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 publicwline 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 telephone, 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 reference provided here.

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 cells 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].
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.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Mobile TX/Base TX (MHz)</th>
<th>Channel spacing (kHz)</th>
<th>Number of channels</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMPS</td>
<td>824-849/869-894</td>
<td>30</td>
<td>832</td>
<td>The Americas1</td>
</tr>
<tr>
<td>TACS</td>
<td>890-915/935-960</td>
<td>25</td>
<td>1000</td>
<td>Europe</td>
</tr>
<tr>
<td>ETACS</td>
<td>872-905/917-950</td>
<td>25</td>
<td>1240</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>NMT 450</td>
<td>453-457.5/463-467.5</td>
<td>25</td>
<td>180</td>
<td>Europe</td>
</tr>
<tr>
<td>NMT 900</td>
<td>890-915/935-960</td>
<td>12.5</td>
<td>1999</td>
<td>Europe1</td>
</tr>
<tr>
<td>C-450</td>
<td>450-455.74/460-465.74</td>
<td>10</td>
<td>573</td>
<td>Germany, Portugal</td>
</tr>
<tr>
<td>RTMS</td>
<td>450-455/460-465</td>
<td>25</td>
<td>200</td>
<td>Italy</td>
</tr>
<tr>
<td>Radiocom 20004</td>
<td>192.5-199.5/200.5-207.5</td>
<td>12.5</td>
<td>560</td>
<td>France</td>
</tr>
<tr>
<td>NTT</td>
<td>925-940/870-8855</td>
<td>25/6.25</td>
<td>600/2400</td>
<td>Japan</td>
</tr>
<tr>
<td>NTT</td>
<td>915-918.5/860-863.5</td>
<td>6.25</td>
<td>560</td>
<td>Japan</td>
</tr>
<tr>
<td>NTT</td>
<td>922-925/867-870</td>
<td>6.25</td>
<td>480</td>
<td>Japan</td>
</tr>
<tr>
<td>JTACS/NTACS</td>
<td>915-925/860-870</td>
<td>25/12.5</td>
<td>400/800</td>
<td>Japan</td>
</tr>
<tr>
<td>JTACS/NTACS</td>
<td>898-901/843-846</td>
<td>25/12.5</td>
<td>120/240</td>
<td>Japan</td>
</tr>
<tr>
<td>JTACS/NTACS</td>
<td>918.5-922/863.5-867.6</td>
<td>12.5</td>
<td>280</td>
<td>Japan</td>
</tr>
</tbody>
</table>

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.
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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. 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-kbit/s rate. To meet cochannel interference objectives, 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). 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...
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 time slots, and each user is assigned a specific frequency/time slot 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.1

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 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 hand-offs, 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 Conference Europeenne des Postes et Telecommunications (CEPT) to establish a “Groupe Special Mobile” in 1982. The work of that group became the GSM system (now “Global System for Mobile communications”).

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Footnote:

1 The digital cordless systems CT2, DECT, and PHS noted in Fig. 1 are discussed in the section to follow on cordless telephony.
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 a approach, a base station only needs one (fast) 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 TDMA systems, no additional hardware is needed for finding candidate base stations.

The time-compression of the user data (22.8 kbps 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, the signal resolution becomes possible. In GSM, the staggering of the paths is estimated using a fixed midamble (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 (e.g., 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 kbps, eight slots/frame) and half-rate (11.4 kbps, 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 full-rate and half-rate operation. In particular, these data services interface to audio modems (e.g., V.22bis or V.32) and 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 microcells 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 DCS1800, 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.

### Figure 2. Digital cellular frequency allocations.

<table>
<thead>
<tr>
<th>Frequency in MHz</th>
<th>North America (IS-54/136, IS-95)</th>
<th>Europe (GSM)</th>
<th>Japan (PDC)</th>
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<tbody>
<tr>
<td>821</td>
<td>824</td>
<td>826, 954</td>
<td>817</td>
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</table>

**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...
provides a raw RF bit rate of 48.6 kbps, achieved using \( \pi/4 \) DQPSK\(^5\) at a 24.3-kb/s 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 kbps 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 kb/s), 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 kbps 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 IS-41 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 capabilities 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 kbps, and the modulation is \( \pi/4 \) 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 87.7 kbps, but due to the relatively low channel rate (42 kbps), the equalizer will be unnecessary. IS-95 is expected to 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 antennae space diversity, the required C/I is reduced, giving a reuse factor of 4. Group 3 FAX (2.4 kbps) as well as 4-kbps modem transmission with MNP class 4 are supported using an adaptor to provide the required transmission quality. There are five PDC operators, and there 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 kbps. This is spread to a channel chip rate of 1.2288 Mcips (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.
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 station 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., a repetition code). This added spreading results in a greater tolerance for interference than would be realized from the non-coherent detection of the pure Walsh functions. A final spreading is achieved by spreading the resulting 512-2 chips/ second by user-specific and base-specific codes. The chips are 2^5-1 and 2^3-1, 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 (i.e., orthogonality among interfering 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 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 received 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 kbps 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 to begin this year. For an 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. There are an estimated 60 million 46/49 MHz cordless telephones in use in the United States, and total sales are roughly 1.5 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, 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 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 from Europe, 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 legal 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]. The cordless standard provides for 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 such a 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
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 CT2/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), 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 service uses the same 32 kHz 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
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 four duplex bearer channels rather than twelve. 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

