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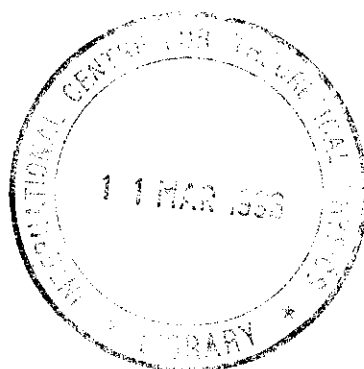
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by

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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.

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].

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

There are more than 30 million cellular subscribers worldwide.

Standard	Mobile TX Base TX (MHz)	Channel spacing (kHz)	Number of channels	Region
AMPS	824-849/869-894	30	1200	USA, Canada, Australia, Japan
TACS	890-915/935-960	12.5	2400	UK, Italy, Spain, Austria, Ireland
NMT	860-885/915-940	10	2400	Scandinavia, Germany, Portugal
RTMS	843-846/898-901	10	2400	Italy
C-450	860-885/915-940	12.5	2400	France, Japan
DDI	822/863-867	12.5	2400	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.

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

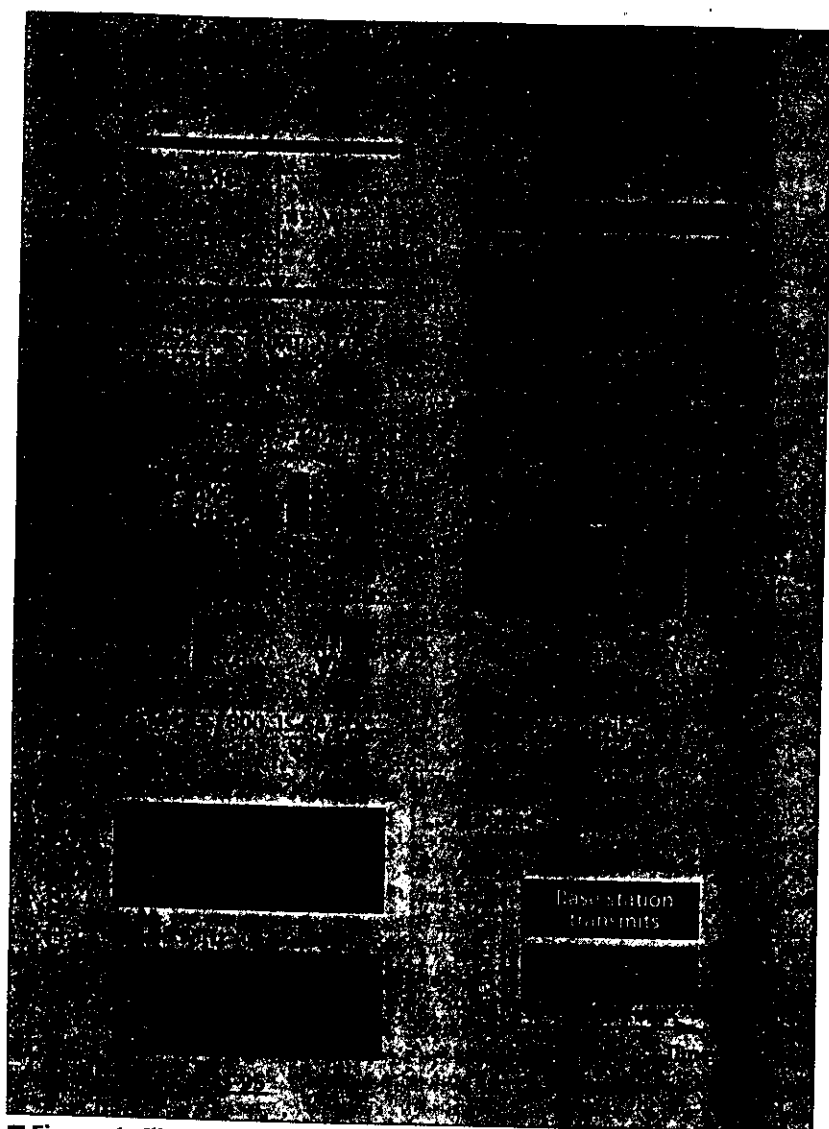
many countries; C-450 in Germany and Portugal; Radiocom 2000 in France; and Radio Telephone Mobile System (RTMS) in Italy. Those systems use frequency modulation for speech, FSK for signaling, and channel spacings of: 25 kHz (TACS, NMT-450, RTMS); 10 kHz (C-450); and 12.5 kHz (NMT-900, Radiocom 2000).³ 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.

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 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 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").

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

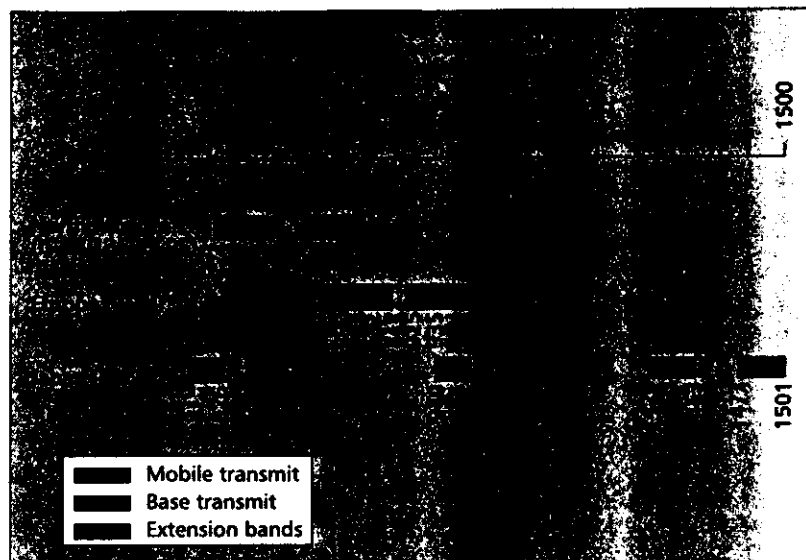
The new system was primarily expected to provide better quality, pan-European roaming, and the transmission of data for fax, e-mail, files, etc. A new design also offered the opportunity to specify a system for lower-cost implementations and the potential for increased spectral efficiency. Finally, a 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 time-slots 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 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, like cities (delays around 1 to 2 μ s), 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.

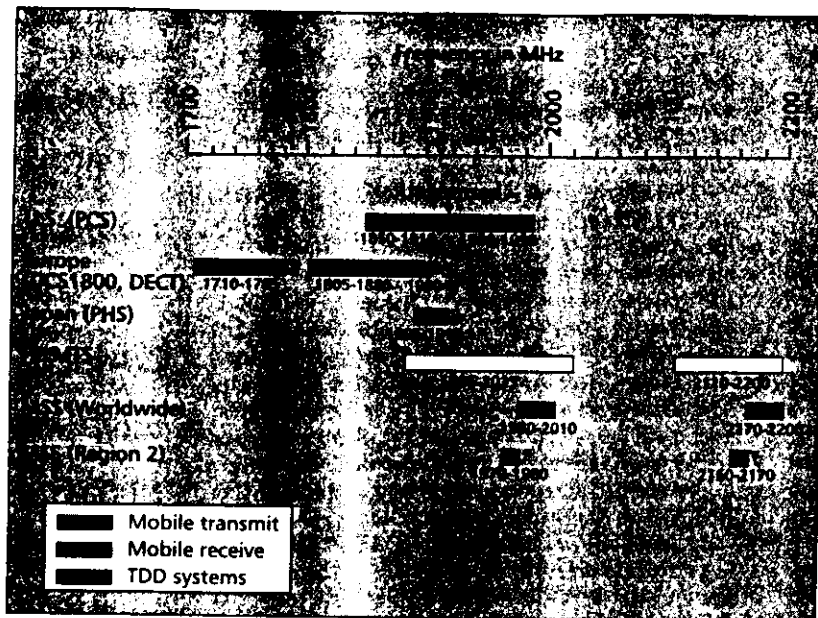
ISDN. Additionally, a connectionless packet service is in preparation, with an emphasis on interworking with X.25 and Internet (see the section on wireless data). Group 3 fax is also supported by the standard.

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 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.

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 $\pi/4$ DQPSK⁵ 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 $\pi/4$ 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 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-CELP⁸ 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 Mcchip/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 $\pi/4$ 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 μ s for IS-54. Delay spreads for cellular environments usually are less than 8 μ s, 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 Mcchip/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 μ W (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
implementa-
tion 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 μ W/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. Tele-

point 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 collocated 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).

	CTZ	CTZ+	DECT	PHS	PACS
Region	Europe	Canada	Europe	Japan	United States
Duplexing	TDD	TDD	TDD	TDD	FDD
Frequency band (MHz)	864-868, 944-948	1880-1900	1890-1900	1895-1918	1850-1910/1910-1990*
Carrier spacing (kHz)	100	1728	300	300	300/300
Number of carriers	70	10	10	77	16 pairs/10 MHz
Bearer channels/carrier	1	12	12	4	8/pair
Channel bitrate (kb/s)	72	1152	1152	384	384
Modulation	GFSK	GFSK	GFSK	$\pi/4$ DQPSK	$\pi/4$ QPSK
Speech Coding	2 kb/s	32 kb/s	32 kb/s	32 kb/s	32 kb/s
Average handset TX power (mW)	5	10	10	10	25
Maximum TX power (mW)	10	250	250	80	200
Frame duration (millisec)	2	10	10	5	2.5

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

*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 $\pi/4$ 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 audiospeech 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 spreading¹⁰ 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 RicochetTM 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.

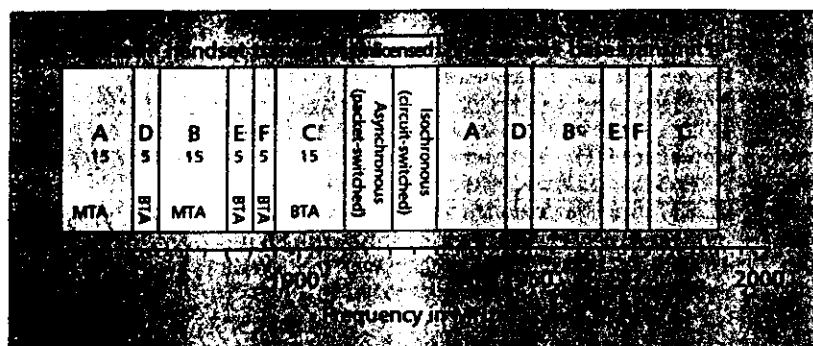
	Digital Cordless	Digital Cellular
Characteristics		
Cell size	small (50 to 500 m)	large (10 to 30 km)
Antenna elevation	low (15m or less)	high (15m or more)
Mobility speed	low (60 mph or less)	high (up to 250 kph)
Coverage	zonal	wide-area continuous
Handset complexity	low	moderate
Base complexity	low	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 FreePortTM 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 (≥ 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 talk-spurt 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 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 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	ISDN	Integrated Services Digital Network
AMPS	Advanced Mobile Phone Service	ISM	Industrial, Scientific, and Medical (bands, devices)
CDMA	Code division multiple access	ITU-R	International Telecommunication Union-radio communication sector
CDPD	Cellular Digital Packet Data (U.S.)		Low earth orbit satellite
CEPT	Conférence Européenne des Postes et Télécommunications	LEOS	Medium access control (layer)
CRC	Cyclic redundancy check	MAC	Microcom Networking Protocol
CT	Cordless Telephone (interim ETSI standards, e.g., CT1)	MNP	Ministry of Posts and Telecommunications (Japan)
DCA	Dynamic channel assignment	MPT	Mobile satellite services (or systems)
DCS1800	Digital Cellular System 1800 (Europe)	MSS	Nordic Mobile Telephone (Europe)
DECT	Digital European Cordless Telecommunications	NMT	Personal Access Communications Services
DLC	Data link control (layer)	PACS	Private branch exchange
DQPSK	Differential quaternary phase shift keying	PBX	Personal Communications Network (Europe)
EIA	Electronic Industries Association (U.S.)	PCN	Personal Communications Services (U.S.)
ERP	Effective radiated power	PCS	Personal Digital Cellular (Japan)
ETSI	European Telecommunications Standards Institute	PDC	Personal Handphone System (Japan, formerly PHP)
FCC	Federal Communications Commission (U.S.)	PHS	Private mobile radio
FDD	Frequency division duplexing	PMR	Packet Reservation Multiple Access
FDMA	Frequency division multiple access	PRMA	Public Switched Telephone Network
FEC	Forward error correction (channel coding; e.g., convolutional coding)	PSTN	Quaternary Phase Shift Keying
FM	Frequency modulation	QPSK	R & D in Advanced Communications Technologies in Europe
FPLMTS	Future Public Land Mobile Telecommunication Systems	RACE	Research & development Center for Radio systems (Japan)
FSK	Frequency shift keying	RCR	Radio frequency
GFSK	Gaussian filtered FSK	RF	Radio local loop
GMSK	Gaussian minimum shift keying	RLL	Radio Telephone Mobile System (Italy)
GPRS	General Packet Radio Service (GSM connectionless packet service, ETSI, Europe)	RTMS	Receive or reception
GSM	Groupe Spécial Mobile (originally) currently Global System for Mobile Communication (ETSI, Europe)	RX	Specialized mobile radio
HIPERLAN	High Performance Radio Local Area Network (ETSI, Europe)	SMR	Total Access Communication System (Europe)
INMARSAT	International Maritime Satellite Organization	TACS	Time division duplexing
IR	Infrared	TDD	Time division multiple access
IS-41	Interim Standard 41 (TIA/EIA cellular network signaling standard, U.S.)	TDMA	Trans European Trunked Radio System
IS-54	Interim Standard 54 (TIA/EIA TDMA cellular standard, U.S.)	TETRA	Telecommunications Industry Association (U.S.)
IS-95	Interim Standard 95 (TIA/EIA CDMA cellular standard, U.S.)	TIA	Telecommunication Technical Committee (Japan)
		TTC	Transmit or transmission
		TX	Universal Mobile Telecommunications System
		UMTS	Vector sum excited linear prediction (speech coding)
		VSELP	Wireless Access Communications Systems
		WACS	World Administrative Radio Conference
		WARC	

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.

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Biographies

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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.

An evolution toward three large groups of applications and services

Wireless Personal Communications: What Is It?

DONALD C. COX

Wireless Personal Communications has captured the attention of the media, and with it, the imagination of the public. Hardly a week goes by without one seeing an article on the subject appearing in a popular U.S. newspaper or magazine. Articles ranging from a short paragraph to many pages regularly appear in local newspapers, as well as in nationwide print media, e.g., *The Wall Street Journal*, *The New York Times*, *Business Week*, and *U.S. News and World Report*. Countless marketing surveys continue to project enormous demand, often projecting that at least half of the households, or half of the people, want wireless personal communications. Trade magazines, newsletters, conferences, and seminars on the subject by many different names have become too numerous to keep track of, and technical journals, magazines, conferences and symposia continue to proliferate and to have ever increasing attendance and numbers of papers presented. It is clear that wireless personal communications is, by any measure, the fastest growing segment of telecommunications.

However, if you look carefully at the seemingly endless discussions of the topic, you cannot help but note that they are often describing different "things", i.e., different versions of wireless personal communications [1, 2]. Some discuss pagers, or messaging, or data systems, or access to the National Information Infrastructure, while others emphasize cellular radio, or cordless telephones, or dense systems of satellites. Many make reference to popular fiction entities like Dick Tracy, Maxwell Smart, or *Star Trek*.

Thus, it appears that almost everyone wants Wireless Personal Communications, but, *What Is It?*!! There are many different ways to segment the complex topic into different communications applications, modes, functions, extent of coverage, or mobility [1, 2]. The complexity of the issues has resulted in considerable confusion in the industry, as evidenced by the many different wireless systems, technologies, and services being offered, planned, or proposed. Many different industry groups and regulatory entities are becoming involved. The confusion is a natural consequence of the massive dislocations that are occurring, and will continue to occur, as we progress along this large change in the paradigm of the way we communicate. Among the different changes that are occurring in our communications paradigm, perhaps the major ingredient is the change from wired fixed place-to-place communications to wireless mobile person-to-person communications. Within this major change are also many other changes, e.g., an increase in the significance of data and message communications, a perception of

possible changes in video applications, and changes in the regulatory and political climates.

