Cox, D.C. “Wireless Personal Communications: A Perspective”
Mobile Communications Handbook
Ed. Suthan S. Suthersan
Boca Raton: CRC Press LLC, 1999

Wireless Personal Communications: A Perspective

Donald C. Cox
Stanford University

{ This chapter has been updated using { } as indicators of inserts into the text of the original chapter of the same title that appeared in the first edition of this Handbook in 1996. }

15.1 Introduction

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. { The explosive growth of wireless personal communications has continued unabated worldwide. Cellular and high-tier PCS pocketphones, pagers, and cordless telephones have become so common in many countries that few people even notice them anymore. These items have become an expected part of everyday life in most developed countries and in many developing countries around the world. }

If you look carefully at the seemingly endless discussions of the topic, however, you cannot help but note that they are often describing different things, i.e., different versions of wireless personal communications [29, 50]. Some discuss pagers, or messaging, or data systems, or access to the national information infrastructure, whereas others emphasize cellular radio, or cordless telephones, or dense systems of satellites. Many make reference to popular fiction entities such as Dick Tracy, Maxwell Smart, or *Star Trek*. { In addition to the things noted above, the topic of wireless loops [24], [30], [32] has also become popular in the widespread discussions of wireless communications. As discussed in [30], this topic includes several fixed wireless applications as well as the low-tier PCS application that was discussed originally under the wireless loop designation [24, 32]. The fixed wireless applications are aimed at reducing the cost of wireline loop-ends, i.e., the so-called "last mile" or "last km" of wireline telecommunications. }

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 [29, 30, 50]. 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 constituent 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. { The fixed wireless loop applications noted earlier do not fit the new mobile communications paradigm. After many years of decline of fixed wireless communications applications, e.g., intercontinental HF radio and later satellites, point-to-point terrestrial microwave radio, and tropospheric scatter, it is interesting to see this rebirth of interest in fixed wireless applications. This rebirth is riding on the gigantic "wireless wave" resulting from the rapid public acceptance of mobile wireless communications. It will be interesting to observe this rebirth to see if communications history repeats; certainly mobility is wireless, but there is also considerable historical evidence that wireless is also mobility. }

This chapter 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 to yield some indication of where they appear to be going in the future. Like any attempt to categorize many complex interrelated issues, however, there are some that do not quite fit into neat categories, and 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.

15.2 Background and Issues

15.2.1 Mobility and Freedom from Tethers

Perhaps the clearest constituents 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% 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 airlines have also become commonplace. Similar or even greater growth in these wireless technologies has been experienced throughout the world. { The explosive growth in cellular and its identical companion, high-tier PCS, has continued to about 55 million subscribers in the U.S. at year-end 1997 and a similar number worldwide. In Sweden the penetration of cellular subscribers by 1997 was over one-third of the total population, i.e., the total including every man, woman, and child! And the growth has continued since. Similar penetrations of mobile wireless services are seen in some other developed nations, e.g., Japan. The growth in users of cordless telephones also has continued to the point that they have become the dominant subscriber terminal on wireline telephone loops in the U.S. It would appear that, taking into account cordless telephones and cellular and high-tier PCS phones, half of all telephone calls in the U.S. terminate with at least one end on a wireless device. }

{ Perhaps the most significant event in wireless personal communications since the writing of this original chapter was the widespread deployment and start of commercial service of personal handphone (PHS) in Japan in July of 1995 and its very rapid early acceptance by the consumer market [53]. By year-end 1996 there were 5 million PHS subscribers in Japan with the growth rate exceeding one-half million/month for some months. The PHS "phenomena" was one of the fastest adoptions of a new technology ever experienced. However, the PHS success story [41] peaked at a little over 7 million subscribers in 1997 and has declined slightly to a little under 7 million in mid-1998. This was the first mass deployment of a low-tier-like PCS technology (see later sections of this chapter), but PHS has some significant limitations. Perhaps the most significant limitation is the inability to successfully handoff at vehicular speeds. This handoff limitation is a result of the cumbersome radio link structure and control algorithms used to implement dynamic channel allocation (DCA) in PHS. DCA significantly increases channel occupancy (base station capacity) but incurs considerable complexity in implementing handoff. Another significant limitation of the PHS standard has been insufficient receiver sensitivity to permit "adequate" coverage from a "reasonably" dense deployment of base stations. These technology deficiencies coupled with heavy price cutting by the cellular service providers to compete with the rapid advancing of the PHS market were significant contributors to the leveling out of PHS growth. It is again evident, as with CT-2 phone point discussed in a later section, that low-tier PCS has very attractive features that can attract many subscribers, but it must also provide vehicle speed handoff and widespread coverage of highways as well as populated regions.

Others might point out the deployment and start of service of CDMA systems as a significant event since the first edition. However, the major significance of this CDMA activity is that it confirmed that CDMA performance was no better than other less-complex technologies and that those, including this author, who had been branded as "unbelieving skeptics" were correct in their assessments of the shortcomings of this technology. The overwhelming failure of CDMA technology to live up to the early claims for it can hardly be seen as a significant positive event in the evolution of wireless communication. It was, of course, a significant negative event. After years of struggling with the problems of this technology, service providers still have significantly fewer subscribers on CDMA worldwide than there are PHS subscribers in Japan alone! CDMA issues are discussed more in later sections dealing with technology issues. }

Paging and associated messaging, although not providing two-way voice, do provide a form of tetherless mobile communications to many subscribers worldwide. These services have also experienced significant growth { and have continued to grow since 1996. } 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. { Wireless data technologies still have many supporters, but they still have fallen far short of the rapid deployment and growth of the more voice oriented wireless technologies. However, hope appears to be eternal in the wireless data arena. }

The topics discussed in the preceding 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 the following.

Messaging is 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 are 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 are 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. { The rapid growth of the worldwide web is based on this mode of communications. }

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 1) user location, which can be differentiated by indoors or outdoors, or on an airplane or a train and 2) degree of mobility, which can be differentiated either by speed, e.g., vehicular, pedestrian, or stationary, or by size of area throughout which communications are provided. { As noted earlier, wireless local loop with stationary terminals has become a major segment in the pursuit of wireless technology. }

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, (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.

15.3 Evolution of Technologies, Systems, and Services

Technologies and systems [27, 29, 30, 39, 50, 59, 67, 87], that are currently providing, or are proposed to provide, wireless communications services can be grouped into about seven relatively distinct groups, { the seven previous groups are still evident in the technology but with the addition of the fixed point-to-multipoint wireless loops there are now eight, } although there may be some disagreement on the group definitions, and in what group some particular technology or system belongs. All 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.

15.3.1 Cordless Telephones

Cordless telephones [29, 39, 50] 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]

{ Personal handyphone (PHS) noted earlier and discussed in later sections and inserts can be considered either as a quite advanced digital cordless telephone similar to DECT or as a somewhat limited low-tier PCS technology. It has most of the attributes of similarity of the digital cordless telephones listed later in this section except that PHS uses $\pi/4$ QPSK modulation. }

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 the following.

- Few users per megahertz
- 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 [29, 50].

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. { CT-2+ deployment was never completed. } Phone-point service was introduced in the United Kingdom twice, but failed to attract enough customers to become a viable service. In Singapore and Hong Kong, however, CT-2 phone point has grown rapidly, reaching over 150,000 subscribers in Hong Kong [75] in mid-1994. The reasons for 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

[1]These ISM technologies either use spread spectrum techniques (direct sequence or frequency hopping) or very low-transmitter power ($<\sim$ 1 mW) as required by the ISM band regulations.