---

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

<table>
<thead>
<tr>
<th>Region</th>
<th>CT2</th>
<th>CT2+</th>
<th>DECT</th>
<th>PHS</th>
<th>PACS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Europe</td>
<td>Canada</td>
<td>Europe</td>
<td>Japan</td>
<td>United States</td>
</tr>
<tr>
<td>Duplexing</td>
<td>TDD</td>
<td></td>
<td>TDD</td>
<td>TDD</td>
<td>FDD</td>
</tr>
<tr>
<td>Frequency band (MHz)</td>
<td>864-868</td>
<td>944-948</td>
<td>1880-1900</td>
<td>1895-1918</td>
<td>1850-1910/1930-1990*</td>
</tr>
<tr>
<td>Carrier spacing (kHz)</td>
<td>100</td>
<td>1278</td>
<td>300</td>
<td>300/300</td>
<td></td>
</tr>
<tr>
<td>Number of carriers</td>
<td>40</td>
<td>10</td>
<td>77</td>
<td>8/pair</td>
<td></td>
</tr>
<tr>
<td>Bearer channels/carrier</td>
<td>1</td>
<td>12</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel bit rate (kb/s)</td>
<td>72</td>
<td>1152</td>
<td>384</td>
<td>384</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>GFSK</td>
<td>GFSK</td>
<td>π/4 DQPSK</td>
<td>π/4 QPSK</td>
<td></td>
</tr>
<tr>
<td>Speech Coding</td>
<td>32 kb/s</td>
<td>32 kb/s</td>
<td>32 kb/s</td>
<td>32 kb/s</td>
<td></td>
</tr>
<tr>
<td>Average handset TX power (mW)</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Peak handset TX power (mW)</td>
<td>10</td>
<td>250</td>
<td>80</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Frame duration (millsec)</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

*General allocation to PCS (see Figs. 3 and 4); licensees may use PACS.
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 ADFPCM speech coding, and error detection in the form of a cyclic redundancy check (CRC) is provided, but there is no air 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 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 multiplexing (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 use 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 n/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 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 unpredictable 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.
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 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 kbps, with upgrades underway to 19.2 kbps 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 kbps. 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 kbps. 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 establishment of a shared 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 are also 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.

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Digital Cordless</th>
<th>Digital Cellular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell size</td>
<td>small (50 to 500 m)</td>
<td>large (0.5 to 30 km)</td>
</tr>
<tr>
<td>Antenna elevation</td>
<td>low (15 m or less)</td>
<td>high (15 m or more)</td>
</tr>
<tr>
<td>Mobility speed</td>
<td>low (6 kph or less)</td>
<td>high (up to 250 kph)</td>
</tr>
<tr>
<td>Coverage</td>
<td>zonal</td>
<td>wide-area continuous</td>
</tr>
<tr>
<td>Handset complexity</td>
<td>low</td>
<td>moderate</td>
</tr>
<tr>
<td>Base complexity</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Spectrum access</td>
<td>shared</td>
<td>exclusive</td>
</tr>
</tbody>
</table>

Wireless Local Area Networks (LANs)

Wireless LANs are targeted primarily for high data rates (generally ≥ 1 Mbps) 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 10 Mbps, 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-multi-point, and broadcast services will be available. While asynchronous packet transmission will be
the dominant mode, distributed time-bounded services (DTBIS) will still be used. Finally, since it is anticipated that many terminals will be battery-powered, the standards will incorporate a sleep mode for power management.

There are also some differences between IEEE 802.11 and HIPERLAN. The initial focus of IEEE 802.11 is the development of a single physical layer standard for the MAC layer, 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 DTBIS.

In Japan, two types of wireless LANs have been standardized. One is for medium rates in the range of 256 kbps to 2 Mbps using spread spectrum in the 2.4 GHz ISM band. The other is for high rates (≥10 Mbps) 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 TGS/1 of the ITU-R (the International Telecommunication Union-Radio-communication 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 service 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 require wide area coverage to cellular systems, and are subdivided into forwarding and non-forwarding nodes, and a self-adapting wireless LAN is created. Finally, HIPERLAN is placing more emphasis on DTBIS.