This article attempts to identify different issues and to put many of the activities in wireless into a framework that can provide perspective on what is driving them, and perhaps even yield some indication of where they appear to be going in the future. However, like any attempt to categorize many complex interrelated issues, there are some that don't quite fit into neat categories, so there will remain some dangling loose ends. Like any major paradigm shift, there will continue to be considerable confusion as many entities attempt to interpret the different needs and expectations associated with the new paradigm.

Background and Issues

Mobility and Freedom from Tethers

Perhaps the clearest ingredients in all of the wireless personal communications activity are the desire for mobility in communications, and the companion desire to be free from tethers, i.e., from physical connections to communications networks. These desires are clear from the very rapid growth of mobile technologies that provide primarily two-way voice services, even though economical wireline voice services are readily available. For example, cellular mobile radio has experienced rapid growth. Growth rates have been between 35 and 60 percent per year in the United States for a decade, with the total number of subscribers reaching 20 million by year-end 1994. The often neglected wireless companions to cellular radio, i.e., cordless telephones, have experienced even more rapid, but harder to quantify, growth with sales rates often exceeding 10 million sets a year in the United States, and with an estimated usage significantly exceeding 50 million in 1994. Telephones in airliners, have also become commonplace. Similar, or even greater, growth in these wireless technologies has been experienced throughout the world.

Paging and associated messaging, while not providing two-way voice, do provide a form of tetherless mobile communications to many subscribers worldwide. These services have also experienced significant growth. There is even a glimmer of a market in the many different specialized wireless data applications evident in the many wireless local area network (WLAN) products on the market, the several wide area data services being offered, and the specialized satellite-based message services being provided to trucks on highways.

The topics discussed in the previous two paragraphs indicate a dominant issue separating the different evolutions of wireless personal communications. That issue is the voice versus data communications issue that permeates all of communications today; this division also is very evident in fixed networks. The packet-oriented computer communications community and the circuit-oriented voice telecommunications (telephone) community hardly talk to each other, and often speak different languages in addressing similar issues. Although they often converge to similar overall solutions at large scales (e.g., hierarchical routing with exceptions for embedded high usage routes), the small scale initial solutions are frequently quite different. Asynchronous Transfer Mode (ATM)-based networks are an attempt to integrate, at least partially, the needs of both the packet-data and circuit-oriented communities.

Superimposed on the voice-data issue is an issue of competing modes of communications that exist in both fixed and mobile forms. These different modes include:

Messaging, where the communication is not real time, but is by way of message transmission, storage, and retrieval. This mode is represented by voice mail, electronic facsimile (fax), and electronic mail (e-mail), the latter of which appears to be a modern automated version of an evolution that includes telegraph and telex. Radio paging systems often provide limited one-way messaging, ranging from transmitting only the number of a calling party, to longer alpha-numeric text messages.

Real-time two-way communications, represented by the telephone, cellular mobile radio telephone, and interactive text (and graphics) exchange over data networks. Two-way video phone always captures significant attention and fits into this mode; however, its benefit/cost ratio has yet to exceed a value that customers are willing to pay.

Paging, i.e., broadcast with no return channel, alerts a paged party that someone wants to communicate with him/her. Paging is like the ringer on a telephone, without having the capability for completing the communications.

Agents, new high level software applications or entities being incorporated into some computer networks. When launched into a data network, an "agent" is aimed at finding information by some title or characteristic, and returning the information to the point from which the agent was launched.

There are still other ways in which wireless communications have been segmented in attempts to optimize a technology to satisfy the needs of some particular group. Examples include:

- User location, that can be differentiated by indoors or outdoors, or on an airplane or a train.
- Degree of mobility, that can be differentiated either by speed, e.g., vehicular, pedestrian, or stationary, or by size of area throughout which communications are provided.

At this point one should again ask: "Wireless Personal Communications — *What Is It?!!*" The evidence suggests that what is being sought by users, and produced by providers, can be categorized according to the following two main characteristics.

Communications Portability and Mobility on many different scales:

- Within a house or building (cordless telephone, wireless local area networks (WLANs)).
- Within a campus, a town, or a city (cellular radio, WLANs, wide area wireless data, radio paging, extended cordless telephone).
- Throughout a state or region (cellular radio, wide area wireless data, radio paging, satellite-based wireless).
- Throughout a large country or continent (cellular radio, paging, satellite-based wireless).
- Throughout the world?!!

Communications by many different modes for many different applications:

- Two-way voice.
- Data.
- Messaging.
- Video?

Thus, it is clear why wireless personal communications today is not one technology, not one system, and not one service, but encompasses many technologies, systems and services optimized for different applications.

Evolution of Technologies, Systems, and Services

Technologies and systems [1-7] that are currently providing, or are proposed to provide, wireless communications services can be grouped into about seven relatively distinct groups, although there may be some disagreement on the group definitions, and in what group some particular technology or system belongs. All

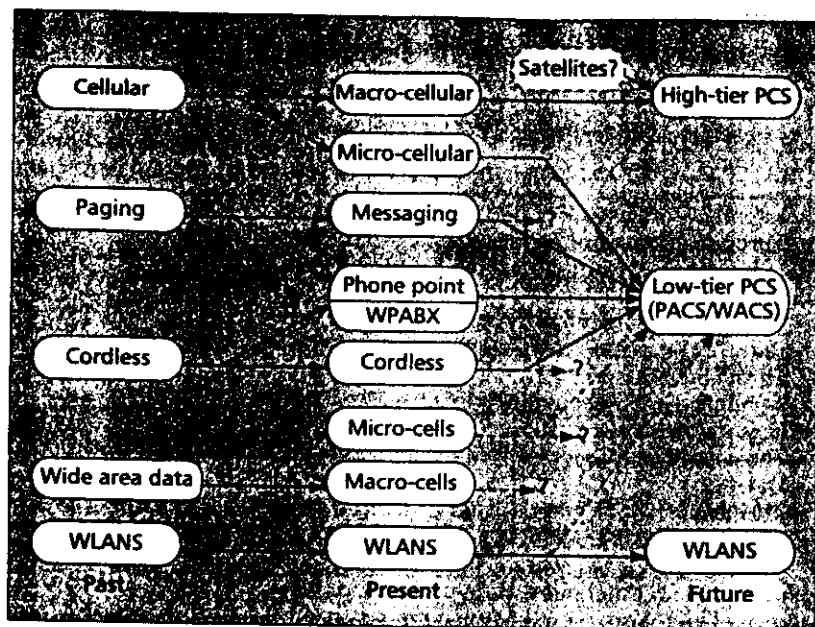
Perhaps the clearest ingredients in all of the wireless personal communications activity are the desire for mobility in communications, and the companion desire to be free from tethers, i.e., from physical connections to communications networks.

of the technologies and systems are evolving as technology advances and perceived needs change. Some trends are becoming evident in the evolutions. In this section, different groups and evolutionary trends are explored along with factors that influence the characteristics of members of the groups. The grouping is generally with respect to scale of mobility and communications applications or modes.

Cordless Telephones

Cordless telephones [1-3] generally can be categorized as providing low mobility, low-power, two-way tetherless voice communications, with low mobility applying both to the range and the user's speed. Cordless telephones using analog radio technologies appeared in the late 1970s, and have experienced spectacular growth. They have evolved to digital radio technologies in the forms of second-generation cordless telephone (CT-2), and Digital European Cordless Telephone (DECT) standards in Europe, and several different Industrial Scientific Medical (ISM) band technologies in the United States.¹

¹ These ISM technologies either use spread spectrum techniques (direct sequence or frequency hopping), or very low transmitter power (≤ 1 mw) as required by the ISM band regulations.



■ Figure 1. Digital wireless access systems evolution.

Cordless telephones were originally aimed at providing economical, tetherless voice communications inside residences, i.e., at using a short wireless link to replace the cord between a telephone base unit and its handset. The most significant considerations in design compromises made for these technologies are to minimize total cost, while maximizing the "talk time" away from the battery charger. For digital cordless phones intended to be carried away from home in a pocket, e.g., CT-2 or DECT, handset weight and size are also major factors. These considerations drive designs toward minimizing complexity, and minimizing the power used for signal processing and for transmitting.

Cordless telephones compete with wireline telephones. Therefore, high circuit quality has become a requirement. Early cordless sets had marginal quality. They were purchased by the millions, and discarded by the millions, until manufacturers produced higher-quality sets. Cordless telephones sales then exploded. Their usage has become commonplace, approaching, and perhaps exceeding, usage of "corded" telephones.

The compromises accepted in cordless telephone design in order to meet the cost, weight, and talk-time objectives are:

- Few users per MHz.
- Few users per base unit (many link together a particular handset and base unit).
- Large number of base units per unit area; one or more base units per wireline access line (in high-rise apartment buildings the density of base units is very large).
- Short transmission range.

There is no added network complexity since a base unit looks to a telephone network like a wireline telephone. These issues are also discussed in [1, 2].

Digital cordless telephones in Europe have been evolving for a few years to extend their domain of use beyond the limits of inside residences. Cordless telephone, second generation, (CT-2) has evolved to provide telepoint or phone-point services. Base units are located in places where people congregate, e.g., along city streets and in shopping malls, train stations, etc. Handsets registered with

the phone-point provider can place calls when within range of a telepoint. CT-2 does not provide capability for transferring (handing off) active wireless calls from one phone point to another if a user moves out of range of the one to which the call was initiated. A CT-2+ technology, evolved from CT-2 and providing limited handoff capability, is being deployed in Canada. Phone-point service was introduced in the United Kingdom twice, but failed to attract enough customers to become a viable service. However, in Singapore and Hong Kong, CT-2 phone-point has grown rapidly, reaching over 150,000 subscribers in Hong Kong [8] in mid-1994. The reasons for the success in some places and failure in others are still being debated, but it is clear that the compactness of the Hong Kong and Singapore populations make the service more widely available, using fewer base stations than in more spreadout cities. Complaints of CT-2 phone-point users in trials have been that the radio coverage was not complete enough, and/or they could not tell whether there was coverage at a particular place, and the lack of handoff was inconvenient. In order to provide the "alerting" or "ringing" function for phone-point service, conventional radio pagers have been built into some CT-2 handsets. (The telephone network to which a CT-2 phone point is attached has no way of knowing from which base units to send a ringing message, even though the CT-2 handsets can be "rung" from a home base unit).

Another European evolution of cordless telephones is Digital European Cordless Telephone (DECT) which was optimized for use inside buildings. Base units are attached through a controller to private branch exchanges (PBXs), key telephone systems, or phone company CENTREX telephone lines. DECT controllers can hand off active calls from one base unit to another as users move, and can "page" or "ring" handsets as a user walks through areas covered by different base units.

These cordless telephone evolutions to more widespread usage outside and inside with telepoints, and to usage inside large buildings are illustrated in Fig. 1, along with the integration of paging into handsets to provide alerting for phone-point services. They represent the first attempts to increase the service area of mobility for low-power cordless telephones.

Some of the characteristics of the digital cordless telephone technologies, CT-2 and DECT, are listed in Table 1. Additional information can be found in References [2, 3]. Even though there are significant differences between these technologies, e.g., multiple access technology (FDMA or TDMA/FDMA), and channel bit rate, there are many similarities that are fundamental to the design objectives discussed earlier, and to a user's perception of them. These similarities and their implications are as follows.

32 kb/s adaptive differential pulse code modulation (ADPCM) digital speech encoding: this is a low complexity (low signal processing power) speech encoding process that provides wireline speech quality and is an international standard.

Average transmitter power ≤ 10 milliwatts: this permits many hours of talk time with small, low-cost, lightweight batteries, but provides limited radio range.

High Power Systems					Low Power Systems			
Digital Cellular (High-Tier PCS)					Low-Tier PCS		Digital Cordless	
System	IS-54	IS-95 (DS)	GSM	PCS-1900	WACS/PACS			
Multiple access	TDMA/FDMA	CDMA/FDMA	TDMA/FDMA	TDMA/FDMA	TDMA/FDMA	TDMA/FDMA	TDMA/FDMA	FDMA
Freq. band (MHz)	824-849	824-849	824-849	824-849	824-849	824-849	824-849	824-849
Uplink (MHz)	869-894	869-894	869-894	869-894	869-894	869-894	869-894	869-894
Downlink (MHz)	824-849	824-849	824-849	824-849	824-849	824-849	824-849	824-849
RF ch. spacing								
Downlink (KHz)	30	1250	200	200	300	300	1728	100
Uplink (KHz)	30	1250	200	200	300	300		
Modulation	QPSK	QPSK	GMSK	GMSK	QPSK	QPSK	QPSK	QPSK
Portable txmit Power, max/avg.	600 mW/200 mW	600 mW	1 W/125 mW	1 W/125 mW	200 mW/25 mW	80 mW/10 mW	250 mW/10 mW	10 mW/5 mW
Speech coding	CELP	CELP	RPE-LTP	RPE-LTP	ADPCM	ADPCM	ADPCM	ADPCM
Speech rate (kb/s)	7.95	8 (var.)	13	13	32/16/8	32	32	32
Speech ch./RF ch.	3		8	8	8/16/32	4	12	4
Ch. bit rate (kb/s)						384	1152	72
Uplink (kb/s)	48.6		270.833	270.833	384			
Downlink (kb/s)	48.6		270.833	270.833	384			
Ch. coding	1/2 rate conv.	1/2 rate fwd 1/3 rate rev.	1/2 rate conv.	1/2 rate conv.	CRC	CRC	CRC (control)	None
Frame (ms)	40	20	4.615	4.615	2.5	5	10	2

* Spectrum is 1.85 to 2.2 GHz allocated by the FCC for emerging technologies; DS is direct sequence.

■ Table 1. Wireless PCS technologies.

Low-complexity radio signal processing: there is no forward error correction and no complex multipath mitigation (i.e., no equalization or spread spectrum).

Low transmission delay, e.g., < 50 ms, and for CT-2 < 10 ms round trip: this is a speech-quality and network-complexity issue. A maximum of 10 ms should be allowed, taking into account additional inevitable delay in long-distance networks. Echo cancellation is generally required for delays > 10 ms.

Simple frequency-shift modulation and non-coherent detection: while still being low in complexity, the slightly more complex 4QAM modulation with coherent detection provides significantly more spectrum efficiency, range and interference immunity.

Dynamic channel allocation: While this technique has potential for improved system capacity, the cordless-telephone implementations do not take full advantage of this feature for handoff, and thus cannot reap the full benefit for moving users [9, 10].

Time division duplex (TDD): this technique permits the use of a single contiguous frequency band, and implementation of diversity from one end of a radio link. However, unless all base station transmissions are synchronized in time, it can incur severe cochannel interference penalties in outside environments [9, 11]. Of course, for cordless telephones used inside with base stations not having a propagation advantage, this is not a problem. Also, for small indoor PBX networks, synchronization of base station transmission is easier than is synchronization throughout a widespread outdoor network, which can have many adjacent

base stations connected to different geographic locations for central control and switching.

Cellular Mobile Radio Systems

Cellular mobile radio systems are becoming known in the United States as high-tier Personal Communications Service (PCS), particularly when implemented in the new 1.9 GHz PCS bands [12]. These systems generally can be categorized as providing high-mobility, wide-ranging, two-way tetherless voice communications. In these systems, high mobility refers to vehicular speeds, and also to widespread regional to nationwide coverage [1, 2, 7]. Mobile radio has been evolving for over 50 years. Cellular radio integrates wireless access with large-scale networks having sophisticated intelligence to manage mobility of users.

Cellular radio was designed to provide voice service to wide-ranging vehicles on streets and highways [1-3, 13], and generally uses transmitter power on the order of 100 times that of cordless telephones (≈ 2 watts for cellular). Thus, cellular systems can only provide reduced service to handheld sets that are disadvantaged by using somewhat lower transmitter power (< 0.5 watts) and less efficient antennas than vehicular sets. Handheld sets used inside buildings have the further disadvantage of attenuation through walls that is not taken into account in system design.

Cellular radio or high-tier PCS has experienced large growth as noted earlier. In spite of the limitations on usage of handheld sets noted above, handheld cellular sets have become very popular,

with their sales becoming comparable to the sales of vehicular sets. Frequent complaints from handheld cellular users are that batteries are too large and heavy, and both talk time and standby time are inadequate.

Cellular radio at 800 MHz has evolved to digital radio technologies [1-3] in the forms of the deployed systems standards:

- Global Standard for Mobile (GSM) in Europe.
- Japanese or Personal Digital Cellular (JDC or PDC) in Japan.
- U.S. TDMA digital cellular known as USDC or IS-54.

and in the form of the code division multiple access (CDMA) standard, IS-95, which is under development, but not yet deployed.