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). { CT-2 phone points in Hong Kong peaked at about 170,000 subscribers. There was then a precipitous decline as these subscribers abandoned the limited service CT-2 in favor of high-tier PCS and cellular services which had reduced their prices to compete with phone points. Phone points have now been removed from Hong Kong. CT-2 phone points were also deployed in Korea, again with initial success followed by decline. The message is clear from the CT-2 and PHS experiences. The attributes of cordless phone-like low-tier PCS are very attractive, but need widespread coverage and vehicle speed handoff in order to be long term attractive and viable in the market. }

Another European evolution of cordless telephones is 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.
{ DECT has increased in deployment in some countries, notably Italy, for several applications including cordless telephone and wireless loop. There are reported to be perhaps 7 million or more DECT users in Europe. }

These cordless telephone evolutions to more widespread usage outside and inside with telepoints and to usage inside large buildings are illustrated in Fig. 15.1, 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.

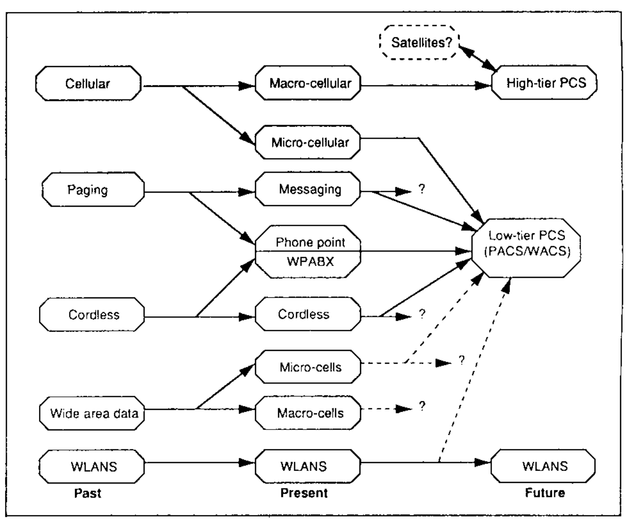

FIGURE 15.1:

Some of the characteristics of the digital cordless telephone technologies, CT-2 and DECT, are listed in Table 15.1. Additional information can be found in [32, 50]. Even though there are significant differences between these technologies, e.g., multiple access technology [frequency division multiple access (FDMA) or time division multiple access (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 $\leq$ 10 mW: This permits many hours of talk time with small, low-cost, lightweight batteries, but provides limited radio range.

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 Noncoherent Detection: Although still being low in complexity, the slightly more complex 4QPSK modulation with coherent detection provides significantly more spectrum efficiency, range, and interference immunity.

Dynamic Channel Allocation: Although 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 [15, 19].

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. Unless all base station transmissions are synchronized in time, however, it can incur severe cochannel interference penalties in outside environments [15, 16]. 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.

15.3.2 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 [20]. 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 [27, 29, 50]. 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 [29, 39, 50, 82], and generally uses transmitter power on the order of 100 times that of cordless telephones ($\approx$ 2 W for cellular). Thus, cellular systems can only provide reduced service to handheld sets that are disadvantaged by using somewhat lower transmitter power ($<$ 0.5 W) 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

TABLE 15.1 Wireless PCS Technologies

	High-Power Systems				Low-Power Systems			
	Digital Cellular (High-Tier PCS)				Low-Tier PCS		Digital Cordless	
System	IS-54	IS-95 (DS)	GSM	DCS-1800	WACS/PACS	Handi-Phone	DECT	CT-2
Multiple Access	TDMA/ FDMA	CDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	FDMA
Freq. band, MHz Uplink, MHz Downlink, MHz	 869–894 824–849 (USA)	 869–894 824–849 (USA)	 935–960 890–915 (Eur.)	 1710–1785 1805–1880 (UK)	 Emerg. Tech.* (USA)	1895–1907 (Japan)	1880–1990 (Eur.)	864–868 (Eur. and Asia)
RF ch. spacing Downlink, KHz Uplink, KHz	 30 30	 1250 1250	 200 200	 200 200	 300 300	300	1728	100
Modulation	$\pi/4$ DQPSK	BPSK/QPSK	GMSK	GMSK	$\pi/4$ QPSK	$\pi/4$ DQPSK	GFSK	GFSK
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	VSELP	QCELP	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	1
Ch. Bit rate, kb/s Uplink, kb/s Downlink, kb/s	 48.6 48.6		 270.833 270.833	 270.833 270.833	 384 384	384	1152	72
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 1.85–2.2 GHz allocated by the FCC for emerging technologies; DS is direct sequence.

limitations on usage of handheld sets already noted, 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 and high-tier PCS pocket handsets have continued to decrease in size and weight and more efficient lithium batteries have been incorporated. This has increased their attractiveness (more on this in the later section "Reality Check"). For several years there have been many more pocket handsets sold than vehicular mounted sets every year. However, despite the improvements in these handsets and batteries, the complaints of weight and limited talk time still persist. The electronics have become essentially weightless compared to the batteries required for these high-tier PCS and cellular handsets. }

Cellular radio at 800 MHz has evolved to digital radio technologies [29, 39, 50] 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. { Since the first edition was published, CDMA systems have been deployed in the U.S., Korea, Hong Kong, and other countries after many months (years) of redesign, reprogramming, and adjustment. These CDMA issues are discussed later in the section "New Technology." }

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 megahertz and to 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 two just cited parameters are as follows.

- High transmitter power consumption.
- High user-set complexity, and thus high signal-processing power consumption.
- Low circuit quality.
- 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. 15.1, 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 15.1 for IS-54, IS-95, and GSM at 900 MHz, and DCS-1800, which is GSM at 1800 MHz. { The technology listed here as IS-54 has also become known as IS-136 having more sophisticated digital control channels. These technologies, IS-54/IS-136 are also sometimes known as DAMPS (i.e., Digital AMPS), as U.S. TDMA or North American TDMA, or sometimes just as "TDMA." } Additional information can be found in [29, 39, 50]. 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. There are also many similarities, however, that are fundamental to the design objectives discussed earlier. These similarities and their implications are as follows.

Low Bit-Rate Speech Coding $\leq$13 kb/s with Some $\leq$8 kb/s: Low bit-rate speech coding obviously increases the number of users per megahertz and per cell site. However, it also significantly reduces speech quality [29], and does not permit speech encodings in tandem while traversing a network; see also the section on Other Issues later in this chapter.

Some Implementations Make Use of Speech Inactivity: This further increases the number of users per cell site, i.e., the cell-site capacity. It also further reduces speech quality [29], however, 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; $\approx$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 code division multiple access (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 [29]. 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; see also the section on Complexity/Coverage Area Comparisons later in this chapter.

Fixed Channel Allocation: The difficulties associated with implementing capacity-increasing dynamic channel allocation to work with handoff [15, 19] 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 [15, 16] 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 cochannel interference and reduced battery drain have been sought by incorporating power control in the digital cellular technologies.

15.3.3 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 [29, 50]. 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 15.2.

TABLE 15.2 Wide-Area Wireless Packet Data Systems

	CDPD[1]	RAM Mobile (Mobitex)	ARDIS[2] (KDT)	Metricom (MDN)[3]
Data rate, kb/s	19.2	8 (19.2)	4.8 (19.2)	76
Modulation	GMSK BT = 0.5	GMSK	GMSK	GMSK
Frequency, MHz	800	900	800	915
Chan. spacing, kHz	30	12.5	25	160
Status	1994 service	Full service	Full service	In service
Access means	Unused AMPS channels	Slotted Aloha CSMA		FH SS (ISM)
Transmit power, W			40	1

Note: Data in parentheses ( ) indicates proposed.
[1]Cellular Digital Packet Data
[2]Advanced Radio Data Information Service
[3]Microcellular Data Network

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- 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 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. { CDPD has been deployed in many U.S. cities for several years. However, it has not lived up to early expectations and has become "just another" wireless data service with some subscribers, but not with the large growth envisioned earlier. }

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. 15.1. 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 distributions, 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. ISM band. Transmitter power is 1 W maximum, and power control is used to minimize interference and maximize battery life time. { The metricom network has been improved and significantly expanded in the San Francisco Bay Area and has been deployed in Washington, D.C. and a few other places in the U.S. However, like all wireless data services so far, it has failed to grow as rapidly or to attract as many subscribers as was originally expected. Wireless data overall has had only very limited success compared to that of the more voice-oriented technologies, systems, and services. }

15.3.4 High-Speed Wireless Local-Area Networks (WLANs)

Wireless local-area data networks can be categorized as providing low-mobility high-data-rate 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 [29, 59]. 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 somewhat limited. A partial list of some advertised products is given in Table 15.3. 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. { This section still describes the WLAN situation in spite of some attempts at standards in the U.S. and Europe, and continuing industry efforts. Some of the products in Table 15.3 have been discontinued because of lack of market and some new products have been offered, but the manufacturers still continue to struggle to find enough customers to support their efforts. Optimism remains high in the WLAN community that “eventually” they will find the “right” technology, service, or application to make WLANs “take off” — but the world still waits. Success is still quite limited. }

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 [44].

