods of measurement for radio aspects of cordless telephones CT1."

[17] T. Hattori, A. Sasaki, and K. Momma, "Emerging Technology and Service Enhancement for Cordless Telephone Systems," *IEEE Commun. Mag.*, vol. 26, no. 1, pp. 53-58, Jan. 1988.

[18] R. Steedman, "The Common Air Interface MPT 1375," in *Cordless Telecommunications in Europe*, W. H. W. Tuttlebee, ed., (Springer Verlag, 1990).

[19] D. Åkerberg, "Novel Radio Access Principles Useful for Third Generation Mobile Radio Systems," Proc. IEEE PIMRC '92 (1992 IEEE Symposium on Personal, Indoor, and Mobile Radio Communications), Boston MA, Oct. 19-21, 1992.

[20] ETSI, Digital European Cordless Telecommunications - Common Interface, Radio Equipment and Systems, Valbonne, France.

[21] T. Hattori *et al.*, "Personal Communication - Concept and Architecture," Proc. 1990 IEEE Internat'l Commun. Conf. (ICC '90), pp. 1351-1357, Apr. 16-19, 1990.

[22] Research & Development Center for Radio Systems (RCR), "Personal Handy Phone Systems," RCR STD-28, Dec. 1993.

[23] K. Ogawa, K. Kohiyama, and T. Kobayashi, "Toward the Personal Communication Era - A Proposal of the 'Radio Access' Concept from Japan," *Internat. J. Wireless Info. Networks*, vol. 1, no. 1, pp. 17-27, Jan. 1994.

[24] D. C. Cox, "Wireless Network Access for Personal Communications," *IEEE Commun. Mag.*, vol. 30, no. 12, pp. 96-115, Dec. 1992.

[25] K. Pahlavan and A. H. Levesque, "Wireless Data Communications," *Proc. IEEE*, vol. 82, no. 9, pp. 1398 - 1430, Sep. 1994.

[26] B. Tuch, "Development of WaveLAN, an ISM Band Wireless LAN," *AT&T Tech. J.*, vol. 72, no. 4, pp. 27-37, July/Aug. 1993.

[27] C. M. Rush, "How WARC '92 Will Affect Mobile Services," *IEEE Commun. Mag.*, vol. 30, no. 10, pp. 90-96, Oct. 1992.

[28] J. L. Grubb, "The Traveler's Dream Come True," *IEEE Commun. Mag.*, vol. 29, no. 11, pp. 48-51, Nov., 1991.

[29] W. W. Wu *et al.*, "Mobile Satellite Communications," *Proc. IEEE*, vol. 82, no. 9, pp. 1431-1448, Sep. 1994.

[30] F. Abrishamkar and E. Biglieri, "An Overview of Wireless Communications," Proc. 1994 IEEE Military Commun. Conf., (MILCOM '94), pp. 900-905, October 2-5, 1994.

Biographies

JAY E. PADGETT [SM '90] received Bachelor's and Master's degrees from the University of Virginia in 1976 and 1977, respectively, and a Ph.D. from Polytechnic University (Brooklyn, New York) in 1987, all in electrical engineering. He has been with AT&T Bell Laboratories in New Jersey since 1977, and became a distinguished member of technical staff in 1986. His activities have included systems engineering for analog and digital cordless telephones, microwave terrestrial radio links, and personal communications systems, focusing on mathematical modeling and analysis of performance and capacity. He is chair of the TIA Mobile & Personal Communications Consumer Radio Section, and a member of Eta Kappa Nu and Tau Beta Pi.

CHRISTOPH G. GUNTHER [M '87] received his diploma and doctor degrees in theoretical physics at the Swiss Federal Institute of Technology (ETH) in Zurich in 1979 and 1984, respectively. In 1984, he joined Brown Boveri Corporate Research and worked in cryptography, mainly in the development and analysis of stream cipher algorithms, homophonic coding, and key-exchange protocols. In 1989, he started working in spread spectrum transmissions and joined Ascom Tech, Mägenwil, Switzerland, in January 1990. Since 1991, he has been the Head of the Cellular System Group of that company, which is the research organization of Ascom. He is working on modulation, synchronization, multi-path receivers, packet transmission, and various aspects of personal communication systems. His interests also include information and coding theory.

TAKESHI HATTORI [M '71] received B.S., M.S., and Ph.D. degrees from the University of Tokyo in 1969, 1971, and 1974, respectively. He joined the Electrical Communication Laboratory, NTT, Japan in 1974. From 1974 to 1986, he was engaged in research on 800-MHz land mobile telephone systems, high-capacity mobile communication systems, and high-speed paging systems and technologies. From 1984 to 1986, he was senior manager at the ECL Research and Development Headquarters and worked on systems engineering and research planning. From 1986 to 1987, he was head of the Mobile Communication Applications Section in the Radio Communications Networks Laboratory, and responsible for the development of new cordless telephone and maritime telephone systems. From 1987 to 1989, he was Research Group Leader of the Radio Communication Systems Laboratory, and was involved in research on high-speed digital mobile radio transmission technologies. From 1989 to 1991, he was Project Team-3 Leader for R & D of personal communications systems. From 1991 to 1992, he was executive manager of the Research Planning Department in the NTT Radio Communication Systems Laboratories. He is currently executive manager of the Personal Communication Systems Laboratory in NTT Wireless Systems Laboratories, Kanagawa, Japan, and is responsible for R & D of wireless personal communication systems. He was awarded the IEEE Vehicular Technology Society Paper of the Year in 1981. He is a member of the IEEE Communications, Vehicular Technology, and Computer Societies, and of the Institute of Electronics and Communications Engineers (IEICE) of Japan.

Wireless personal communications has achieved mainstream status and will be a major force in driving the development of telecommunications systems and services.