The most significant consideration in the design compromises made for the U.S. digital cellular or high-tier PCS systems was the high cost of cell sites (base stations). A figure often quoted is U.S. \$1 million for a cell site. This consideration drove digital system designs to:

- Maximize users per MHz.
- Maximize the users per cell site.

Because of the need to cover highways running through low population-density regions between cities, the relatively high transmitter power requirement was retained to provide maximum range from high antenna locations.

Compromises that were accepted while maximizing the above parameters are:

- High transmitter power consumption.
- High user-set complexity, and thus high signal-processing power consumption.
- Low circuit quality.

The use of microcell base stations provides large increases in overall system capacity, while also reducing the cost per available radio channel, and the battery drain on portable subscriber equipment.

- High network complexity, e.g., the new IS-95 technology will require complex new switching and control equipment in the network, as well as high-complexity wireless-access technology.

Cellular radio or high-tier PCS has also been evolving for a few years in a different direction, toward very small coverage areas or microcells. This evolution provides increased capacity in areas having high user density, as well as improved coverage of shadowed areas. Some microcell base stations are being installed inside, in conference center lobbies and similar places of high user concentrations. Of course, microcells also permit lower transmitter power that conserves battery power when power control is implemented, and base stations inside buildings circumvent the outside wall attenuation. Low complexity microcell base stations also are considerably less expensive than conventional cell sites, perhaps two orders of magnitude less expensive. Thus, the use of microcell base stations provides large increases in overall system capacity, while also reducing the cost per available radio channel, and the battery drain on portable subscriber equipment. This microcell evolution, illustrated in Fig. 1, moves handheld cellular sets in a direction similar to that of the

expanded-coverage evolution of cordless telephones to phone points and wireless PBX.

Some of the characteristics of digital-cellular or high-tier PCS technologies are listed in Table 1 for IS-54, IS-95, and GSM at 900 MHz, and DCS-1800, which is GSM at 1800 MHz. Additional information can be found in [1-3]. The JDC or PDC technology, not listed, is similar to IS-54. As with the digital cordless technologies, there are significant differences among these cellular technologies, e.g., modulation type, multiple access technology, and channel bit rate. However, there are also many similarities that are fundamental to the design objectives discussed earlier. These similarities and their implications are as follows.

Low bit-rate speech coding; ≤ 13 kb/s with some ≤ 8 kb/s: low bit-rate speech coding obviously increases the number of users per MHz and per cell site. However, it also significantly reduces speech quality [1], and does not permit the tandemming of speech encoding while traversing a network. That is, when low bit rate speech is transcoded to a different encoding format, e.g., to 64 kb/s as is used in many networks, or from an IS-54 phone on one end to a GSM or IS-95 phone on the other end, the speech quality deteriorates precipitously. While this may not be a serious issue for a vehicular mobile user who has no choice other than not to communicate at all, it is likely to be a serious issue in an environment where a wire-line telephone is available as an alternative. It is also less serious when there are few mobile-to-mobile calls through the network, but, as wireless usage increases, and digital mobile-to-mobile calls become commonplace, the marginal transcoded speech quality is likely to become a serious issue.

Some implementations make use of speech inactivity: this further increases the number of users per cell site, i.e., the cell-site, capacity. However, it also further reduces speech quality [1] because of the difficulty of detecting the onset of speech. This problem is even worse in an acoustically noisy environment like an automobile.

High transmission delay; ≈ 200 ms round trip: this is another important circuit-quality issue. Such large delay is about the same as one-way transmission through a synchronous-orbit communications satellite. A voice circuit with digital cellular technology on both ends will experience the delay of a full satellite circuit. It should be recalled that one reason long-distance circuits have been removed from satellites and put onto fiber-optic cable is because customers find the delay to be objectionable. This delay in digital cellular technology results from both computation for speech bit-rate reduction, and from complex signal processing, e.g., bit interleaving, error correction decoding, and multipath mitigation (equalization or spread spectrum (CDMA)).

High-complexity signal processing, both for speech encoding and for demodulation: signal processing has been allowed to grow without bound, and is about a factor of 10 greater than that used in the low-complexity digital cordless telephones [1]. Since several watts are required from a battery to produce the high transmitter power in a cellular or high-tier PCS set, signal-processing power is not as significant as it is in the low-power cordless telephones.

Fixed channel allocation: the difficulties associated with implementing capacity-increasing dynamic channel allocation to work with handoff [9, 10] have impeded its adoption in systems requiring reliable and frequent handoff.

Frequency division duplex (FDD): cellular systems have already been allocated paired-frequency bands suitable for FDD. Thus, the network or system complexity required for providing synchronized transmissions [9, 11] from all cell sites for TDD has not been embraced in these digital cellular systems. Note that TDD has not been employed in IS-95 even though such synchronization is required for other reasons.

Mobile/portable set power control: the benefits of increased capacity from lower overall co-channel interference, and reduced battery drain have been sought by incorporating power control in the digital cellular technologies.

Wide Area Wireless Data Systems

Existing wide area data systems generally can be categorized as providing high mobility, wide-ranging, low-data-rate digital data communications to both vehicles and pedestrians [1, 2]. These systems have not experienced the rapid growth that the two-way voice technologies have, even though they have been deployed in many cities for a few years and have established a base of customers in several countries. Examples of these packet data systems are shown in Table 2.

The earliest and best known of these systems in the United States are the ARDIS network developed and run by Motorola, and the RAM mobile data network based on Ericsson Mobitex Technology. These technologies were designed to make use of standard, two-way voice, land mobile-radio channels, with 12.5 KHz or 25 kHz channel spacing. In the United States these are specialized mobile radio services (SMRS) allocations around 450 MHz and 900 MHz. Initially, the data rates were low: 4.8 kb/s for ARDIS and 8 kb/s for RAM. The systems use high transmitter power (several tens of watts) to cover large regions from a few base stations having high antennas. The relatively low data capacity of a relatively expensive base station has resulted in economics that have not favored rapid growth.

The wide area mobile data systems also are evolving in several different directions in an attempt to improve base station capacity, economics, and the attractiveness of the service. The technologies used in both the ARDIS and RAM networks are evolving to higher channel bit rates of 19.2 kb/s.

The cellular carriers and several manufacturers in the United States are developing and deploying a new wide area packet data network as an overlay to the cellular radio networks. This Cellular Digital Packet Data (CDPD) technology shares the 30 kHz spaced 800 MHz voice channels used by the analog FM Advanced Mobile Phone Service (AMPS) systems. Data rate is 19.2 kb/s. The CDPD base station equipment also shares cell sites with the voice cellular radio system. The aim is to reduce the cost of providing packet data service by sharing the costs of base stations with the better-established and higher cell-site capacity cellular systems. This is a strategy similar to that used by nationwide fixed wireline packet-data-

	CDPD	RAM Mobile (Mobitex)	ARDIS (KDT)	Metricom (MDN)
Data rate	19.2 Kb/s	8 Kb/s [19.2 Kb/s]	4.8 Kb/s [19.2 Kb/s]	75 Kb/s
Modulation	GMSK BT = 0.5	GMSK	GMSK	GMSK
Frequency	~ 800 MHz	~ 900 MHz	~ 450 MHz	915 MHz
Chan. spacing	30 KHz	12.5 KHz	25 KHz	160 KHz
Status	1994 service	Full service	Full service	In service
Access means	Unused AMPS channels	Slotted Aloha CSMA		FH SS (ISM)
Transmit power			40 watt	1 watt

Note: data in square brackets [] indicates proposed.
 CDPD: Cellular Digital Packet Data
 MDN: Microcellular Data Network
 ARDIS: Advanced Radio Data Information Service

■ Table 2. Wide area wireless packet data systems.

networks that could not provide an economically viable data service if they did not share costs by leasing a small amount of the capacity of the interexchange networks that are paid for largely by voice traffic.

Another evolutionary path in wide area wireless packet data networks is toward smaller coverage areas or microcells. This evolutionary path also is indicated on Fig. 1. The microcell data networks are aimed at stationary or low-speed users. The design compromises are aimed at reducing service costs by making very small and inexpensive base stations that can be attached to utility poles, the sides of buildings, and inside buildings, and can be widely distributed throughout a region. Base-station-to-base-station wireless links are used to reduce the cost of the interconnecting data network. In one network this decreases the overall capacity to serve users, since it uses the same radio channels that are used to provide service. Capacity is expected to be made up by increasing the number of base stations that have connections to a fixed-distribution network as service demand increases. Another such network uses other dedicated radio channels to interconnect base stations. In the high-capacity limit, these networks will look more like a conventional cellular network architecture, with closely spaced, small, inexpensive base stations, i.e., microcells, connected to a fixed infrastructure. Specialized wireless data networks have been built to provide metering and control of electric power distribution, e.g., Celldata, and Metricom in California.

A large microcell network of small inexpensive base stations has been installed in the lower San Francisco Bay Area by Metricom, and public packet-data service was offered during early 1994. Most of the small (shoe-box-size) base stations are mounted on street light poles. Reliable data rates are about 75 kb/s. The technology is based on slow frequency-hopped spread spectrum in the 902-928 MHz U.S. Industrial Scientific Medical (ISM) band. Transmitter power is 1 watt maximum, and power control is used to minimize interference and maximize battery life time.

High-Speed Wireless Local-Area Networks (WLANs)

Wireless local-area data networks (WLANs) can be categorized as providing low-mobility high-speed data communications within a confined region, e.g., a campus or a large building. Coverage range from a wireless data terminal is short, tens to hundreds of feet, like cordless telephones. Coverage is limited to within a room or to several rooms in a building. WLANs have been evolving for a

few years, but overall, the situation is chaotic, with many different products being offered by many different vendors [1, 6]. There is no stable definition of the needs or design objectives for WLANs, with data rates ranging from hundreds of kb/s to more than 10 MB/s, and with several products providing one or two MB/s wireless link rates. The best description of the WLAN evolutionary process is: "having severe birth pains." An IEEE standards committee, 802.11, has been attempting to put some order into this topic, but their success has been

Product/ Company/ Location	Freq. (MHz)	Link rate	User rate	Protocol(s)	Access	No. of chan. or spread factor	Mod./coding	Power	Network topology
								25 mW peak	Eight devices/ radio; radio to base to Ethernet
WaveLAN NCR/AT&T Dayton, OH	902-928	2 Mb/s	1.6 Mb/s	Ethernet-like	DS SS		DQPSK	250 mW	Peer-to-peer
			2 Mb/s	Ethernet	DS SS		DQPSK	250 mW	PCMCIA w/ant; radio to hub
Freeport Windata Inc. Northboro, MA	902-928	16 Mb/s	5.7 Mb/s	Ethernet	DS SS	32 chips/bit	16 PSK trellis coding	650 mW	Hub
			2 Mb/s	Ethernet, token ring	DS SS		DQPSK	250 mW	Hub
LAWN O'Neill Comm. Horsham, PA	902-928		38.4 kb/s	AX.25	SS	20 users/chan.; max. 4 chan.		20 mW	Peer-to-peer
WLAN WLAN Inc. Calgary, Alberta	902-928	20 Mb/s	1.5 Mb/s/ chan.	Ethernet, token ring	CDMA/ TDMA	3 chan. 10-15 links each	"unconventional"	30 mW	Peer-to-peer
RadioPort ALPS Electric USA	902-928		242 kb/s	Ethernet	SS	7/3 channels		100 mW	Peer-to-peer
ArLAN 600 Telsys. SLW Don Mills, Ont.	902-928; 2.4 GHz		1.35 Mb/s	Ethernet	SS			1 W max	PCs with ant.; radio to hub
RadioLink Cal. Microwave Sunnyvale, CA	902-928; 2.4 GHz	250 kb/s	64 kb/s		FH SS	250 ms/hop 500 kHz space			Hub
RangeLAN Proxim, Inc. Mountain View, CA	902-928		242 kb/s	Ethernet, token ring	DS SS	3 chan.		100 mW	
RangeLAN2 Proxim, Inc. Mountainview, CA	2.4 GHz	1.6 Mb/s	50 kb/s max.	Ethernet, token ring	FH SS	10 chan. @ 5 kb/s; 15 sub- ch. each		100 mW	Peer-to-peer bridge
Netwave Xircom Calabasas, CA	2.4 GHz	1 Mb/s adaptor		Ethernet, token ring	FH SS	82 1-MHz chan. or "hops"			Hub
Freelink Cabletron Sys. Rochester, NH	2.4 and 5.8 GHz		5.7 Mb/s	Ethernet	DS SS	32 chips/bit	16 PSK trellis coding	100 mW	Hub

■ Table 3. Partial list of WLAN products

somewhat limited. A partial list of some advertised products is given in Table 3. Users of WLANs are not nearly as numerous as the users of more voice-oriented wireless systems. Part of the difficulty stems from these systems being driven by the computer industry that views the wireless system as just another plug-in interface card, without giving sufficient consideration to the vagaries and needs of a reliable radio system.

There are two overall network architectures pursued by WLAN designers. One is a centrally coordinated and controlled network that resembles other wireless systems. There are base stations in these networks that exercise overall control over channel access [14].

The other type of network architecture is the self organizing and distributed controlled network where every terminal has the same function as every other terminal, and networks are formed ad-hoc by communications exchanges among terminals. Such ad-hoc networks are more like citizen band (CB) radio networks, with similar expected limitations if they were ever to become very widespread. Nearly all WLANs in the United States have attempted to use one of the ISM frequency bands for unlicensed operation under part 15 of the FCC rules. These bands are 902 to 928 MHz, 2400 to 2483.5 MHz, and 5725 to 5850 MHz, and they require users to accept interference from any interfering source that may also be using the frequency. The use of ISM bands has further handicapped WLAN development because of the requirement for use of either frequency hopping or direct sequence spread spectrum as an access technology, if transmitter power is to be adequate to cover more than a few feet. One exception to the ISM band implementations is the Motorola ALTAIR, which operates in a licensed band at 18 GHz. The technical and economic challenges of operation at 18 GHz have hampered the adoption of this 10 to 15 MB/s technology. The frequency-spectrum constraints have been improved in the United States with the recent FCC allocation of spectrum from 1910 to 1930 MHz for unlicensed "data PCS" applications. Use of this new spectrum requires implementation of an access "etiquette" incorporating "Listen before Transmit" in an attempt to provide some coordination of an otherwise potentially chaotic, uncontrolled environment [15]. Also, since spread spectrum is not a requirement, access technologies and multipath mitigation techniques more compatible with the needs of packet data transmission [6], e.g., multipath equalization or multicarrier transmission can be incorporated into new WLAN designs.

Three other widely different WLAN activities also need mentioning. One is a large European Telecommunications Standards Institute (ETSI) activity to produce a standard for High Performance Radio Local Area Network (HIPERLAN), a 20 MB/s WLAN technology to operate near 5 GHz. Other activities are large, U.S. Advance Research Projects Agency (ARPA)-sponsored, WLAN research projects at the Universities of California at Berkeley (UCB), and at Los Angeles (UCLA). The UCB Infopad project is based on a coordinated network architecture with fixed coordinating nodes and direct-sequence spread spectrum (CDMA), whereas, the UCLA project

is aimed at peer-to-peer networks and uses frequency hopping. Both ARPA sponsored projects are concentrated on the 900 MHz ISM band.

As computers shrink in size from desktop, to laptop, to palmtop, mobility in data network access is becoming more important to the user. This fact, coupled with the availability of more usable frequency spectrum, and perhaps some progress on standards, may speed the evolution and adop-

As computers shrink in size from desktop, to laptop, to palmtop, mobility in data network access is becoming more important to the user. This fact, coupled with the availability of more usable frequency spectrum, and perhaps some progress on standards, may speed the evolution and adoption of wireless mobile access to WLANs.

tion of wireless mobile access to WLANs. From the large number of companies making products, it is obvious that many believe in the future of this market.

Paging/Messaging Systems

Radio paging began many years ago as a "one bit" messaging system. The one bit was "some one wants to communicate with you." More generally, paging can be categorized as one-way messaging over wide areas. The one-way radio link is optimized to take advantage of the asymmetry. High transmitter power (hundreds of watts to kilowatts), and high antennas at the fixed base stations permit low complexity, very-low-power-consumption, pocket paging receivers that provide long usage time from small batteries. This combination provides the large radio-link margins needed to penetrate walls of buildings without burdening the user set battery. Paging has experienced steady rapid growth for many years and serves about 15 million subscribers in the United States.