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 902–928 MHz, 2400–2483.5 MHz, and 5725–5850 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. { It appears that ALTAIR has been discontinued because of the limited market. } The technical and economic challenges of operation at 18 GHz have hampered the adoption of this 10–15 Mb/s technology. The frequency-spectrum constraints have been improved in the United States with the recent FCC allocation of spectrum from 1910–1930 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 [68]. Also, since spread spectrum is not a requirement, access technologies and multipath mitigation techniques more compatible with the needs of packet-data transmission [59], e.g., multipath equalization or multicarrier transmission can be incorporated into new WLAN designs. { The FCC is allocating spectrum at 5 GHz for wideband wireless data for internet and next generation data network access, BUT it remains to be seen whether this initiative is any more successful than past wireless data attempts. Optimism is again high, BUT... }

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 adoption 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. { It should be noted that the objective for 10 MB/s data service with widespread coverage from a sparse distribution of widely separated base stations equivalent to cellular is unrealistic and unrealizable. This can be readily seen by considering a simple example. Consider a cellular coverage area that requires full cellular power of 0.5 watt to cover from a handset. Consider the handset to use a typical digital cellular bit rate of about 10 kb/s (perhaps 8 kb/s speech coding + overhead). With all else in the system the same, e.g., antennas, antenna height, receiver noise figure, detection sensitivity, etc., the 10 MB/s data would require 10 MB/s $\div$ 10 kb/s

TABLE 15.3 Partial List of WLAN Products

Product Company Location	Freq., MHz	Link Rate, Mb/s	User Rate	Protocol(s)	Access	No. of chan. or Spread Factor	Mod./ Coding	Power, mW	Network Topology
Altair Plus Motorola Arlington Hts, IL	18–19 GHz	15	5.7 Mb/s	Ethernet			4-level FSK	25 peak	Eight devices/ radio; radio to base to ethernet
WaveLAN NCR/AT&T Dayton, OH	902–928	2	1.6 Mb/s	Ethernet-like	DS SS		DQPSK	250	Peer-to-peer
AirLan Solectek San Diego, CA	902–928		2 Mb/s	Ethernet	DS SS		DQPSK	250	PCMCIA w/ant.; radio to hub
Freeport Windata Inc. Northboro, MA	902–928	16	5.7 Mb/s	Ethernet	DS SS	32 chips/bit	16 PSK trellis coding	650	Hub
Intersect Persoft Inc. Madison, WI	902–928		2 Mb/s	Ethernet token ring	DS SS		DQPSK	250	Hub
LAWN O’Neill Comm. Horsham, PA	902–928		38.4 kb/s	AX.25	SS	20 users/chan.; max. 4 chan.		20	Peer-to-peer
WILAN Wi-LAN Inc. Calgary, Alberta	902–928	20	1.5 Mb/s/ chan.	Ethernet, token ring	CDMA/ TDMA	3 chan. 10–15 links each	unconven- tional	30	Peer-to-peer
RadioPort ALPS Electric USA	902–928		242 kb/s	Ethernet	SS	7/3 channels		100	Peer-to-peer
ArLAN 600 Telesys. SLW Don Mills, Ont.	902–928; 2.4 GHz		1.35 Mb/s	Ethernet	SS			1 W max	PCs with ant.; radio to hub
Radio Link Cal. Microwave Sunnyvale, CA	902–928; 2.4 GHz	250 kb/s	64 kb/s		FH SS	250 ms/hop 500 kHz space			Hub
Range LAN Proxim, Inc. Mountain View, CA	902–928		242 kb/s	Ethernet, token ring	DS SS	3 chan.		100	
RangeLAN 2 Proxim, Inc. Mountain View, CA	2.4 GHz	1.6	50 kb/s max.	Ethernet, token ring	FH SS	10 chan. at 5 kb/s; 15 sub-ch. each		100	Peer-to-peer bridge
Netwave Xircom Calabasas, CA	2.4 GHz	1/adaptor		Ethernet, token ring	FH SS	82 1-MHz chn. 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	Hub

$=1000$ times as much power as the 10 kb/s cellular. Thus, it would require $0.5 \times 1000 = 500$ watts for the wireless data transmitter. This is a totally unrealistic situation. If the data system operates at a higher frequency (e.g., 5 GHz) than the cellular system (e.g., 1 or 2 GHz) then there will be even more power required to overcome the additional loss at a higher frequency. The sometimes expressed desire by the wireless data community for a system to provide network access to users in and around buildings and to provide 10 MB/s over 10 miles with 10 milliwatts of transmitter power and costing $10.00 is totally impossible. It requires violation of the "laws of physics." }

15.3.5 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 1-b 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. 15.1.

The region over which a page is transmitted has also increased from 1) local, around one transmitting antenna; to 2) regional, from multiple widely-dispersed antennas; to 3) 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. This is an ambiguous and unrealizable concept, however, 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 of 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. { The two-way paging situation is as unrealistic as that noted earlier for wide-area, high-speed, low-power wireless data. This can be seen by looking at the asymmetry situation in paging. In order to achieve comparable coverage uplink and downlink, a 500-watt paging transmitter downlink advantage must be overcome in the uplink. Even considering the relatively high cellular handset transmit power levels on the order of 0.5 watt results in a factor of 1000 disadvantage, and 0.5 watt is completely incompatible with the low power paging receiver power requirements. If the same uplink and downlink coverage is required for an equivalent set of system parameters, then the only variable left to work with is bandwidth. If the paging link bit rate is taken to be 10 kb/sec (much higher than many paging systems), then the usable uplink rate is 10 kb/s/1000 $=$ 10 B/s, an unusably low rate. Of course, some uplink benefit can be gained because of better base station receiver noise figure and by using forward error correction and perhaps ARQ. However, this is unlikely to raise the allowable rate to greater than 100 B/s which even though likely overoptimistic is still unrealistically low and we have assumed an unrealistically high transmit power in the two-way "pager!" }

15.3.6 Satellite-Based Mobile Systems

Satellite-based mobile 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 Omnitracs system.

A few large-scale mobile satellite systems have been proposed and are being pursued: perhaps the best known is Motorola's Iridium; 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. { Some of the mobile satellite systems have been withdrawn, e.g., Odyssey. Some satellites in the Iridium and Globalstar systems have been launched. The industry will soon find out whether these systems are economically viable. }

Proposed satellite systems range from 1) low-Earth-orbit systems (LEOS) having tens to hundreds of satellites through 2) intermediate- or medium-height systems (MEOS) to 3) 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 s. Of course, MEOS fall in between these extremes. The possible evolution of satellite systems to complement high-tier PCS is indicated in Fig. 15.1.

15.3.7 {Fixed Point-to-Multipoint Wireless Loops

Wideband point-to-multipoint wireless loop technologies sometimes have been referred to earlier as "wireless cable" when they were proposed as an approach for providing interactive video services to homes [30]. However, as the video application started to appear less attractive, the application emphasis shifted to providing wideband data access for the internet, the worldwide web, and future wideband data networks. Potentially lower costs are the motivation for this wireless application. As such, these technologies will have to compete with existing coaxial cable and fiber/coax distribution by CATV companies, with satellites, and with fiber and fiber/coax systems being installed or proposed by telephone companies and other entities [30]. Another competitor is asymmetric digital subscriber line technology, which uses advanced digital signal processing to provide high-bandwidth digital distribution over twisted copper wire pairs.