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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 TGS/1 of the ITU-R (the International Telecommunication Union-Radio-communication 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].
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 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, interference handover is included to switch from embedded microcells to overlaying macrocells on a cellular (wire, cordless, or uncoordinated) environment. 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 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 interference 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 by issuing "I am there", and answers using a wrist pager sending a dual-tone multifrequency (DTMF) tone 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 exploring 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 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 BAs (basic trading areas). There are 51 MTAs and 492 BAs in the United States (which suggests a rough comparison of MTAs to states and BAs 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 different 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 main 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 11 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 will 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 links before PCS systems can be deployed.12 The PCS licensee is required to compensate the incumbent for the cost of relocating. For the unli

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12 In some cases, it may be possible to frequency-coordinate between the PCS operator and an incumbent to avoid interference.
ADPCM
AMPS
CDMA
CEPT
CDPD
CDMA
AMPS
INMARSAT International Maritime Satellite Organization
IS-54
GSM
GMSK
GFSK
FSK
FEC
FDD
FDD
EIA
DCS1800
DCA
DCA
CRC
CT
Dynamic channel assignment
Digital Cellular System 1800 (Europe)
Digital European Cordless Telecommunications
Data link control (layer)
Differential quaternary phase shift keying
Electronic Industries Association (U.S.)
Effective radiated power
European Telecommunications Standards Institute
Federal Communications Commission (US.)
Frequency division multiplexing
Frequency division multiple access
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
GMSS
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.)
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Guide to Wireless Acronyms and Abbreviations

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CEPT Conference Européenne des Postes et TBICcom-
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., CTI)
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 multiplexing
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GSM Groupe Spécial Mobile (originally) currently Global System for Mobile Communication (ETSI, Europe)
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was formed to deal with these issues.

FPLMTS Work in Japan
Japan has established a new standardization committee and related working groups in connection with FPLMTS work. CDMA as well as advanced TDMA technologies are being studied, including propagation 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 neither economically viable (such as in remote, sparsely-populated areas), nor 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 2 satellites at about 10,600 km, and the ELMSAT proposal specifies a HEOS approach with two or three satellites.

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standard, U.S.)
Integrated Services Digital Network
Industrial, Scientific, and Medical (bands, devices)
International Telecommunication Union-radio communication sector
Low earth orbit satellite
Medium access control (layer)
Microcom Networking Protocol
Ministry of Posts and Telecommunications (Japan)
Mobile satellite services (or systems)
Nordic Mobile Telephone (Europe)
Personal Access Communications Services
Private branch exchange
Personal Communications Network (Europe)
Personal Communications Services (U.S.)
Personal Digital Cellular (Japan)
Personal Handyphone System (Japan, formerly PHP)
Private mobile radio
Packet Reservation Multiple Access
Public Switched Telephone Network
Quaternary Phase Shift Keying
RACE R & D in Advanced Communications Technologies in Europe
Research & development Center for Radio systems (Japan)
Radio frequency
Radio local loop
Radio Telephone Mobile System (Italy)
Receive or reception
Specialized mobile radio
Total Access Communication System (Europe)
Time division duplexing
Time division multiple access
Trans European Trunked Radio System
Telecommunications Industry Association (U.S.)
Telecommunication Technical Committee (Japan)
Transmit or transmission
Universal Mobile Telecommunications System
Vector sum excited linear prediction (speech coding)
Wireless Access Communications Systems
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 54-km grazing angle 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, 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 standards. 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.

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

Biographies

Jay E. Pascal (SM '90) received his 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 1981, 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 link, and personal communications systems. He is currently working on mathematical modeling and analysis of performance and capacity. He is chair of the TIA Mobile 
and Personal Communications Consumer Radio Section, and a member of Eta Kappa Nu and Tau Beta Pi.

Christopher G. Atkinson (M '87) received his diploma and doctor degrees in theoretical physics at the Swiss Federal Institute of Technology (ETH) in Zurich in 1978 and 1984, respectively. In 1984, he joined Brown Boveri Corporate Research and worked in cryptography, mainly in development and analysis of stream ciphers, homomorphic coding, and key-exchange protocols. In 1989, he started working in spread spectrum transmissions and joined Ascot Tech, Mibergen, 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 Ascot. He is working on modulation, synchronization, multi-path receivers, packet transmission, and various aspects of personal communications systems. He also interests include information and coding theory.

Takeshi Hatton (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 1985, 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 1985, he was senior manager at the ECL Research and Development Headquarters and was in charge of planning and research planning. From 1986 to 1987, he was head of the Mobile Communication Applications Section in the Radio Communications Laboratories and responsible for the development of new cordless telephone and microwave 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 Leader for R & D of personal communication 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 1985. He has been a member of the IEEE Communications, Vehicular Technology, and Computer Societies, and of the Institute of Electronics and Communications Engineers (IEICE) of Japan.