Paging also has evolved in several different directions. It has changed from analog tone coding for user identification to digitally encoded messages. It has evolved from the one-bit message, "someone wants you," to multibit messages from, first, the calling party's telephone number to, now, short e-mail text messages. This evolution is noted in Fig. 1.

The region over which a page is transmitted has also increased from a) local, around one transmitting antenna; to b) regional, from multiple widely-dispersed antennas; to c) nationwide, from large networks of interconnected paging transmitters. The integration of paging with CT-2 user sets for phone-point call alerting was noted previously.

Another "evolutionary" paging route sometimes proposed is "two-way" paging. However, this is an ambiguous and unrealizable concept, since the requirement for two-way communications destroys the asymmetrical link advantage so well exploited by paging. "Two-way" paging puts a transmitter in the user's set, and brings along with it all the design compromises that must be faced in such a two-way radio system. Thus, the word "paging" is not appropriate to describe a system that provides two-way communications.

Satellite-Based Mobile Systems

Satellite-based systems are the epitome of wide-area-coverage, expensive, base station systems. They generally can be categorized as providing two-way (or one-way) limited quality voice, and/or very limited data or messaging, to very wide-ranging vehicles (or fixed locations). These systems can provide very widespread, often global, coverage, e.g., to ships at sea by INMARSAT. There are a few messaging systems in operation, e.g., to trucks on highways in the United States by Qualcomm's Omnitrac system.

It remains to be seen whether there will be enough users with enough money in low population density regions of the world to make satellite mobile systems economically viable.

A few large scale mobile satellite systems have been proposed and are being pursued; perhaps the best known is Motorola's Iridium, and others include Odyssey, Globalstar, and Teledesic. The strength of satellite systems is their ability to provide large regional or global coverage to users outside buildings. However, it is very difficult to provide adequate link margin to cover inside buildings, or even to cover locations shadowed by buildings, trees or mountains. A satellite system's weakness is also its large coverage area. It is very difficult to provide from earth orbit the small coverage cells that are necessary for providing high overall systems capacity from frequency reuse. This fact, coupled with the high cost of the orbital base stations, results in low capacity along with the wide overall coverage, but also in expensive service. Thus, satellite systems are not likely to compete favorably with terrestrial systems in populated areas, or even along well traveled highways. They can complement terrestrial cellular or PCS systems in low population density areas. It remains to be seen whether there will be enough users with enough money in low population density regions of the world to make satellite mobile systems economically viable.

Proposed satellite systems range from a) low-earth-orbit (LEOS) systems, having tens to hundreds of satellites, through b) intermediate or medium height systems (MEOS?), to c) geostationary or geosynchronous orbit systems (GEOS), having fewer than ten satellites. LEOS require more, but less expensive, satellites to cover the earth, but they can more easily produce smaller coverage areas, and thus provide higher capacity within a given spectrum allocation. Also, their transmission delay is significantly less (perhaps two orders of magnitude!), providing higher-quality voice links as discussed previously. On the other hand, GEOs require only a few, somewhat more expensive, satellites (perhaps only three), and are likely to provide lower capacity within a given spectrum allocation, and suffer severe transmission-delay impairment on the order of 0.5 seconds. Of course, MEOS fall in-between these extremes. The possible evolution of satellite systems to complement high tier PCS is indicated in Fig. 1.

Evolution Toward the Future and To Low-Tier Personal Communications Services

After looking at the evolution of several wireless technologies and systems in the previous sections, it appears appropriate to ask again: "Wireless Personal Communications — What Is It?" All of the technologies in the previous sections claim to provide wireless personal communications, and all do to some extent. However, all have significant limitations and all are evolving in attempts to overcome the limitations. It seems appropriate to ask, what are the likely endpoints? Perhaps some hint of the endpoints can be found by exploring what users see as limitations of existing technologies and systems, and by looking at the evolutionary trends.

In order to do so, we summarize some important clues from the previous sections, and project them, along with some U.S. standards activity, toward the future.

Digital Cordless Telephones

- Strengths: good circuit quality; long talk time; small lightweight battery; low-cost sets and service.
- Limitations: limited range; limited usage regions.
- Evolutionary trends: phone-points in public places; wireless PBX in business.
- Remaining limitations and issues: limited usage regions and coverage holes; limited or no hand-off; limited range.

Digital Cellular Pocket Handsets

- Strength: widespread service availability.
- Limitations: limited talk time; large heavy batteries; high-cost sets and service; marginal circuit quality; holes in coverage and poor in-building coverage; limited data capabilities; complex technologies.
- Evolutionary trends: microcells to increase capacity and in building coverage, and to reduce battery drain; satellite systems to extend coverage.
- Remaining limitations and issues: limited talk time and large battery; marginal circuit quality; complex technologies.

Wide Area Data

- Strength: digital messages.
- Limitations: no voice; limited data rate; high cost.
- Evolutionary trends: microcells to increase capacity and reduce cost; share facilities with voice systems to reduce cost.
- Remaining limitations and issues: no voice; limited capacity.

Wireless Local Area Networks (WLANs)

- Strength: high data rate.
- Limitations: insufficient capacity for voice; limited coverage; no standards; chaos.
- Evolutionary trends: hard to discern from all the churning.

Paging/messaging

- Strengths: widespread coverage; long battery life; small lightweight sets and batteries; economical.
- Limitations: one-way message only; limited capacity.
- Evolutionary desire: two-way messaging and/or voice; capacity.
- Limitations and issues: two-way link cannot exploit the advantages of one-way link asymmetry.

There is a strong trajectory evident in these systems and technologies, aimed at providing the following features.

High Quality Voice and Data

- To small, lightweight, pocket carried communicators.
- Having small lightweight batteries.
- Having long talk time, and long standby battery life.
- Providing service over large coverage regions.
- For pedestrians in populated areas (but not requiring high population density).
- Including low to moderate speed mobility with handoff.

Economical Service

- Low subscriber-set cost.
- Low network-service cost.

Privacy and Security of Communications

- Encrypted radio links.

This trajectory is evident in all of the evolving technologies, but can only be partially satisfied by any of the existing and evolving systems and technologies! Trajectories from all of the evolving technologies and systems are illustrated in Fig. 1 as being aimed at low-tier personal communications systems or services, i.e., low-tier PCS.

Taking characteristics from cordless, cellular, wide area data and, at least moderate-rate, WLANs, suggests the following attributes for this low-tier PCS:

- 32 kb/s ADPCM speech encoding in the near future to take advantage of the low complexity and low power consumption, and to provide low-delay high-quality speech.

- Flexible radio link architecture that will support multiple data rates from several kb/s to several hundred kb/s. This is needed to permit evolution in the future to lower bit rate speech as technology improvements permit high quality without excessive power consumption or transmission delay, and to provide multiple data rates for data transmission and messaging.

- Low transmitter power (≤ 25 mW average) with adaptive power control to maximize talk time and data transmission time. This incurs short radio range which requires many base stations to cover a large region. Thus, base stations must be small and inexpensive, like cordless telephone phone points or the Metricom wireless data base stations.

- Low complexity signal processing to minimize power consumption. Complexity one-tenth that of digital cellular or high-tier PCS technologies is required [1]. With only several tens of milliwatts (or less under power control) required for transmitter power, signal processing power becomes significant.

- Low co-channel interference and high coverage area design criteria. In order to provide high-quality service over a large region, at least 99 percent of any covered area must receive good or better coverage, and be below acceptable co channel interference limits. This implies less than 1 percent of a region will receive marginal service. This is an order-of-magnitude higher service requirement than the ten percent of a region permitted to receive marginal service in vehicular cellular system (high-tier PCS) design criteria.

- Four-level phase modulation with coherent detection to maximize radio link performance and capacity with low complexity.

- Frequency division duplexing to relax the

requirement for synchronizing base station transmissions over a large region.

Such technologies and systems have been designed, prototyped, and laboratory- and field-tested and evaluated for several years [1, 2, 7, 16-23]. The viewpoint expressed here is consistent with the progress in the Joint Technical Committee (JTC) of the U.S. standards bodies, Telecommunications Industry Association (TIA) and Committee T1 of the Alliance for Telecommunications Industry Solutions (ATIS). Many technologies and systems were submitted to the JTC for consideration for wireless PCS in the new 1.9 GHz frequency bands for use in the United States [12]. Essentially all of the technologies and systems listed in Table 1, and some others, were submitted in late 1993. It was evident that there were at least two, and perhaps three distinct different classes of submissions. No systems optimized for packet data were submitted, but some of the technologies are optimized for voice.

One class of submissions was the group labeled High Power Systems, Digital Cellular (High-Tier PCS) in Table 1. These are the technologies discussed previously in this article. They are highly optimized for low bit-rate voice, and therefore have somewhat limited capability for serving packet-data applications. Since it is clear that wireless services to wide ranging high speed mobiles will continue to be needed, and that the technology described above for low-tier PCS may not be

It is not clear what the future roles are for paging/messaging, cordless-telephone appliances, or wide area packet-data networks in an environment having widespread contiguous coverage by low-tier and high-tier PCS.

optimum for such services, Fig. 1 shows a continuing evolution and need in the future for high-tier PCS systems that are the equivalent of today's cellular radio. There are more than 100 million vehicles in the United States alone. In the future, most, if not all, of these will be equipped with high-tier cellular mobile phones. Therefore, there will be a continuing and rapidly expanding market for high-tier systems.

Another class of submissions to the JTC [12] included the Japanese Personal Handiphone System (PHS), and a technology and system originally developed at Bellcore, but carried forward to prototypes, and submitted to the JTC, by Motorola and Hughes Network Systems. This system was known as Wireless Access Communications System (WACS).² These two submissions were so similar in their design objectives and system characteristics that, with the agreement of the delegations from Japan and the United States, the PHS and WACS submissions were combined under a new name, Personal Access Communication Systems (PACS), that was to incorporate the best features of both. This advanced, low-power wireless access system, PACS, was to be known as low-tier PCS. Both WACS/PACS and Handiphone (PHS) are shown in Table 1 as Low-Tier PCS and represent the evolution to low-tier PCS, on Fig. 1. The WACS/PACS/

² WACS was known previously as Universal Digital Portable Communications (UDPC).

Parameters	Cellular (high-tier)	Low-tier PCS	Capacity factors
Speech coding	8 kb/s (MOS 3.4) No tandem coding	32 kb/s (MOS 4.1) 20% tandem	
Speech activity	Yes (MOS 3.2)	No (MOS 4.1)	x 2.5
Percentage of good areas	90%	5%	
Propagation α	8 dB	10 dB	x 1.5
Total: trading quality for capacity			x 30

■ **Table 4.** A comparison of cellular (IS-54/IS-95) and low tier PCS (WACS/PACS). Capacity comparisons made without regard to quality factors, complexity, and cost per base station are not meaningful.

UDPC system and technology are discussed in [1, 2, 16-23].

In the JTC, submissions for PCS of DECT and CT-2 and their variations were also lumped under the class of low-tier PCS, even though these advanced digital cordless telephone technologies were somewhat more limited in their ability to serve all of the low-tier PCS needs. They are included under Digital Cordless technologies in Table 1. Other technologies and systems were also submitted to the JTC for high-tier and low-tier applications, but they have not received widespread industry support.

One wireless access application discussed earlier that is not addressed by either high-tier or low-tier PCS is the high-speed WLAN application. Specialized high-speed WLANs also are likely to find a place in the future. Therefore, their evolution is also continued in Fig. 1. The figure also recognizes that widespread low-tier PCS can support data at several hundred kb/s, and thus can satisfy many of the needs of WLAN users.

It is not clear what the future roles are for paging/messaging, cordless telephone appliances, or wide area packet-data networks in an environment with widespread contiguous coverage by low-tier and high-tier PCS. Thus, their extensions into the future are indicated with a (?) on Fig. 1.

Those who may object to the separation of Wireless PCS into high tier and low tier, should review this section again, and note that we have two tiers of PCS now. On the voice side there is Cellular Radio, i.e., high-tier PCS, and cordless telephone, i.e., an early form of low-tier PCS. On the data side there is wide area data, i.e., high-tier data PCS, and WLANs, i.e., perhaps a form of low-tier data PCS. In their evolutions, these all have the trajectories discussed and shown on Fig. 1 that point surely toward low-tier PCS. It is this low-tier PCS that marketing studies continue to project is wanted by more than half the U.S. households or by half of the people, a potential market of over 100 million subscribers in the United States alone. Similar projections have been made worldwide.

Quality, Capacity, and Economic Issues

Although the several trajectories toward low-tier PCS discussed in the previous section are clear, it does not fit the existing wireless communications paradigms. Thus, low-tier PCS has

attracted less attention than the systems and technologies that are compatible with the existing paradigms. Some examples are cited in the following paragraphs.

The need for intense interaction with an intelligent network infrastructure in order to manage mobility is not compatible with the cordless telephone appliance paradigm. In that paradigm, independence of network intelligence, and base units that mimic wireline telephones, are paramount.

Wireless data systems often do not admit to the dominance of wireless voice communications, and, thus, do not take advantage of the economics of sharing network infrastructure and base station equipment. Also, wireless voice systems often do not recognize the importance of data and messaging, and, thus, only add them in as "bandaids" to systems.

The need for a dense collection of many low-complexity low-cost low-tier PCS base stations interconnected with inexpensive fixed-network facilities (copper or fiber based) does not fit the cellular high-tier paradigm that expects sparsely distributed \$1 million cell sites. Also, the need for high transmission quality to compete with wireline telephones is not compatible with the drive toward maximizing users-per-cell-site and per MHz to minimize the number of expensive cell sites. These concerns, of course, ignore the hallmark of frequency-reusing cellular systems. That hallmark is the production of almost unlimited overall system capacity by reducing the separation between base stations.

This list could be extended, but the above examples are sufficient, along with the earlier sections of the paper, to indicate the many complex interactions among circuit quality, spectrum utilization, complexity (circuit and network), system capacity, and economics that are involved in the design compromises for a large, high-capacity wireless-access system. Unfortunately, the tendency has been to ignore many of the issues, and focus on only one, e.g., the focus on cell site capacity that drove the development of digital-cellular high-tier systems in the United States. Interactions among circuit quality, complexity, capacity and economics are considered in the following sections.

Capacity, Quality, and Complexity

Although "capacity" comparisons frequently are made without regard to circuit quality, complexity, or cost per base station, such comparisons are not meaningful. An example in Table 4 compares capacity factors for U.S. cellular or high-tier PCS technologies with the low-tier PCS technology, PACS/WACS. The Mean Opinion Scores (MOS) (noted in Table 4) for speech coding are discussed in reference [1]. Detection of speech activity and turning off the transmitter during times of no activity is implemented in IS-95. Its impact on MOS also is noted in reference [1]. A similar technique has been proposed as E-TDMA for use with IS-54, and is discussed with respect to TDMA systems in reference [1]. Note that the use of low bit-rate speech coding combined with speech activity degrades the high-tier system's quality by nearly one full MOS point on the 5-point MOS scale when compared to 32 kb/s ADPCM. Tandem encoding is discussed in the previous section. These speech

quality-degrading factors alone provide a base station capacity increasing factor of $x 4 \times 2.5 = x 10$ over the high speech-quality low-tier system! Speech coding, of course, directly affects base station capacity and thus overall system capacity by its effect on the number of speech channels that can fit into a given bandwidth.

The allowance of extra system margin to provide coverage of 99 percent of an area for low-tier PCS versus 90 percent coverage for high-tier is discussed in the previous section and [1]. This additional quality factor costs a capacity factor of $x 2$. The last item in Table 4 does not change the actual system, but only changes the way that frequency reuse is calculated. The additional 2-dB margin in standard deviation, σ , allowed for coverage into houses and small buildings for low-tier PCS, costs yet another factor of $x 1.5$ in calculation only. Frequency reuse factors affect the number of sets of frequencies required, and thus the bandwidth available for use at each base station. Thus, these factors also affect the base station capacity and the overall system capacity.

For the example in Table 4, significant speech and coverage quality has been traded for a factor of $x 30$ in base station capacity!! While base station capacity affects overall system capacity directly, it should be remembered that overall system capacity can be increased arbitrarily by decreasing the spacing between base stations. Thus, if the PACS low-tier PCS technology were to start with a base station capacity of $x 0.5$ of AMPS cellular³ (a much lower figure than the $x 0.8$ sometimes quoted [12]), and then were degraded in quality as described above to yield the $x 30$ capacity factor, it would have a resulting capacity of $x 15$ of AMPS! Thus, it is obvious that making such a base station capacity comparison without including quality is not meaningful.