In the U.S. two widely different frequency bands are being pursued for fixed point-to-multipoint wireless loops. These bands are at 28 GHz for local multipoint distribution systems or services (LMDS) [52] and 2.5 to 2.7 GHz for microwave or metropolitan distribution systems (MMDS) [74]. The goal of low-cost fixed wireless loops is based on the low cost of point-to-multipoint line-of-sight wireless technology. However, significant challenges are presented by the inevitable blockage by trees, terrain, and houses, and by buildings in heavily built-up residential areas. Attenuation in rainstorms presents an additional problem at 28 GHz in some localities. Even at the 2.5-GHz MMDS frequencies, the large bandwidth required for distribution of many video channels presents a challenge to provide adequate radio-link margin over obstructed paths. From mobile satellite investigations it is known that trees can often produce over 15 dB additional path attenuation [38]. Studies of blockage by buildings in cities have shown that it is difficult to have line-of-sight access to more than 60% of the buildings from a single base station [55]. Measurements in a region in Brooklyn, NY [60], suggest that access from a single base station can range from 25% to 85% for subscriber antenna heights of 10 to 35 ft and a base station height of about 290 ft. While less blockage by houses could be expected in residential areas, such numbers would suggest that greater than 90% access to houses could be difficult, even from multiple elevated locations, when mixes of one- and two-story houses, trees, and hills are present. In regions where tree cover is heavy, e.g., the eastern half of the U.S., tree cover in many places will present a significant obstacle. Heavy rainfall is an additional problem at 28 GHz in some regions. In spite of these challenges, the lure of low-cost wireless loops is attracting many participants, both service providers and equipment manufacturers. }

15.3.8 Reality Check

Before we go on to consider other applications and compromises, perhaps it would be helpful to see if there is any indication that the previous discussion is valid. For this check, we could look at cordless telephones for telepoint use (i.e., pocketphones) and at pocket cellular telephones that existed in the 1993 time frame.

Two products from one United States manufacturer are good for this comparison. One is a third-generation hand-portable analog FM cellular phone from this manufacturer that represents their second generation of pocketphones. The other is a first-generation digital cordless phone built to the United Kingdom CT-2 common air interface (CAI) standard. Both units are of flip phone type with the earpiece on the main handset body and the mouthpiece formed by or on the flip-down part. Both operate near 900 MHz and have 1/4 wavelength pull-out antennas. Both are fully functional within their class of operation (i.e., full number of U.S. cellular channels, full number of CT-2 channels, automatic channel setup, etc.) Table 15.4 compares characteristics of these two wireless access pocketphones from the same manufacturer.

The following are the most important items to note in the Table 15.4 comparison.

1. The talk time of the low-power pocketphone is four times that of the high-power pocketphone.
2. The battery inside the low-power pocketphone is about one-half the weight and size of the battery attached to the high-power pocketphone.
3. The battery-usage ratio, talk time/weight of battery, is eight times greater, almost an order of magnitude, for the low-power pocketphone compared to the high-power pocketphone!
4. Additionally, the lower power (5 mW) digital cordless pocketphone is slightly smaller and lighter than the high-power (500 mW) analog FM cellular mobile pocketphone.

{ Similar comparisons can be made between PHS advanced cordless/low-tier PCS phones and advanced cellular/high-tier PCS pocketphones. New lithium batteries have permitted increased talk

TABLE 15.4 Comparison of CT-2 and Cellular Pocket Size Flip-Phones from the Same Manufacturer

Characteristics/Parameter	CT-2	Cellular
Weight, oz		
Flip phone only	5.2	4.2
Battery[1] only	1.9	3.6
Total unit	7.1	7.8
Size (max.dimensions), in		
Flip phone only	5.9 × 2.2 × 0.95	5.5 × 2.4 × 0.9
	8.5 in^3	—
Battery[1] only	1.9 × 1.3 × 0.5 internal	4.7 × 2.3 × 0.4 external
Total unit	5.9 × 2.2 × 0.95 8.5 in^3	5.9 × 2.4 × 1.1 11.6 in^3
Talk-time, min (h)		
Rechargeable battery[2]	180 (3)	45
Nonrechargeable battery	600 (10)	N/A
Standby time, h		
Rechargeable battery	30	8
Nonrechargeable battery	100	N/A
Speech quality	32 kb/s telephone quality	30 kHz FM depends on channel quality
Transmit power avg., W	0.005	0.5

[1] Rechargeable battery.
[2] Ni-cad battery.

time in pocketphones. Digital control/paging channels facilitate significantly extended standby time. Advances in solid-state circuits have reduced the size and weight of cellular pocketphone electronics so that they are almost insignificant compared to the battery required for the high power transmitter and complex digital signal processing. However, even with all these changes, there is still a very significant weight and talk time benefit in the low complexity PHS handsets compared to the most advanced cellular/high-tier PCS handsets. Picking typical minimum size and weight handsets for both technologies results in the following comparisons.

	PHS	Cellular
weight, oz		
total unit	3	4.5
size		
total unit	4.2 in^3	—
talk-time, h	8	3
standby time, h	600	48

From the table, the battery usage ratio has been reduced to a factor of about 4 from a factor of 8, but this is based on total weight, not battery weight alone as used for the earlier CT-2 and cellular comparison.

Thus, there is still a large talk time and weight benefit for low-power low-complexity low-tier PCS compared to higher power high-complexity, high tier PCS and cellular. }

The following should also be noted.

1. The room for technology improvement of the CT-2 cordless phone is greater since it is first generation and the cellular phone is second/third generation.

2. A digital cellular phone built to the IS-54, GSM, or JDC standard, or in the proposed United States CDMA technology, would either have less talk time or be heavier and larger than the analog FM phone, because: a) the low-bit-rate digital speech coder is more complex and will consume more power than the analog speech processing circuits; b) the digital units have complex digital signal-processing circuits for forward error correction—either for delay dispersion equalizing or for spread-spectrum processing—that will consume significant amounts of power and that have no equivalents in the analog FM unit; and c) power amplifiers for the shaped-pulse nonconstant-envelope digital signals will be less efficient than the amplifiers for constant-envelope analog FM. Although it may be suggested that transmitter power control will reduce the weight and size of a CDMA handset and battery, if that handset is to be capable of operating at full power in fringe areas, it will have to have capabilities similar to other cellular sets. Similar power control applied to a CT-2-like low-maximum-power set would also reduce its power consumption and thus also its weight and size.

The major difference in size, weight, and talk time between the two pocketphones is directly attributable to the two orders of magnitude difference in average transmitter power. The generation of transmitter power dominates power consumption in the analog cellular phone. Power consumption in the digital CT-2 phone is more evenly divided between transmitter-power generation and digital signal processing. Therefore, power consumption in complex digital signal processing would have more impact on talk time in small low-power personal communicators than in cellular handsets where the transmitter-power generation is so large. Other than reducing power consumption for both functions, the only alternative for increasing talk time and reducing battery weight is to invent new battery technology having greater density; see section on Other Issues later in this chapter.

In contrast, lowering the transmitter power requirement, modestly applying digital signal processing, and shifting some of the radio coverage burden to a higher density of small, low-power, low-complexity, low-cost fixed radio ports has the effect of shifting some of the talk time, weight, and cost constraints from battery technology to solid state electronics technology, which continues to experience orders-of-magnitude improvements in the span of several years. Digital signal-processing complexity, however, cannot be permitted to overwhelm power consumption in low-power handsets; whereas small differences in complexity will not matter much, orders-of-magnitude differences in complexity will continue to be significant.

Thus, it can be seen from Table 15.4 that the size, weight, and quality arguments in the preceding sections generally hold for these examples. It also is evident from the preceding paragraphs that they will be even more notable when comparing digital cordless pocketphones with digital cellular pocketphones of the same development generations.

15.4 Evolution Toward the Future and to Low-Tier Personal Communications Services

After looking at the evolution of several wireless technologies and systems in the preceding sections it appears appropriate to ask again: wireless personal communications, What is it? All of the technologies in the preceding sections claim to provide wireless personal communications, and all do to some extent. All have significant limitations, however, 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 preceding 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 handoff; limited range.

{ Experience with PHS and CT-2 phone point have provided more emphasis on the need for vehicle speed handoff and continuous widespread coverage of populated areas and of highways in between. }

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 of 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.

{Fixed Wireless Loops

- Strength: High data rates.
- Limitations: no mobility. }

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. { It has become evident from the experience with PHS and CT-2 phone point that vehicle speed handoff is essential so that handsets can be used in vehicles also. }

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. 15.1 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.

1. 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.
2. Flexible radio link architecture that will support multiple data rates from several kilobits per second. 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.
3. Low transmitter power ($\leq$ 25 mW average) with adaptive power control to maximize talk time and data transmission time. This incurs short radio range that 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. { The lower power will require somewhat closer spacing of base stations in cluttered environments with many buildings, etc. This issue is dealt with in more detail in Section 15.5. The issues associated with greater base station spacing along highways are also considered in Section 15.5. }
4. Low-complexity signal processing to minimize power consumption. Complexity one-tenth that of digital cellular or high-tier PCS technologies is required [29]. With only

several tens of milliwatts (or less under power control) required for transmitter power, signal processing power becomes significant.

5. Low cochannel interference and high coverage area design criteria. In order to provide high-quality service over a large region, at least 99% of any covered area must receive good or better coverage and be below acceptable cochannel interference limits. This implies less than 1% of a region will receive marginal service. This is an order-of-magnitude higher service requirement than the 10% of a region permitted to receive marginal service in vehicular cellular system (high-tier PCS) design criteria.
6. Four-level phase modulation with coherent detection to maximize radio link performance and capacity with low complexity.
7. Frequency division duplexing to relax the requirement for synchronizing base station transmissions over a large region. { PHS uses time division duplexing and requires base station synchronization. In first deployments, one provider did not implement this synchronization. The expected serious performance degradation prompted system upgrades to provide the needed synchronization. While this is not a big issue, it does add complexity to the system and decreases the overall robustness. }
8. { As noted previously, experience with PHS and CT-2 phone point have emphasized the need for vehicular speed handoff in these low-tier PCS systems. Such handoff is readily implemented in PACS and has been demonstrated in the field [51]. This issue is discussed in more detail later in this section. }

Such technologies and systems have been designed, prototyped, and laboratory and field tested and evaluated for several years [7, 23, 24, 25, 26, 27, 28, 29, 31, 32, 50]. 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 [20]. Essentially all of the technologies and systems listed in Table 15.1, and some others, were submitted in late 1993. It was evident that there were at least two and perhaps three distinctly 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 15.1. These are the technologies discussed previously in this chapter. 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 already described for low-tier PCS may not be optimum for such services, Fig. 15.1 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 [20] included the Japanese personal handyphone 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 systems (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 Handyphone (PHS) are shown in Table 15.1 as low-tier PCS and represent the evolution to low-tier PCS in Fig. 15.1. The WACS/PACS/ UDPC system and technology are discussed in [7, 23, 24, 25, 26, 28, 29, 31, 32, 50].

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 15.1. 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. 15.1. The figure also recognizes that widespread low-tier PCS can support data at several hundred kilobits per second 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 question mark in Fig. 15.1.

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 in Fig. 15.1 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 of 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.

{ PACS technology [6] has been prototyped by several manufacturers. In 1995 field demonstrations were run in Boulder, CO at a U.S. West test site using radio ports (base stations) and radio port control units made by NEC. "Handset" prototypes made by Motorola and Panasonic were trialed. The handsets and ports were brought together for the first time in Boulder. The highly successful trial demonstrated the ease of integrating the subsystems of the low-complexity PACS technology and the overall advantages of PACS from a user's perspective as noted throughout this chapter. Effective vehicular speed operation was demonstrated in these tests. Also, Hughes Network Systems (HNS) has developed and tested many sets of PACS infrastructure technology with different handsets in several settings and has many times demonstrated highly reliable high vehicular speed (in excess of 70 mi/hr) operation and handoff among several radio ports. Motorola also has demonstrated PACS equipment in several settings at vehicular speeds as well as for wireless loop applications. Highly successful demonstrations of PACS prototypes have been conducted from Alaska to Florida, from New York to California, and in China and elsewhere.

A PACS deployment in China using NEC equipment started to provide service in 1998. The U.S.

---

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

Service Provider, 21st Century Telesis, is poised to begin a PACS deployment in several states in the U.S. using infrastructure equipment from HNS and handsets and switching equipment from different suppliers. Perhaps, with a little more support of these deployments, the public will finally be able to obtain the benefits of low-tier PCS. }

15.5 Comparisons with Other Technologies

15.5.1 Complexity/Coverage Area Comparisons

Experimental research prototypes of radio ports and subscriber sets [64, 66] have been constructed to demonstrate the technical feasibility of the radio link requirements in [7]. These WACS prototypes generally have the characteristics and parameters previously noted, with the exceptions that 1) the portable transmitter power is lower (10 mW average, 100 mW peak), 2) dynamic power control and automatic time slot transfer are not implemented, and 3) a rudimentary automatic link-transfer implementation is based only on received power. The experimental base stations transmit near 2.17 GHz; the experimental subscriber sets transmit near 2.12 GHz. Both operated under a Bellcore experimental license. The experimental prototypes incorporate application-specific, very large-scale integrated circuits[3] fabricated to demonstrate the feasibility of the low-complexity high-performance digital signal-processing techniques [63, 64] for symbol timing and coherent bit detection. These techniques permit the efficient short TDMA bursts having only 100 b that are necessary for low-delay TDMA implementations. Other digital signal-processing functions in the prototypes are implemented in programmable logic devices. All of the digital signal-processing functions combined require about 1/10 of the logic gates that are required for digital signal processing in vehicular digital cellular mobile implementations [42, 62, 63]; that is, this low-complexity PCS implementation having no delay-dispersion-compensating circuits and no forward error-correction decoding and is about 1/10 as complex as the digital cellular implementations that include these functions.[4] The 32 kb/s ADPCM speech-encoding in the low-complexity PCS implementation is also about 1/10 as complex as the less than 10-kb/s speech encoding used in digital cellular implementations. This significantly lower complexity will continue to translate into lower power consumption and cost. It is particularly important for low-power pocket personal communicators with power control in which the DC power expended for radio frequency transmitting can be only tens of milliwatts for significant lengths of time.

The experimental radio links have been tested in the laboratory for detection sensitivity [bit error rate (BER) vs SNR] [18, 61, 66] and for performance against cochannel interference [1] and intersymbol interference caused by multipath delay spread [66]. These laboratory tests confirm the performance of the radio-link techniques. In addition to the laboratory tests, qualitative tests have been made in several PCS environments to compare these experimental prototypes with several United States CT-1 cordless telephones at 50 MHz, with CT-2 cordless telephones at 900 MHz, and with DCT-900 cordless telephones at 900 MHz. Some of these comparisons have been reported [8, 71, 84, 85]. In general, depending on the criteria, e.g., either no degradation or limited degradation of circuit quality, these WACS experimental prototypes covered areas inside buildings that ranged from 1.4

[3] Applications specific integrated circuits (ASIC), very large-scale integration (VLSI).