Economics, System Capacity, and Coverage Area Size

Claims are sometimes made that low-tier PCS cannot be provided economically, even though IT is what the user wants. These claims are often made based on economic estimates from the "cellular paradigm." These include:

- Very low estimates of market penetration, much less than cordless telephones, and often even less than cellular.
- High estimates of base station costs more appropriate to high-complexity high-cost cellular technology than to low-complexity low-cost low-tier technology.

Such economic estimates are often done by making "absolute" economic calculations based on very uncertain input data. The resulting estimates for low-tier and high-tier are often closer together than the large uncertainties in the input data. A perhaps more realistic approach for comparing such systems is to vary only one or two parameters while holding all others fixed, and then look at relative economics between high-tier and low-tier systems. This is the approach used in the following examples.

Example 1 — In the first example (see textbox), the number of channels per MHz is held constant for cellular and for low-tier PCS. Only the spacing

System Capacity/Coverage Area Size/Economics

Example 1

Assume channels/MHz are the same for cellular and PCS

Cell site: spacing = 20,000 ft cost = \$1 M

PCS port: spacing = 1,000 ft

PCS system capacity is $(20000/1000)^2 = 400 \times$ cellular capacity

Then, for the system costs to be the same

Port cost = $(\$1M/400) = \$2,500$, a reasonable figure

If, cell site and port each have 180 channels

Cellular cost/circuit = $\$1M/180 = \$5,555/\text{circuit}$

PCS cost/circuit = $\$2500/180 = \$14/\text{circuit}$

Example 2

Assume equal cellular and PCS system capacity

Cell site: spacing = 20,000 ft

PCS port: spacing = 1,000 ft

If, a cell site has 180 channels

Then, for equal system capacity, a PCS port needs $180/400 < 1$ channel/port!!

Example 3

A Quality/cost trade

Cell site: Spacing = 20,000 ft cost = \$1 M channels = 180

PCS port: Spacing = 1,000 ft cost = \$2,500

Cellular to PCS: base station spacing capacity factor = $x 400$

PCS to Cellular "quality" reduction factors:

32 kb/s to 8 kb/s speech	$x 4$
Voice activity (buying)	$x 2$
99% to 90% good areas	$x 2$
Both in same environment (same σ)	$x 1$
capacity factor traded	$x 16$

$180 \text{ ch}/16 = 11.25 \text{ channels/port}$ then, $\$2500/11.25 = \$222/\text{circuit}$
and remaining is $x 400/16 = x 25$ system capacity of PCS over cellular

is varied between base stations, e.g., cell sites for cellular and radio ports for low-tier PCS, to account for the differences in transmitter power, antenna height, etc. In this example, overall system capacity varies directly as the square of base station spacing, but base station capacity is the same for both cellular and low-tier PCS. For the typical values in the example, the resulting low-tier system capacity is $x 400$ greater, only because of the closer base station spacing. If the two systems were to cost the same, the equivalent low-tier PCS base stations would have to cost less than \$2,500.

This cost is well within the range of estimates for such base stations, including equivalent infrastructure. These low-tier PCS base stations are of comparable or lower complexity than cellular vehicular subscriber sets, and large-scale manufacture will be needed to produce the millions that will be required. Also, land, building, antenna tower and legal fees for zoning approval, or rental of expensive space on top of commercial buildings, represent large expenses for cellular cell sites. Low-tier PCS base stations that are mounted on utility poles and sides of buildings will not incur such large additional expenses. Therefore, costs of the order of magnitude indicated above seem reasonable in large quantities. Note that, with these estimates, the per-wireless-circuit cost of the low-tier PCS circuits would be only \$14/circuit compared to \$5,555/circuit for the high-tier circuits. Even if there were a factor of 10 error in cost estimates, or a reduction of channels per radio port of a factor of 10, the per-circuit cost of low-tier PCS would

³ Note that the $x 0.5$ factor is an arbitrary factor taken for illustrating this example. The so called x AMPS factors are only with regard to base station capacity, although they are often misused as system capacity.

still be only \$140/circuit, which is still much less than the per-circuit cost of high-tier.

Example 2 — In the second example (see textbox), the overall system capacity is held constant, and the number of channels/port, i.e., channels/(base station) is varied. In this example, less than 1/2 channel/port is needed, again indicating the tremendous capacity that can be produced with close-spaced low-complexity base stations.

Example 3 — Since the first two examples are somewhat extreme, the third example (see textbox), uses a more moderate, intermediate approach. In this example, some of the cellular high-tier channels/(base station) are traded to yield higher quality low-tier PCS as in the previous subsection. This reduces the channels/port to 11 +, with an accompanying increase in cost/circuit up to \$222/circuit, which is still much less than the \$5,555/circuit for the high-tier system. Note, also, that the low-tier system still has x 25 the capacity of the high-tier system!

Low-tier base station (PORT) cost would have to exceed \$62,500 for the low-tier per-circuit cost to exceed that of the high-tier cellular system. Such a high port cost far exceeds any existing realistic estimate of low-tier system costs.

It can be seen from these examples, and particularly Example 3, that the circuit economics of low-tier PCS are significantly better than for high-tier PCS, IF the user demand and density is sufficient to make use of the large system capacity. Considering the high penetration of cordless telephones, the rapid growth of cellular handsets, and the enormous market projections for "wireless PCS" noted earlier in this paper, filling such high capacity in the future would appear to be certain. The major problem is providing rapidly the widespread coverage (buildout) required by the FCC in the United States. If this unrealistic regulatory demand

(many decades) of concerted attempts to improve it. Increases in battery capacity have come in small increments, a few percent, and very slowly over many years, and the shortfall is well over a factor of 10. In contrast, integrated electronics and radio frequency devices needed for low-power low-tier PCS continue to improve and to decrease in cost by factors of greater than 2 in time spans on the order of a year or so. It also should be noted that, as the energy density of a battery is increased, the energy release rate per volume must also increase in order to supply the same amount of power. If energy storage density and release rate are increased significantly, the difference between a battery and a bomb become indistinguishable! The likelihood of a x 10 improvement in battery capacity appears to be essentially zero. If even a modest improvement in battery capacity were possible, many people would be driving electric vehicles.

New Technology

New technology, e.g., spread spectrum or CDMA, is sometimes offered as a solution to both the high-tier cell site capacity and transmitter power issues. However, as these new technologies are pursued vigorously, it becomes increasingly evident that the early projections were considerably over-optimistic, that the base station capacity will be about the same as other technologies [1], and that the high complexity will result in more, not less, power consumption.

With the continuing problems and delays in initial deployments, there is increasing concern throughout the industry as to whether CDMA is a viable technology for high capacity cellular applications. With the passage of time, it is becoming more obvious that Viterbi was correct in his 1985 paper in which he questioned the use of spread spectrum for commercial communications [33].

Thus, it is clear that new high-complexity high-tier technology will not be a substitute for low-complexity, low-power low-tier PCS.

People Only Want One Handset

This issue is often raised in support of high-tier cellular handsets over low-tier handsets. While the statement is likely true, the assumption that the handset must work with high-tier cellular is not. Such a statement follows from the current large usage of cellular handsets; but such usage results because that is the only form of widespread wireless service currently available, not because it is what people want. The statement assumes inadequate coverage of a region by low-tier PCS, and that low-tier handsets will not work in vehicles. The only way that high-tier handsets could serve the desires of people discussed earlier would be for an unlikely "breakthrough" in battery technology to occur [7]. However, a low-tier system can cover economically any large region having some people in it. (It will not cover rural or isolated areas — but, by definition, there is essentially no one there to want communications anyway).

Low-tier handsets will work in vehicles on village and city streets at speeds up to 30 or 40 miles per hour, and the required handoffs make use of computer technology that is rapidly becoming inexpensive. Highways between populated areas, and also streets within them, will need to be covered by high-tier cellular PCS, but, users are likely

With the continuing problems and delays in initial deployments, there is increasing concern throughout the industry as to whether CDMA is a viable technology for high capacity cellular applications.

can be overcome, low-tier wireless PCS promises to provide the wireless personal communications that everyone wants.

Other Issues

Several issues in addition to those addressed in the previous two sections continue to be raised with respect to low-tier PCS. These are treated in this section.

Improvement of Batteries

Frequently, the suggestion is made that battery technology will improve so that high-power handsets will be able to provide the desired five or six hours of talk time in addition to 10 or 12 hours of standby time, and still weigh less than half of the weight of today's smallest cellular handset batteries. This "hope" does not take into account the maturity of battery technology, and the long history

to use vehicular sets in these cellular systems. Frequently the vehicular mobile user will want a different communications device anyway, e.g., a hands-free phone. The use of hands-free phones in vehicles is becoming a legal requirement in some places now, and is likely to become a requirement in many more places in the future. Thus, handsets may not be legally usable in vehicles anyway. With widespread deployment of low-tier PCS systems, the one handset of choice will be the low-power low-tier PCS pocket handset or voice/data communicator.

There are approaches for integrating low-tier pocket phones or pocket communicators with high-tier vehicular cellular mobile telephones. The user's identity could be contained either in memory in the low-tier set, or in a small smart card inserted into the set, as is a feature of the European GSM system. When entering an automobile, the small low-tier communicator or card could be inserted into a receptacle in a high-tier vehicular cellular set installed in the automobile.⁴ The user's identity would then be transferred to the mobile set. The mobile set could then initiate a data exchange with the high-tier system, indicating that the user could now receive calls at that mobile set. This information about the user's location would then be exchanged between the network intelligence so that calls to the user could be correctly routed.⁵ In this approach the radio sets are optimized for their specific environments, high-power high-tier vehicular or low-power low-tier pedestrian, as discussed earlier, and the network access and call routing is coordinated by the interworking of network intelligence. This approach does not compromise the design of either radio set or radio system. It places the burden on network intelligence technology that benefits from the large and rapid advances in computer technology.

The approach of using different communications devices for pedestrians than for vehicles is consistent with what has actually happened in other applications of technology in similarly different environments. For example, consider the case of audio cassette tape players. Pedestrians often carry and listen to small portable tape players with lightweight headsets (e.g., a Walkman⁶). When one of these people enters an automobile, he or she often removes the tape from the Walkman and inserts it into a tape player installed in the automobile. The automobile player has speakers that fill the car with sound. The Walkman is optimized for a pedestrian, whereas the vehicular-mounted player is optimized for an automobile. Both use the same tape, but they have separate tape heads, tape transports, audio preamps, etc. They do not attempt to share electronics. In this example, the tape cassette is the information-carrying entity similar to the user identification in the personal communications example discussed earlier. The main points are that the information is shared among different devices, but the devices are optimized for their environments and do not share electronics.

Similarly, a high-tier vehicular-cellular set does not need to share oscillators, synthesizers, signal processing, or even frequency bands or protocols with a low-power low-tier pocket-size communicator. Only the information identifying the user and where he or she can be reached needs to be shared

among the intelligence elements, e.g., routing logic, databases, and common channel signaling [1, 22] of the infrastructure networks. This information exchange between network intelligence functions can be standardized and coordinated among infrastructure subnetworks owned and operated by different business entities (e.g., vehicular cellular mobile radio networks, and intelligent low-tier PCS networks). Such standardization and coordination are the same as are required today

The approach of using different communications devices for pedestrians than for vehicles is consistent with what has actually happened in other applications of technology in similarly different environments.

to pass intelligence among local exchange networks and interexchange carrier networks.

Other Environments — Low-tier personal communications can be provided to occupants of airplanes, trains, and buses by installing compatible low-tier radio access ports inside these vehicles. The ports can be connected to high-power high-tier vehicular cellular mobile sets or to special air-ground or satellite-based mobile communications sets. Intelligence between the internal ports and mobile sets could interact with cellular mobile, air-ground, or satellite networks in one direction, using protocols and spectrum allocated for that purpose, and with low-tier personal communicators in the other direction to exchange user identification and route calls to and from users inside these large vehicles. Radio isolation between the low-power units inside the large metal vehicles and low-power systems outside the vehicles can be ensured by using windows that are opaque to the radio frequencies. Such an approach also has been considered for automobiles (i.e., a radio port for low-tier personal communications connected to a cellular mobile set in a vehicle so that the low-tier personal communicator can access a high-tier cellular network. This could be done in the United States using unlicensed PCS frequencies within the vehicle.)

High-Tier to Low-Tier or Low-Tier to High-Tier Dual Mode

Industry and the FCC in the United States appear willing to embrace multi-mode handsets for operating in very different high-tier cellular systems, e.g., analog FM AMPS, TDMA IS-54, and CDMA IS-95. Such sets incur significant penalties for dual mode operation with dissimilar air interface standards, and, of course, incur the high-tier complexity penalties.

It has been suggested that multi-mode high-tier and low-tier handsets could be built around one air-interface standard, for example, TDMA IS-54 or GSM. When closely spaced low-power base stations were available, the handset could "turn off" unneeded power-consuming circuitry, e.g., the multipath equalizer. The problem with this approach is that the handset is still encumbered with power-consuming and quality-reducing signal processing inherent in the high-tier technology,

⁴ Inserting the small personal communicator in the vehicular set would also facilitate charging the personal communicator's battery.

⁵ This is a feature proposed for FPLMTS in CCIR Rec. 687.

⁶ Walkman is a registered trademark of Sony Corporation.

e.g., error correction decoding, and low-bit-rate speech encoding and decoding.

An alternative "dual-mode" low-tier, high-tier system based on a common air-interface standard can be configured around the low-tier PACS/WACS system, if such a dual-mode system is deemed desirable in spite of the discussion in this article. The range of PACS can readily be extended by increasing transmitter power and/or the height and gain of base station antennas. With increased range, the multipath delay-spread will be more severe in some locations [24-26]. Two different solutions to the increased delay-spread can be employed, one for the downlink and another for the uplink. The

The signaling, control processing, and data base interactions required for wireless access PCS are considerably greater than those required for fixed place-to-place networks, but that fact must be accepted when considering such networks.

PACS radio-link architecture has a specified bit sequence, i.e., a unique word, between each data word on the TDM downlink [16, 17]. This unique word can be used as a training sequence for setting the tap weights of a conventional equalizer added to subscriber sets for use in a "high-tier" PACS mode. Since received data can be stored digitally [27, 28], tap weights can be trimmed, if necessary, by additional "passes" through an adaptive equalizer algorithm, e.g., a decision feedback equalizer algorithm.

The PACS TDMA uplink has no "unique word." However, the "high-tier" uplink will terminate on a base station that can support greater complexity, but still be no more complex than the high-tier cellular technologies. Research at Stanford University has indicated that blind equalization, using constant-modulus algorithms (CMA) [29, 30], can be effective for equalizing the PACS uplink. Techniques have been developed for converging the CMA equalizer on the short TDMA data burst.

Advantages of building a dual-mode high-tier, low-tier PCS system around the low-tier PACS air-interface standard are that:

- The interface can still support small low-complexity, low-power, high-speech-quality low-tier handsets.
- Both data and voice can be supported in a PACS personal communicator.
- In high-tier low-tier dual mode PACS sets, circuits used for low-tier operation will also be used for high-tier operation, with additional circuits being activated only for high-tier operation.
- The flexibility built into the PACS radio link to handle different data rates from 8 kb/s to several hundred kb/s will be available to both modes of operation.

Infrastructure Networks

It is beyond the scope of this article to consider the details of PCS network infrastructures. However, there are perhaps as many network issues as there are wireless access issues discussed herein [22, 23, 31, 32]. With the possible

exception of the self-organizing WLANs, wireless PCS technologies serve as access technologies to large integrated intelligent fixed communications infrastructure networks.

These infrastructure networks must incorporate intelligence i.e., data-base storage, signaling, processing and protocols, to handle both small-scale mobility, i.e., handoff from base station to base station as users move, and large-scale mobility, i.e., providing service to users who roam over large distances, and perhaps from one network to another. The fixed infrastructure networks also must provide the interconnection among base stations and other network entities, e.g., switches, data bases, and control processors. Of course, existing cellular mobile networks now contain or are incorporating these infrastructure network capabilities. However, existing cellular networks are small compared to the expected size of future high-tier and low-tier PCS networks, e.g., 20 million cellular users in the United States compared with perhaps 100 million users or more each in the future for high-tier and low-tier PCS.

Several other existing networks have some of the capabilities needed to serve as access networks for PCS. Existing networks that could provide fixed base station interconnection include:

- Local exchange networks that could provide interconnection using copper or glass-fiber distribution facilities.
- Cable TV networks that could provide interconnection using new glass-fiber and coaxial-cable distribution facilities.
- Metropolitan fiber digital networks that could provide interconnection in some cities in which they are being deployed.

Networks that contain intelligence, e.g., databases, control processors, and signaling that is suitable, or could be readily adapted, to support PCS access include:

- Local exchange networks that are equipped with signaling system 7 common channel signaling (SS7 CCS), data bases and digital control processors.
- Interexchange networks that are similarly equipped.

Data networks, e.g., the Internet, could perhaps be adapted to provide the needed intelligence for wireless data access, but it does not have the capacity needed to support large voice/data wireless low-tier PCS access.

Many entities and standards bodies worldwide are working on the access network aspects of wireless PCS. The signaling, control processing, and data base interactions required for wireless access PCS are considerably greater than those required for fixed place-to-place networks, but that fact must be accepted when considering such networks.

Low-tier PCS, when viewed from a cellular high-tier paradigm, requires much greater fixed interconnection for the much closer spaced base stations. However, when viewed from a cordless telephone paradigm of a base unit for every handset, and perhaps several base units per wireline, the requirement is much less fixed interconnection because of the concentration of users and trunking that occurs at the multi-user base stations. One should remember that there are economical fixed wireline connections to almost all houses and business offices in the United States now. If wireless access displaces some of the wireline

connections, as expected, the overall need for fixed interconnection could decrease!

Conclusion

Wireless personal communications embraces about seven relatively distinct groups of tetherless voice and data applications or services having different degrees of mobility for operation in different environments. Many different technologies and systems are evolving to provide the different perceived needs of different groups. Different design compromises are evident in the different technologies and systems. The evidence suggests that the evolutionary trajectories are aimed toward at least three large groups of applications or services, namely, high-tier PCS (current cellular radio), high-speed wireless local-area networks (WLANS), and low-tier PCS (an evolution from several of the current groups). It is not clear to what extent several groups, e.g., cordless telephones, paging, and wide area data, will remain after some merging with the three large groups. Major considerations that separate current cellular technologies from evolving low-tier low-power PCS technologies are speech quality, complexity, flexibility of radio-link architecture, economics for serving high-user-density or low-user-density areas, and power consumption in pocket carried handsets or communicators. High-tier technologies make use of large complex expensive cell sites and have attempted to increase capacity and reduce circuit costs by increasing the capacity of the expensive cell sites. Low-tier technologies increase capacity by reducing the spacing between base stations, and achieve low circuit cost by using low-complexity low-cost base stations. The differences between these approaches result in significantly different compromises in circuit quality and power consumption in pocket sized handsets or communicators. These kinds of differences also can be seen in evolving wireless systems optimized for data. Advantages of the low-tier PACS/WACS technology are reviewed in the article, along with techniques for using that technology in high-tier PCS systems.

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Biography

DONALD C. COX [F '79] did research at Bell Laboratories from 1968 to 1973 on advanced mobile radio systems that still provides basic input to the design of digital cellular, cordless, and PCS systems. From 1978 to 1993 he led and was actively involved in pioneering wireless research, first at Bell Labs and then at Bellcore, that started and fueled the current explosion in wireless personal communications. He was instrumental in evolving this research into the WACS/PACS specification being standardized by the U.S. TIA/T1 JTC. For this pioneering work, he received the IEEE 1993 Alexander Graham Bell Medal and Bellcore Fellow Award, and was elected into the National Academy of Engineering. He received the IEEE Morris E. Leeds award in 1985 and the Prize Guglielmo Marconi from Italy in 1983 and is a Fellow of the AAAS and the RCA. He holds 12 patents, has authored or coauthored more than 75 journal papers, including three that won prizes, was coauthor of a book, *Microwave Mobile Communications*, and has been guest editor of special issues on Wireless Communications in IEEE journals. He managed Radio Research at Bellcore from 1984 to 1993, and is currently the Harald Trap Friis Professor of Engineering and director of the Telecommunications Center at Stanford University, Stanford, California. He received B.S. and M.S. degrees in electrical engineering and an Honorary Dr. of Science from the University of Nebraska, and a Ph.D. in electrical engineering from Stanford.

Wireless Networks

In the decade ahead, they will deliver personalized communications to people on the go and basic service to many who still lack telephones

by George I. Zysman

Near the end of the 19th century a young man named Guglielmo Marconi connected a spark emitter to a short antenna and sent a burst of radio waves through the air to a simple receiver. It responded by ringing a bell, signaling the birth of a technology that promised to allow people to communicate across distances while in motion. In the closing decades of the 20th century, several waves of innovation have made wireless communications the fastest-growing segment of the global telecommunications industry.

Wireless networks are proliferating rapidly, going digital and harnessing "intelligent network" technology to lo-

cate and identify roaming subscribers and to customize the services they receive. An intelligent network consists of a distributed signaling network of switches, databases and dedicated computer servers that is separate from, yet intimately connected to, the transport networks on which subscribers' voice calls and data actually flow. This architectural framework, which has been refined over the past 30 years to support such services as 800-number calling, caller identification and "911," will soon make personalized communications services as portable as a pocket telephone.

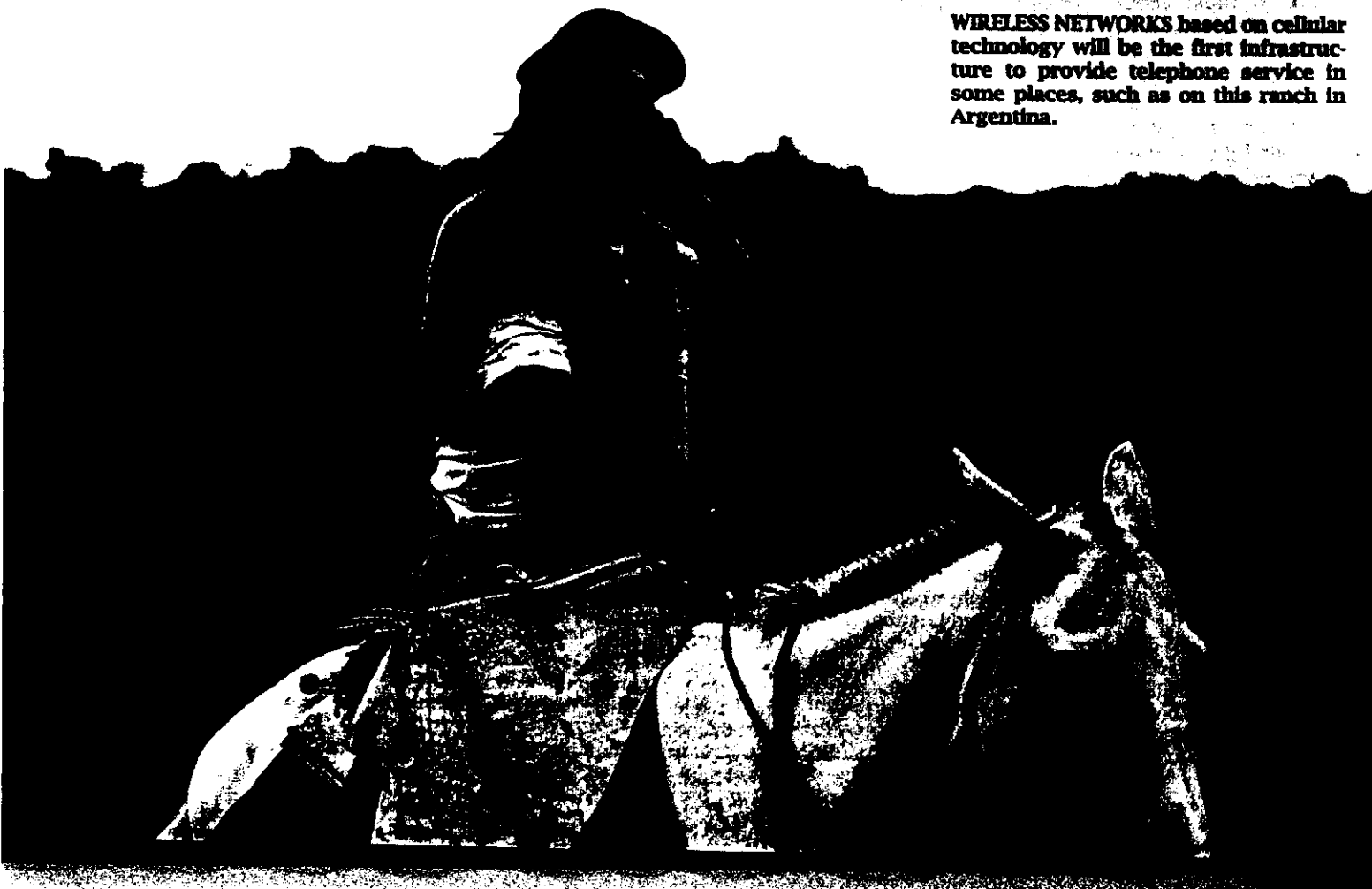
As advances in microelectronics, digital radio, signal processing and net-

work software converge in the marketplace, portable telephones are getting smaller, smarter and less expensive. Some are taking on new forms, such as the wireless handheld computers called personal digital assistants (PDAs), so that they can handle text and graphics as well as audio messages; video is not far behind. Increasingly, the software running on "smart" terminals—typified by the graphical user interfaces and intelligent software agents available today in PDAs—will work hand in hand with intelligent networks to enhance portable communications.

Over the past five years the demand for wireless services has risen beyond all expectations. In 1983 some industry analysts predicted that fewer than one million Americans would use cellular services by the year 2000. Currently more than 20 million do. Cellular services now spearhead the market penetration of wireless communications, as the number of cellular users grows annually by approximately 50 percent in North America, 60 percent in western Europe, 70 percent in Australia and Asia, and more than 200 percent in South America's largest markets.

Analysts now project that by 2001, three quarters of the households in the U.S. and nearly half a billion people

WIRELESS NETWORKS based on cellular technology will be the first infrastructure to provide telephone service in some places, such as on this ranch in Argentina.



worldwide will subscribe to a wireless service of some kind. The Federal Communications Commission has raised nearly \$8 billion in the past year, with more to come, by auctioning licenses to use emerging technologies and radio spectrum around the frequency of two gigahertz to provide a new set of wireless capabilities known as personal communications services, or PCS. The terms of these auctions require licensees to move quickly to install the infrastructure needed to provide PCS. The magnitude of the investment that has been made by PCS licensees and equipment manufacturers is a measure of the industry's confidence in the projected market demand. This phenomenon is not limited to the U.S. Before the century is out, service providers in Europe, Japan, Thailand, Singapore, Malaysia, China, Australia, New Zealand and India all reportedly plan to have PCS systems up and running.

The growth of the wireless market has increased pressure on regulatory bodies to allocate more spectrum and on service providers to use spectrum more efficiently by converting to digital technology.

The Switch to Digital

The present analog standards used by most cellular systems encode voices and even digital data into continuous variations of a carrier wave, which are then decoded by the receiver. Already many cellular service providers are converting their networks to one of several digital standards that translate voices and data into a bit stream, which is sent in waveforms that represent discrete pulses. Compared with their analog counterparts, digital systems can both expand the capacity of the medium and compress the messages it carries.

Most cellular and PCS networks will soon use one of the digital air interface standards—different ways of sharing the limited spectrum among many users at a time—that are now vying for acceptance. Whether one will eventually win out remains to be seen. In the most likely scenario, intelligent base stations and dual-mode terminals will adapt to a patchwork of multiple-access air interface standards spread across the wireless landscape. But all the leading digital air interface standards offer a similar benefit: the ability to pack more bits of conversations into a slice of spectrum than an analog system can.

Once wireless service providers switch to digital, they can further increase the

number of customers served by employing compression techniques, which are improving steadily. A stream of eight kilobits per second can transmit good-quality speech; better quality, delivered not long ago at the rate of 32 kilobits per second, now requires only 13.

Service providers can also keep ahead of demand by shrinking the size of each cell—the area covered by a single base station—in crowded areas. It is much easier to add small cells with digital standards, since they provide error correction and help the receivers resolve interference between adjacent cells.

The move to all-digital technology is driving communications terminals toward greater functionality, smaller size and lower power. Portable telephones and other wireless devices are essentially miniature computers with some extra electronics to transmit and receive radio signals. As such, they are susceptible to Moore's Law, an axiom first postulated by Gordon Moore, co-founder of Intel, in 1965. It observes that the performance of mass-produced microchips doubles every 18 months or so.

Every year and a half the digital chips needed to run a wireless terminal or base station shrink by about 50 percent. Already cellular telephones are slipped into pockets. Soon they could be strapped onto wrists. Analog base stations that currently require towers, real estate and air-conditioned shacks will eventually be replaced by inconspicuous digital base stations serving minicells. Microcell systems deployed to cover very small areas may even become the size of a smoke detector.

Over the next few years, cable television operators will begin adding base stations to their fiber-optic and coaxial-cable networks, carrying telephone traffic on unused cable channels and supplying wireless access to neighborhoods in competition with other local access providers. If they use the same air interface standard as a local cellular carrier, their telephone customers could be able to place calls over the cellular network, and vice versa. Power companies, which own ubiquitous grids of communications as well as power facilities, are entertaining similar thoughts.

Data on the Air

Although portable phones and pagers are certainly convenient—after all, two out of three business calls still end in “telephone tag”—new devices and network systems that can transmit and receive text and images over the air will

P. J. GRIFFITHS/Magnum

WIRELESS WRISTPHONE created at AT&T Bell Laboratories demonstrates that although the market may not be ready for wearable communications devices, the technology is close at hand.

have a larger impact, in the long term, on the way people communicate. Built-in radio modems can link laptops, PDAs and other handheld digital devices over today's predominantly analog cellular networks, and there are several dedicated wireless data networks in service. Digital cellular networks for mobile and packet data services are beginning to offer other alternatives. Licenses to provide “narrowband PCS”—two-way paging and moderate-speed data messaging services at frequencies around 900 megahertz—were awarded by the FCC through auctions held in 1994.

First-generation handheld wireless computers did not catch on, perhaps because they were somewhat awkward and had too little functionality for the price. But as people of every age and income grow increasingly familiar with electronic mail, commercial on-line services and the Internet, it stands to reason that they will want access to the information these media offer at any time, according to need or whim—not just when they happen to be sitting at a computer.

It is possible to adapt old-fashioned devices to receive newfangled messages. Several companies offer to filter and

forward E-mail, one line at a time, to your alphanumeric pager via satellite. Artificial-speech chips are now sophisticated and inexpensive enough that they could be put into telephones, so that they would read incoming text aloud. But more versatile devices will require displays and reasonably fast transmission rates to handle graphics and text.

Analog network technology limits data communications via modem to relatively slow speeds: 14.4 kilobits per second or less. Digital networking will help somewhat by eliminating conversions between analog and digital formats; it will not necessarily increase data rates for standard service beyond the equivalent of a telephone line.

Eventually, even the boost from the present digital standards and compression techniques will prove insufficient to provide enough room to pass data-intensive messages among hundreds of millions of customers. By the turn of the century, wireless faxes will be common, and video mail could be widely used throughout wireless as well as wire-line networks. If spectrum is allocated to ac-

commodate the resulting deluge of images, it will probably be at frequencies of around 30 to 40 gigahertz, although some video services may be available at 2.5 gigahertz. Because radio signals at these short wavelengths behave like light, buildings and even foliage block them, and coverage is essentially limited to line of sight. So wireless broadband services would be fixed rather than mobile, and service providers would need to shrink cells further to serve large numbers of subscribers.

Air interface standards will also probably evolve to accommodate broadband data and video transmission. The first generation of digital standards presumes a circuitlike connection between two devices for an entire call. That arrangement is better suited to telephone calls than to surfing the Net. The Internet uses standards based on routing individually addressed packets of data.

Telephone companies designing fiber-optic networks to carry interactive video services plan to connect them with broadband packet switches—using a technology called asynchronous transfer mode, or ATM—that can shunt pack-

ets of data, voice and video along the appropriate paths at extremely fast rates. Wireless networks will follow this trend when it becomes the most efficient way to combine voice and multimedia services. It is possible, in fact, that wireless service providers and cable TV companies may lead the shift to ATM. The timing will depend on existing network assets, technological plans and investment strategies.