[4] Some indication of VLSI complexity can be seen by the number of people required to design the circuits. For the low-complexity TDMA ASIC set, only one person part time plus a student part time were required; the complex CDMA ASIC has six authors on the paper alone.

to 4 times the areas covered by the other technologies. The coverage areas for the experimental prototypes were always substantially limited in two or three directions by the outside walls of the buildings. These area factors could be expected to be even larger if the coverage were not limited by walls, i.e., once all of a building is covered in one direction, no more area can be covered no matter what the radio link margin. The earlier comparisons [8, 84, 85] were made with only two-branch uplink diversity before subscriber-set transmitting antenna switching was implemented and, with only one radio port before automatic radio-link transfer was implemented. The later tests [71] included these implementations. These reported comparisons agree with similar unreported comparisons made in a Bellcore Laboratory building. Similar coverage comparison results have been noted for a 900-MHz ISM-band cordless telephone compared to the 2-GHz experimental prototype. The area coverage factors (e.g., $\times 1.4$ to $\times 4$) could be expected to be even greater if the cordless technologies had also been operated at 2 GHz since attenuation inside buildings between similar small antennas is about 7 dB greater at 2 GHz than at 900 MHz [35, 36] and the 900 MHz handsets transmitted only 3 dB less average power than the 2-GHz experimental prototypes. The greater area coverage demonstrated for this technology is expected because of the different compromises noted earlier; the following, in particular.

1. Coherent detection of QAM provides more detection sensitivity than noncoherent detection of frequency-shift modulations [17].
2. Antenna diversity mitigates bursts of errors from multipath fading [66].
3. Error detection and blanking of TDMA bursts having errors significantly improves perceived speech quality [72]. (Undetected errors in the most significant bit cause sharp audio pops that seriously degrade perceived speech quality.)
4. Robust symbol timing and burst and frame synchronization reduce the number of frames in error due to imperfect timing and synchronization [66].
5. Transmitting more power from the radio port compared to the subscriber set offsets the less sensitive subscriber set receiver compared to the port receiver that results from power and complexity compromises made in a portable set.

Of course, as expected, the low-power (10-mW) radio links cover less area than high-power (0.5-W) cellular mobile pocketphone radio links because of the 17-dB transmitter power difference resulting from the compromises discussed previously. In the case of vehicular mounted sets, even more radio-link advantage accrues to the mobile set because of the higher gain of vehicle-mounted antennas and higher transmitter power (3 W).

{ The power difference between a low-tier PACS handset and a high-tier PCS or cellular pocket handset is not as significant in limiting range as is often portrayed. Other differences in deployment scenarios for low-tier and high-tier systems are as large or even larger factors, e.g., base station antenna height and antenna gain. This can be seen by considering using the same antennas and receiver noise figures at base stations and looking at the range of high-tier and low-tier handsets. High-tier handsets typically transmit a maximum average power of 0.5 watt. The PACS handset average transmit power is 25 milliwatts (peak power is higher for TDMA, but equal comparisons can be made considering average power and equivalent receiver sensitivities). This power ratio of $\times 20$ translates to approximately a range reduction of a factor of about 0.5 for an environment with a distance dependence of $1/(d)^4$ or a factor of about 0.4 for a $1/(d)^{3.5}$ environment. These represent typical values of distance dependence for PCS and cellular environments. Thus, if the high-tier handset would provide a range of 5 miles in some environment, the low-tier handset would provide a range of 2 to 2.5 miles in the same environment, if the base station antennas and receiver noise figures were the same. This difference in range is no greater than the difference in range between high-tier PCS handsets used in 1.9 GHz systems and cellular handsets with the same power used in 800 MHz systems. Range factors are discussed further in the next section. }

15.5.2 {Coverage, Range, Speed, and Environments

Interest has been expressed in having greater range for low-tier PCS technology for low-population-density areas. One should first note that the range of a wireless link is highly dependent on the amount of clutter or obstructions in the environment in which it is operated. For example, radio link calculations that result in a 1400-ft base station (radio-port) separation at 1.9 GHz contain over 50-dB margin for shadowing from obstructions and multipath effects [25, 37]. Thus, in an environment without obstructions, e.g., along a highway, the base station separation can be increased at least by a factor of 4 to over a mile, i.e., 25 dB for an attenuation characteristic of d^{-4}, while providing the same quality of service, without any changes to the base station or subscriber transceivers, and while still allowing over 25-dB margin for multipath and some shadowing. This remaining margin allows for operation of a handset inside an automobile. In such an unobstructed environment, multipath RMS delay spread [21, 33] will still be less than the 0.5 μs in which PACS was designed to operate [28].

Operation at still greater range along unobstructed highways or at a range of a mile along more obstructed streets can be obtained in several ways. Additional link gain of 6 dB can be obtained by going from omnidirectional antennas at base stations to 90° sectored antennas (four sectors). Another 6 dB can be obtained by raising base station antennas by a factor of 2 from 27 ft to 55 ft in height. This additional 12 dB will allow another factor of 2 increase in range to 2-mile base station separation along highways, or to about 3000-ft separation in residential areas. Even higher-gain and taller antennas could be used to concentrate coverage along highways, particularly in rural areas. Of course, range could be further increased by increasing the power transmitted.

As the range of the low-tier PACS technology is extended in cluttered areas by increasing link gain, increased RMS delay spread is likely to be encountered. This will require increasing complexity in receivers. A factor of 2 in tolerance of delay spread can be obtained by interference-canceling signal combining [76, 77, 78, 79, 80] from two antennas instead of the simpler selection diversity combining originally used in PACS. This will provide adequate delay-spread tolerance for most suburban environments [21, 33].

The PACS downlink contains synchronization words that could be used to train a conventional delay-spread equalizer in subscriber set receivers. Constant-modulus (blind) equalization will provide greater tolerance to delay spread in base station receivers on the uplink [45, 46, 47, 48] than can be obtained by interference-cancellation combining from only two antennas. The use of more base-station antennas and receivers can also help mitigate uplink delay spread. Thus, with some added complexity, the low-tier PACS technology can work effectively in the RMS delay spreads expected in cluttered environments for base station separations of 2 miles or so.

The guard time in the PACS TDMA uplink is adequate for 1-mile range, i.e., 2-mile separation between base station and subscriber transceivers. A separation of up to 3 miles between transceivers could be allowed if some statistical outage were accepted for the few times when adjacent uplink timeslots are occupied by subscribers at the extremes of range (near–far). With some added complexity in assigning timeslots, the assignment of subscribers at very different ranges to adjacent timeslots could be avoided, and the base station separation could be increased to several miles without incurring adjacent slot interference. A simple alternative in low-density (rural) areas, where lower capacity could be acceptable and greater range could be desirable, would be to use every other timeslot to ensure adequate guard time for range differences of many tens of miles. Also, the capability of transmitter time advance has been added to PACS standard in order to increase the range of operation. Such time advance is applied in the cellular TDMA technologies.

The synchronization, carrier recovery, and detection in the low-complexity PACS transceivers will perform well at highway speeds. The two-receiver diversity used in uplink transceivers also will perform well at highway speeds. The performance of the single-receiver selection diversity used in the low-complexity PACS downlink transceivers begins to deteriorate at speeds above about 30 mi/h. However, at any speed, the performance is always at least as good as that of a single transceiver without the low-complexity diversity. Also, fading in the relatively uncluttered environment of a highway is likely to have a less severe Ricean distribution, so diversity will be less needed for mitigating the fading. Cellular handsets do not have diversity. Of course, more complex two-receiver diversity could be added to downlink transceivers to provide two-branch diversity performance at highway speeds. It should be noted that the very short 2.5-ms TDMA frames incorporated into PACS to provide low transmission delay (for high speech quality) also make the technology significantly less sensitive to high-speed fading than the longer-frame-period cellular technologies. The short frame also facilitates the rapid coordination needed to make reliable high-speed handoffs between base stations. Measurements on radio links to potential handoff base stations can be made rapidly, i.e., a measurement on at least one radio link every 2.5 ms. Once a handoff decision is made, signalling exchanges every 2.5 ms ensure that the radio link handoff is completed quickly. In contrast, the long frame periods in the high-tier (cellular) technologies prolong the time it takes to complete a handoff. As noted earlier, high speed handoff has been demonstrated many times with PACS technology and at speeds over 70 mi/hr. }

15.6 Quality, Capacity, and Economic Issues

Although the several trajectories toward low-tier PCS discussed in the preceding 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 megahertz 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. The cellular paradigm does not recognize the fact that almost all houses in the U.S. have inexpensive copper wires connecting telephones to the telephone network. The use of low-tier PCS base stations that concentrate individual user services before backhauling in the network will result in less fixed interconnecting facilities than exist now for wireline telephones. Thus, inexpensive techniques for interconnecting many low-tier base stations are already deployed to provide wireline telephones to almost all houses. { The cost of backhaul to many base stations (radio ports) in a low-tier system is often cited as an economic disadvantage that cannot be overcome.

However, this perception is based on existing tariffs for T1 digital lines which are excessive considering current digital subscriber line technology. These tariffs were established many years ago when digital subscriber line electronics were very expensive. With modern low-cost high-rate digital subscriber line (HDSL) electronics, the cost of backhaul could be greatly reduced. If efforts were made to revise tariffs for digital line backhaul based on low cost electronics and copper loops like residential loops, the resulting backhaul costs would more nearly approach the cost of residential telephone lines. As it is now, backhaul costs are calculated based on antiquated high T1 line tariffs that were established for "antique" high cost electronics. }

This list could be extended, but the preceding 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.

15.6.1 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 15.5 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 15.5) for speech coding are discussed later. 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 later. A similar technique has been proposed as E-TDMA for use with IS-54 and is discussed with respect to TDMA system in [29]. 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 five-point MOS scale when compared to 32 kb/s ADPCM. Tandem encoding is discussed in a later section. These speech quality degrading factors alone provide a base station capacity increasing factor of $\times 4 \times 2.5 = \times 10$ 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.

TABLE 15.5 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

Parameter	Cellular (High-Tier)	Low-Tier PCS	Capacity Factor
Speech Coding, kb/s	8 (MOS 3.4) No tandem coding	32 (MOS 4.1) 3 or 4 tandem	$\times 4$
Speech activity	Yes (MOS 3.2)	No (MOS 4.1)	$\times 2.5$
Percentage of good areas, %	90	99	$\times 2$
Propagation σ, dB	8	10	$\times 1.5$
Total: trading quality for capacity			$\times 30$

The allowance of extra system margin to provide coverage of 99% of an area for low-tier PCS versus 90% coverage for high-tier is discussed in the previous section and [29]. This additional quality factor costs a capacity factor of $\times 2$. The last item in Table 15.5 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 $\times 1.5$ 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 15.5, significant speech and coverage quality has been traded for a factor of $\times 30$ in base station capacity! Whereas 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 $\times 0.5$ of AMPS cellular[5] (a much lower figure than the $\times 0.8$ sometimes quoted [20]), and then were degraded in quality as described above to yield the $\times 30$ capacity factor, it would have a resulting capacity of $\times 15$ of AMPS! Thus, it is obvious that making such a base station capacity comparison without including quality is not meaningful.

15.6.2 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 the following.

- 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.
- Very low estimates of circuit usage time more appropriate to cellular than to cordless/wireline telephone usage, which is more likely for low-tier PCS.
- { Backhaul costs based on existing T1 line tariffs that are based on "antique" high cost digital loop electronics. (See discussion in fourth paragraph at start of Section 15.6.) }

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 looking at relative economics between high-tier and low-tier systems. This is the approach used in the following examples.

EXAMPLE 15.1:

In the first example (see Table 15.6), the number of channels per megahertz is held constant for cellular and for low-tier PCS. Only the spacing 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

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

example, the resulting low-tier system capacity is $\times 400$ 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.

TABLE 15.6 System Capacity/Coverage Area Size/Economics

Example 15.1
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 = (\$ 1 M/400) \$2,500 a reasonable figure
If, cell site and port each have 180 channels
Cellular cost/circuit = \$ 1 M/180 = \$5,555/circuit
PCS cost/circuit = \$2500/180 = \$14/circuit
Example 15.2
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 15.3
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 = $\times$ 400
PCS to cellular quality reduction factors:
32 to 8 kb/s speech $\times 4$
Voice activity (buying) $\times 2$
99–90% good areas $\times 2$
Both in same environment (same σ) $\underline{\times 1}$
Capacity factor traded $\times 16$
180 ch/16 = 11.25 channels/port then, \$2500/11.25 = \$222/circuit
and remaining is $\times 400/16 = \times 25$ system capacity of PCS over cellular

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

EXAMPLE 15.2:

In the second example (see Table 15.6), 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 15.3:

Since the first two examples are somewhat extreme, the third example (see Table 15.6) 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 $\times 25$ 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 15.3, 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 chapter, 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 can be overcome, low-tier wireless PCS promises to provide the wireless personal communications that everyone wants.

15.6.3 {Loop Evolution and Economics

It is interesting to note that several wireless loop applications are aimed at reducing cost by replacing parts of wireline or CATV loops with wireless links between transceivers. The economics of these applications are driven by the replacing of labor-intensive wireline and cable technologies with mass-produced solid-state electronics in transceivers.

Consider first a cordless telephone base unit. The cordless base-unit transceiver usually serves one or, at most, two handsets at the end of one wireline loop. Now consider moving such a base unit back along the copper-wire-pair loop end a distance that can be reliably covered by a low-power wireless link [25, 31], i.e., several hundred to a thousand feet or so, and mounting it on a utility pole or a street light pole. This replaces the copper loop end with the wireless link. Many additional copper loop ends to other subscribers will be contained within a circle around the pole having a maximum usable radius of this wireless link. Replace all of the copper loop ends within the circle with cordless base units on the same pole. Note that this process replaces the most expensive parts of these many loops, i.e., the many individual loop ends, with the wireless links from cordless handsets to“equivalent” cordless base units on a pole. Of course, being mounted outside will require somewhat stronger enclosures and means of powering the base units, but these additional costs are considerably more than offset by eliminating the many copper wire drops.

It is instructive to consider how many subscribers could be collected at a pole containing base units. Consider, as an example, a coverage square of 1400 ft on a side (PACS will provide good coverage over this range, i.e., for base unit pole separations of about 1400 ft, at 1.9 GHz). Within this square will be 45 houses for a 1 house/acre density typical of low-housing-density areas, or 180 houses for 4 house/acre density more typical of high-density single-family housing areas. These represent significant concentration of traffic at a pole.

Because of the trunking advantage of the significant number of subscribers concentrated at a pole, they can share a smaller number of base unit, i.e., wireless base unit transceivers, than there are wireless subscriber sets. Therefore, the total cost compared with having a cordless base unit per subscriber also is reduced by the concentration of users.

A single PACS transceiver will support simultaneously eight TDMA channels or circuits at 32 kb/s (or 16 at 16 kb/s or 32 at 8 kb/s) [56]. Of these, one channel is reserved for system control. The cost of such moderate-rate transceivers is relatively insensitive to the number of channels supported; i.e., the cost of such an 8-channel (or 16 or 32) transceiver will be significantly less than twice the cost of a similar one-channel transceiver. Thus, another economic advantage accrues to this wireless loop approach from using time-multiplexed (TDMA) transceivers instead of single-channel-per-transceiver cordless telephone base units.

For an offered traffic of 0.06 Erlang, a typical busy-hour value for a wireline subscriber, a seven-channel transceiver could serve about 40 subscribers at 1% blocking, based on the Erlang B queuing discipline. From the earlier example, such a transceiver could serve most of the 45 houses within a 1400-ft square. Considering partial penetration, the transceiver capacity is more than adequate for the low-density housing.[6]

Considering the high-density example of 4 houses/acre, a seven-channel transceiver could serve only about 20% of the subscribers within a 1400-ft square. If the penetration became greater than about 20%, either additional transceivers, perhaps those of other service providers, or closer transceiver spacing would be required.