Intelligence in Motion

As portable telephones grow in popularity, they will also tend to offer more features. Ten years from now you will almost certainly still be able to buy a simple wireless device that is limited to voice calls; it will probably be quite inexpensive. More common, however, will be devices that can handle faxes and video and run software applications. Doubtless there will be many styles with widely varying capabilities.

This could cause problems. The smarter a device must be, the greater the risk that its complexity will baffle the user. And different models will work differ-

Wireless Telephony for Developing Countries

The same technologies that provide flip-phone service to people on the go can provide basic dial tone to regions where it has never been heard before. This is much of the planet: about half the people alive today have never made a telephone call. A number of developing countries have expressed a desire to leapfrog over a generation or two of network technology, using wireless infrastructure to jump-start telephone service.

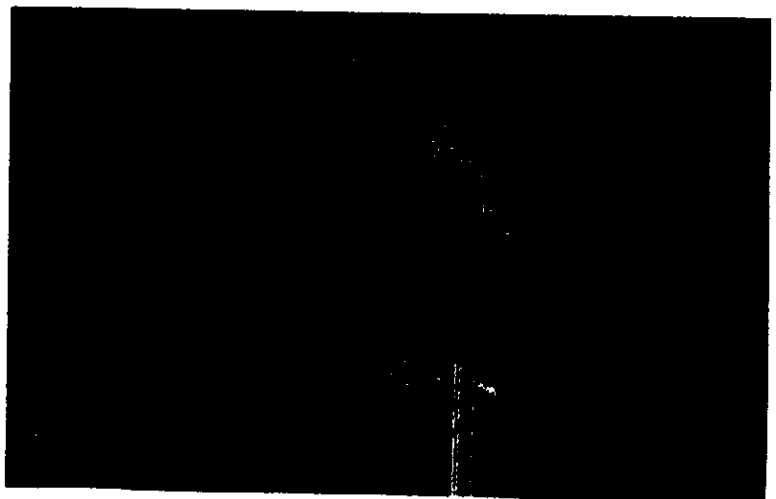
These countries see two advantages in wireless telephone systems. The first is cost. Many of the facilities necessary for a conventional wire-line access network are typically engineered for 20 to 30 years of service expansion. As a result, the cost of building such a network where no infrastructure exists may be prohibitively high.

With a "fixed wireless" network geared for access rather than mobility, a service provider can cover a large region with base stations and a single unit for switching and control—a significantly smaller investment. Subscribers can then connect to the global network using portable telephones, wireless public telephones, or terminals mounted on buildings and wired to conventional telephones. As the number of subscribers grows, the service provider can easily add more base stations to split the area covered by the network into smaller segments.

The second benefit is time. Wireless networks can be installed in months rather than the years required to install copper wires. Argentina, for

example, announced in February 1994 that it was awarding licenses for the entire country to CTI, a GTE-led consortium. By May an 800-cell fixed wireless network that AT&T built for CTI was up and running. It can serve as many as 160,000 subscribers.

Telecommunications, many have observed, constitutes the main infrastructure for the global economy. Where there is a potential for revenue, wireless technology could offer a bootstrap to participation in that market for many regions of the world that might otherwise be excluded.



PARTS OF ARGENTINA inaccessible to wire-line telephone service are now served by a wireless network built in less than six months.

RICHARD HUSLEY

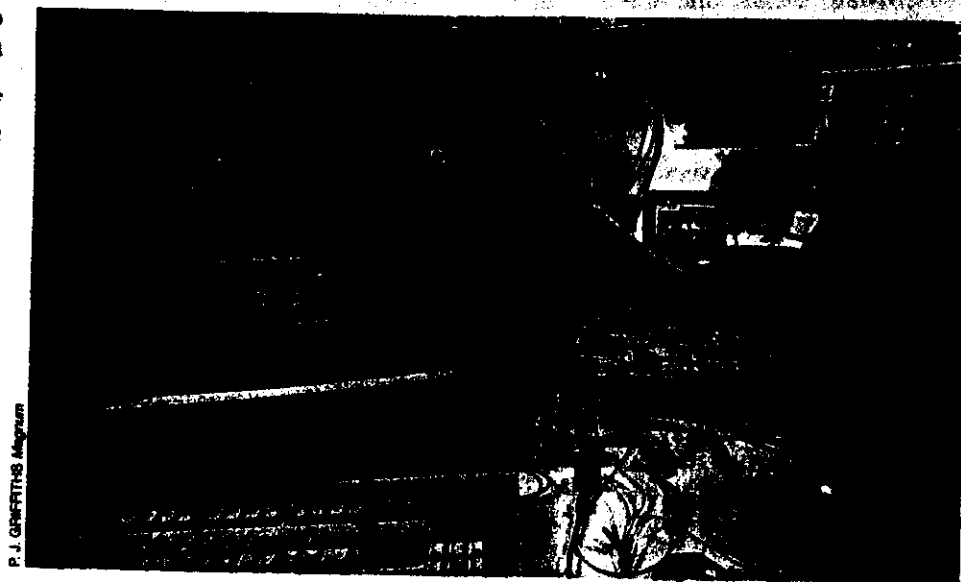
ently. Picking up a friend's telephone to make a call might leave you staring at a completely unfamiliar user interface.

One way to simplify the operation of handheld wireless gadgets and make them more user-friendly is to place some of the intelligence needed to accomplish useful tasks in the network. Intelligent network services available now can, for example, forward calls automatically to a subscriber's car, office, home, portable telephone or voice mail. Software architectures and systems that facilitate collaboration between intelligent devices and intelligent networks will improve the accuracy of personal mobility services—ringing the right device on the first try—and will make much more sophisticated interactions possible.

At AT&T, our vision of PCS is that it will deliver the right service to the right location and device without any intervention by the caller or the subscriber. The trick is keeping track of where subscribers are. One solution is to use personal numbers: one per person, instead of the three, five, seven or more that today address different devices and network locations where a person might be reached. Register with the network, and the network will translate your personal number, as dialed by a caller, to the number for the appropriate local device or mailbox, depending on the type of call or message and on your service preferences.

Smart cards offer another solution. If all telephones were equipped with a card reader, you could insert your card in the nearest telephone, even if it belonged to someone else, and register your presence with the network. It would then direct all your calls—or perhaps only those from a special list of priority numbers—to that telephone. Or you could simply send the network a normal daily schedule and use the card to register exceptions. People who would rather not be found would register that with the network, too.

Smart cards might also help get around the complexity of using sophisticated telephones. Currently when one travels to another country, dialing 911 does not get an emergency operator; 011 is rarely the correct prefix for international calls. Such country-specific codes may proliferate as devices become more complex. But an interface description could be stored on a smart card. Insert that card in a strange device, and it could reconfigure itself to work just like your own. You would not have to learn how to use a plethora of



WIRELESS DIGITAL VIDEO researchers at Bell Labs are using innovative signal-processing techniques to minimize the effects of compression and the vagaries of transmission through the air on image quality.

new devices; instead they would learn how to work with you.

Smart cards have been technologically demonstrated. Whether the business and personal privacy issues they raise can be settled is another matter. Companies in a wide variety of businesses see uses for smart cards, but each has an interest in controlling the personal information that will be stored on them.

There are other, less controversial ways to track callers and to provide location-specific services. Cellular systems can already locate a caller's position to within a few square miles. A more precise alternative would be to equip devices with Global Positioning System receivers, which can often pinpoint their location to within about 100 feet using signals from a constellation of orbiting satellites. Equipping cell sites to locate devices by triangulation could be less expensive than using the GPS; this third method might even be more accurate.

In emergencies, such techniques could help 911 services reach callers who do not know where they are. More routinely, networks could offer customers intelligent access to interactive data services in a kind of "information mall" that pulls together services from many

independent companies. Arriving in an unfamiliar town, a traveler might use her PDA to request a list of nearby Italian restaurants from the network. The network could pass this request to a program run by the Italian Restaurant Association of America. The listing it generates might then be sent to an interface program provided by a third company before appearing on the traveler's screen. Her PDA would not have to do much work at all.

Such advanced services will have to wait for the business to develop. One of the biggest hurdles is billing: every company wants to be the one that bonds with customers and collects information about them, since that can lead to new business opportunities.

Ultimately, the distinction between wireless and wire-line networks will recede to the vanishing point. Portable devices will be no more difficult to use than their wired counterparts and will offer equivalent performance and services. Hiding the complexity of wireless networking technology from the people it serves is admittedly a challenge. But the technology is here and will ultimately be put to its proper use—making itself invisible.

The Author

GEORGE I. ZYSMAN is chief technical officer of AT&T's Network Wireless Systems business unit and a director of AT&T Bell Laboratories.

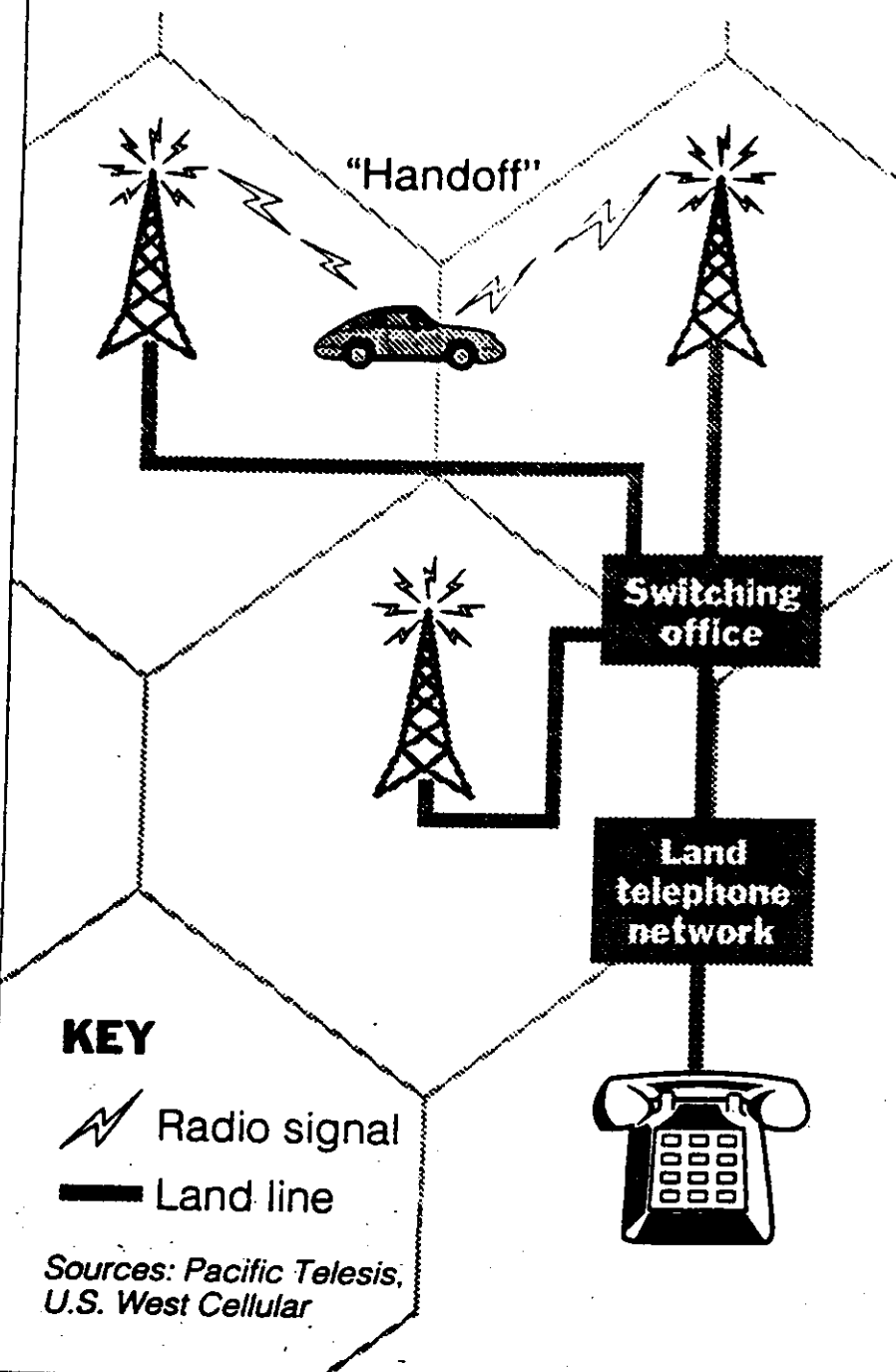
Further Reading

WIRELESS TECHNOLOGY. Special issue of *AT&T Technical Journal*, Vol. 72, No. 4; July-August 1993.

WIRELESS PERSONAL COMMUNICATIONS. Special issue of *IEEE Communications Magazine*, Vol. 33, No. 1; January 1995.

HOW IT WORKS

Calling by Cellular Telephone



Cellular technology divides a city into areas called cells. Each cell is from 1 to 10 miles across, depending on the population density of the area.

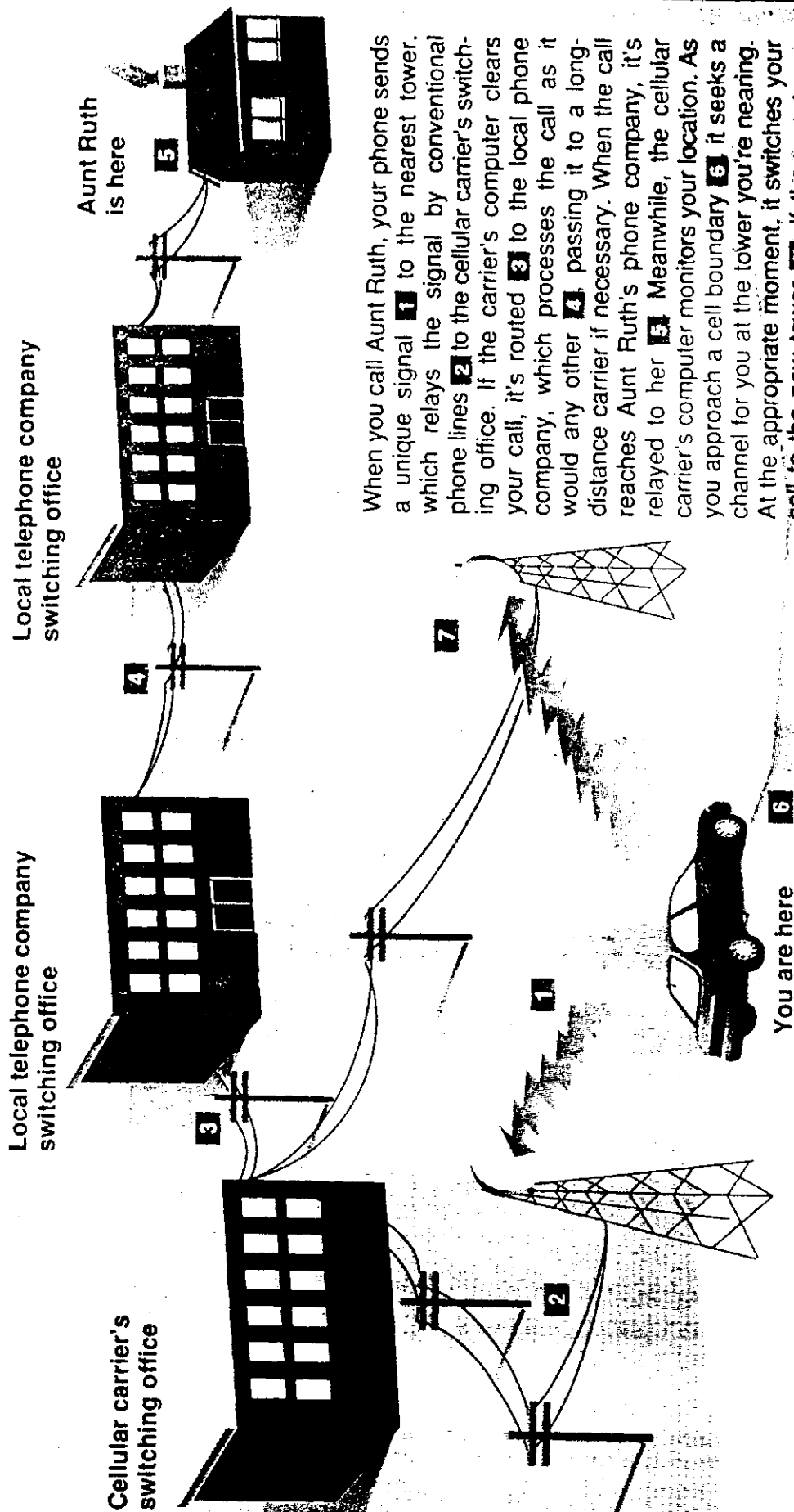
Each cell contains a radio transceiver, which sends and receives information. Calls from mobile phones are sent to a switching office, which is linked to the regular land-line telephone network. Calls can be sent either to a regular phone or another mobile phone.

As a caller drives from one cell to another, the call is automatically passed to the nearest transceiver, and the caller's new location is passed to the switching station.



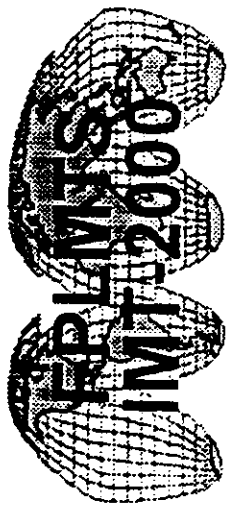
The word "cellular" reflects the carving of cities, counties, and rural regions into areas called cells, each of which has its own transmission tower. The towers receive calls via FM radio waves like those your FM tuner receives but at a different frequency, to avoid interfering with your radio.

Because the system's signals are low in power, they remain within the cell, which generally has a diameter of between 1 mile and 20 miles. That way, the same frequencies, or channels, can be used in nearby cells with little chance of interference.

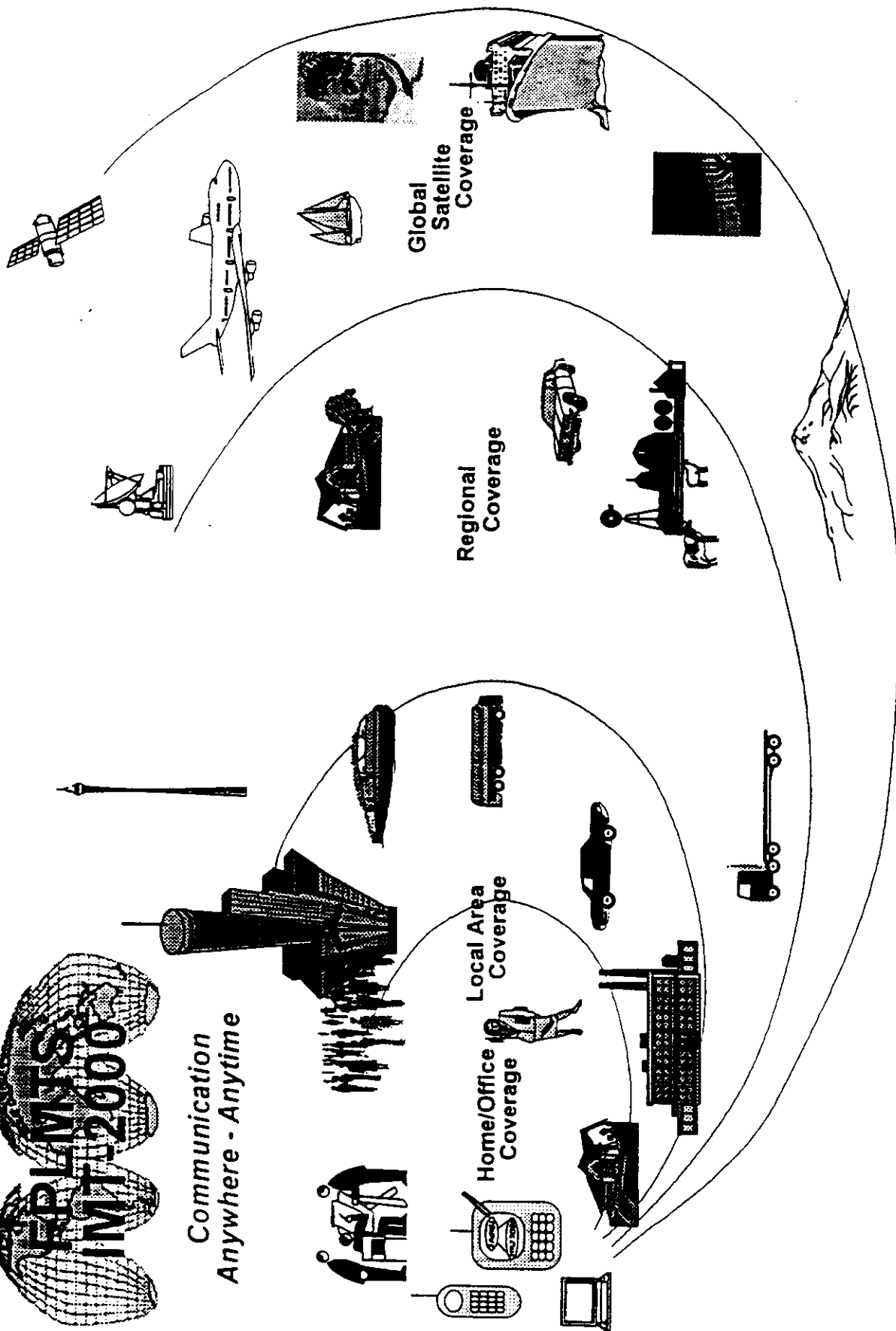


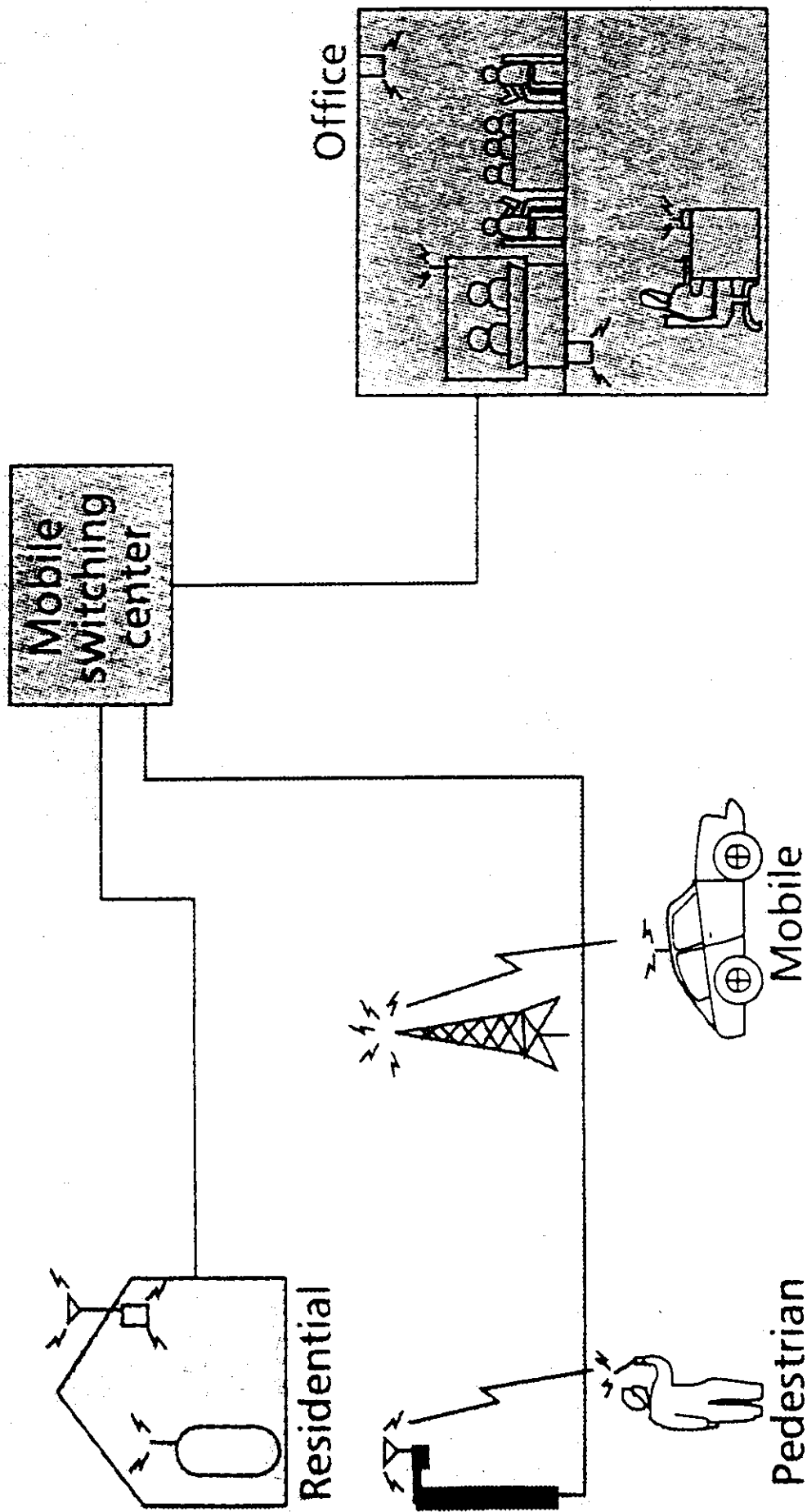
When you call Aunt Ruth, your phone sends a unique signal **1** to the nearest tower, which relays the signal by conventional phone lines **2** to the cellular carrier's switching office. If the carrier's computer clears your call, it's routed **3** to the local phone company, which processes the call as it would any other **4**, passing it to a long-distance carrier if necessary. When the call reaches Aunt Ruth's phone company, it's relayed to her **5**. Meanwhile, the cellular carrier's computer monitors your location. As you approach a cell boundary **6** it seeks a channel for you at the tower you're nearing. At the appropriate moment, it switches your call to the new tower **7**. If the new tower lacks an available channel, your call is instead dropped, an indignity that plagued one in eight of our phone-owning readers.





Communication
Anywhere - Anytime



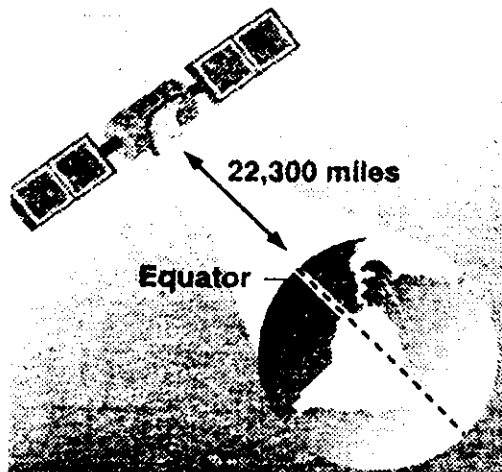


■ Figure 1. Universal mobile telecommunications system's operational scenario.

High Beams and Low

In a departure from traditional high-orbit satellite communications, a number of companies plan to use fleets of low-orbit craft instead. Here is how two of the most ambitious plans compare with older methods.

Traditional communications satellite in geostationary orbit



SATELLITES One or a few.

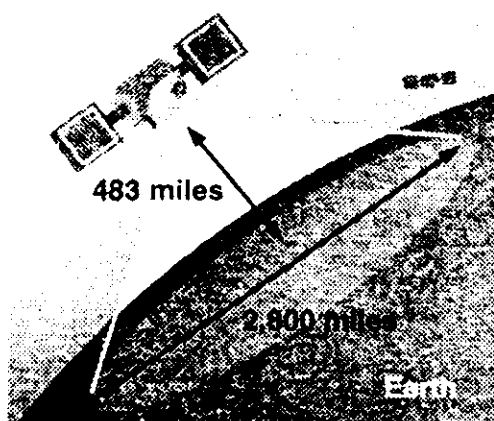
ORBIT High over the Equator, where the satellite is always over a single on Earth, a difficult and expensive orbit to achieve.

GROUND FOOTPRINT Huge; can communicate with ground stations in most of a hemisphere. Transmissions get through even if the satellite is very low in the sky.

POWER REQUIRED A lot is needed to cover the distances involved. That means bulky ground stations with big dish antennas, and big and expensive satellites.

SIGNAL CAPACITY Very broad. Can handle voice links or high-speed data and video signals up to broadcast-quality television.

Motorola's planned Iridium network of satellites



SATELLITES 66.

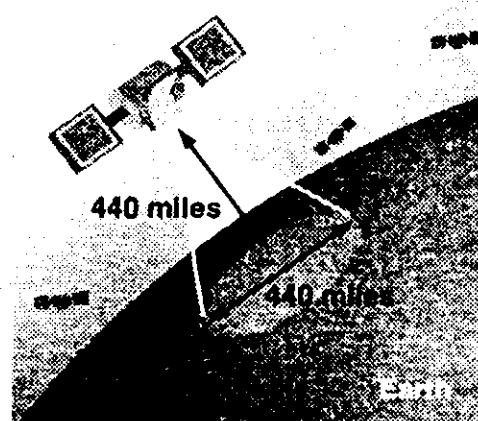
ORBIT Low orbit from pole to pole; 11 different routes with 6 satellites on each route; much cheaper to reach than high orbit.

GROUND FOOTPRINT Smaller; each satellite covers an area 2,800 miles across and need not be high in the sky for transmissions to get through.

POWER REQUIRED Not much. Ground stations can be as compact and as mobile as cellular phones; satellites can be as small as a phone booth.

SIGNAL CAPACITY Narrow. Meant to handle simple voice and data links comparable in quality to a cellular phone call.

Teledesic's planned network of satellites



SATELLITES 840.

ORBIT Low polar orbit similar to Iridium; 21 different routes with 40 satellites along each route; 1 in 10 will be a spare.

GROUND FOOTPRINT Much smaller; each satellite covers an area 440 miles across and must be almost directly overhead for signals to get through reliably.

POWER REQUIRED Not much. Ground stations and satellites can be small. But unlike Iridium, the system will not allow users to move about while connected.

SIGNAL CAPACITY Broad. Meant to handle medium to high quality voice, data and video signals, though not broadcast-quality TV.

Sources: Teledesic; Motorola.

Getting a Word In Edgewise

Interdigital Communications is pressing patent claims for a digital wireless communications technique called time-division multiple access, or T.D.M.A. The technique is competing with another approach — code-division multiple access, or C.D.M.A. — to be the preferred technology for new types of cellular telephone networks and other wireless communications.

Conversations:

- A "You know how to whistle, don't you, Steve?"
- B **"The rich are different from you and me."**
- C *"Frankly, my dear, I don't give a damn."*

METHOD 1: TIME-DIVISION MULTIPLE ACCESS

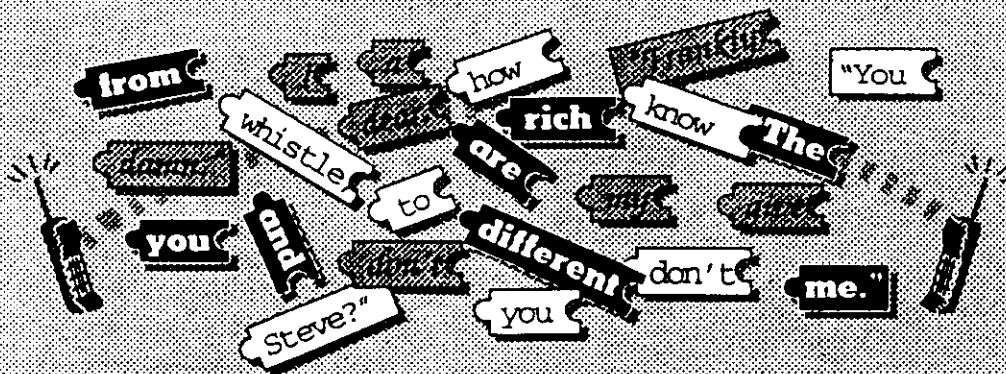
Three or four conversations can be condensed into one channel by transmitting fragments at precisely timed bursts.



SUPPORTED BY THE FOLLOWING CELLULAR COMPANIES McCaw Cellular Communications (AT&T), SBC Communications and BellSouth.

METHOD 2: CODE-DIVISION MULTIPLE ACCESS

Each conversation is coded with unique identifiers. Fragments can be sent haphazardly, and reassembled at the receiving end. This method allows as many as 20 conversations to fit in one channel.



SUPPORTED BY U.S. West, Air Touch Communications, Ameritech, Bell Atlantic, Sprint Cellular, Nynex and GTE.