Another advantageous economic factor for wireless loops results when considering time-multiplexed transmission in the fixed distribution facilities. For copper or fiber digital subscriber loop carrier (SLC), e.g., T1 or high-rate digital subscriber line (HDSL), a demultiplexing/multiplexing terminal and drop interface are required at the end of the time-multiplexed SLC line to provide the individual circuits for each subscriber loop-end circuit, i.e., for each drop. The most expensive part of such an SLC terminating unit is the subscriber line cards that provide per-line interfaces for each subscriber drop. Terminating a T1 or HDSL line on a wireless loop transceiver eliminates all per-line interfaces, i.e., all line cards, the most expensive part of a SLC line termination. Thus, the greatly simplified SLC termination can be incorporated within a TDMA wireless loop transceiver, resulting in another cost savings over the conventional copper-wire-pair telephone loop end.

The purpose of the previous discussions is not to give an exact system design or economic analysis, but to illustrate the inherent economic advantages of low-power wireless loops over copper loop ends and over copper loop ends with cordless telephone base units. Some economic analyses have found wireless loop ends to be more economical than copper loop ends when subscribers use low-power wireless handsets. Rizzo and Sollenberger [56] have also discussed the advantageous economics of PACS wireless loop technology in the context of low-tier PCS.

The discussions in this section can be briefly summarized as follows. Replacing copper wire telephone loop ends with low-complexity wireless loop technology like PACS can produce economic benefits in at least four ways. These are.

1. Replacing the most expensive part of a loop, the per-subscriber loop-end, with a wireless link.
2. Taking advantage of trunking in concentrating many wireless subscriber loops into a

[6]The range could be extended by using higher base unit antennas, by using higher-gain directional (sectored) antennas, and/or by increasing the maximum power that can be transmitted.

smaller number of wireless transceiver channels.

3. Reducing the cost of wireless transceivers by time multiplexing (TDMA) a few (7, 15, or 31) wireless loop circuits (channels) in each transceiver.
4. Eliminating per-line interface cards in digital subscriber line terminations by terminating time-multiplexed subscriber lines in the wireless loop transceivers. }

15.7 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.

15.7.1 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 5 or 6 hours of talk time in addition to 10 or 12 hours of standby time, and still weigh less than one-fourth 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 (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 $\times 10$ 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.

{ As noted in the addition to the "Reality Check" section, new lithium batteries have become the batteries of choice for the smallest cellular/high-tier PCS handsets. While these lithium batteries have higher energy density than earlier nickel cadmium batteries, they still fall far short of the factor of 10 improvement that was needed to make long talk time, small size, and low weight possible. With the much larger advance in electronics, the battery is even more dominant in the size and weight of the newest cellular handsets. The introduction of these batteries incurred considerable startup pain because of the greater fire and explosive hazard associated with lithium materials, i.e., closer approach to a bomb. Further attempts in this direction will be even more hazardous. }

15.7.2 People Only Want One Handset

This issue is often raised in support of high-tier cellular handsets over low-tier handsets. Whereas 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. A low-tier system, however, 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 mi/h, and the required handoffs make use of computer technology that is rapidly becoming inexpensive. { As noted earlier, vehicular speed handoff is readily accomplished with PACS. Reliable handoff has been demonstrated for PACS at speeds in excess of 70 mi/hr. } Highways between populated areas, and also streets within them, will need to be covered by high-tier cellular PCS, but users are likely 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.

{ As discussed in earlier sections, it is quite feasible economically to cover highways between cities with low-tier systems, if the low-tier base stations have antennas with the same height and gain as used for cellular and high-tier PCS systems. (The range penalty for the lower power was noted earlier to be only on the order of 1/2, or about the same as the range penalty in going from 800 MHz cellular to 1.9 GHz high-tier PCS.) }

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.[7] The user's identity would then be transferred to the mobile set. { "Car adapters" that have a cradle for a small cellular handset providing battery charging and connection to an outside antenna are quite common — e.g., in Sweden use of such adapters is commonplace. Thus, this concept has already evolved significantly, even for the disadvantaged cellular handsets when they are used in vehicles. } 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.[8] 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 Walkman).[9] 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

---

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

[8] This is a feature proposed for FPLMTS in CCIR Rec. 687.

[9] Walkman is a registered trademark of Sony Corporation.

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 that 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-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 signalling [26, 29] 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 to pass intelligence among local exchange networks and interexchange carrier networks.

15.7.3 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.)

15.7.4 Speech Quality Issues

All of the PCS and cordless telephone technologies that use CCITT standardized 32-kb/s ADPCM speech encoding can provide similar error-free speech distortion quality. This quality often is rated on a five-point subjective mean opinion score (MOS) with 5 excellent, 4 good, 3 fair, 2 poor, and 1 very poor. The error-free MOS of 32-kb/s ADPCM is about 4.1 and degrades very slightly with tandem encodings. Tandem encodings could be expected in going from a digital-radio PCS access link, through a network using analog transmission or 64-kb/s PCM, and back to another digital-radio PCS access link on the other end of the circuit. In contrast, a low-bit-rate (<10-kb/s) vocoder proposed for a digital cellular system was recently reported [54] to yield an MOS of 3.4 on an error-free link without speech-activity detection. This score dropped to 3.2 when speech-activity detection was implemented to increase system capacity. This nearly one full point decrease on the five-point MOS score indicates significant degradation below accepted CCITT wireline speech distortion quality. Either almost half of the population must have rated it as poor or most of the population must have rated it as only fair. It should also be noted that these MOS scores may not reflect additional degradation that may occur in low-bit-rate speech encoding when the speech being encoded is combined with acoustical noise in a mobile environment, e.g., tire, wind, and engine noise in automobiles and street noise, background talking, etc., in handheld phone environments along streets and in buildings. Comments from actual users of low-bit-rate speech technology in acoustically noisy environments suggest that the MOS scores just quoted are significantly degraded in these real world environments. Waveform coders, e.g., ADPCM are not likely to experience degradation from such background noise. In addition, the low-bit-rate speech encoding is not at all tolerant of the tandem speech encodings that will inevitably occur for PCS for many years. 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. Although 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 wireline 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. These comments in this paragraph are generally applicable to speech encoding at rates of 13 kb/s or less. { The predictions above about the seriousness of the speech coding quality issues have been proven to be true in virtually all cellular technologies [2, 5]. The much touted speech quality of the original IS-95 CDMA 8 kb/s QCELP speech coder proved to be unacceptable to users.

The 8 kb/s speech coder was replaced with a 13 kb/s speech coder when IS-95 CDMA technology was deployed for high-tier PCS at 1.9 GHz. Many of the 800 MHz CDMA systems are converting or considering converting to the higher bit rate coder to improve their speech quality. This change was accompanied by a base station capacity reduction of 1/3, but the CDMA advocates seldom acknowledge this fact. The GSM effort to create a “half-rate” speech coder was redirected to develop an improved speech quality coder at 13 kb/s that would be less sensitive to acoustic background noise, bit errors, tandem encoding, etc. The quality of the new coder is better under some conditions. The 8 kb/s North American TDMA/IS-136 speech coder was redesigned to improve speech quality. Some improvement has been achieved. In all these revised coder cases, the issues discussed above in the original article still apply. }

In the arena of transmission delay, the short-frame (2-ms) FDMA/TDD and TDMA technologies (e.g., CT-2 and WACS noted earlier) can readily provide single-radio-link round-trip delays of $<$10 ms and, perhaps, even $<$5 ms. The longer frame (10 ms and greater) cordless-phone TDMA technologies, e.g., DCT-900/CT-3/DECT and some ISM-band implementations, inherently have a single-link round-trip delay of at least 20 ms and can range 30-40 ms or more in some implementations. As mentioned earlier, the digital vehicular-cellular technologies with low-bit-rate speech encoding, bit interleaving, forward error-correction decoding, and relatively long frame time ($\sim$16–20 ms) result in single-link round-trip delays on the order of 200 ms, well over an order of magnitude greater than the short-frame technologies, and on the same order of magnitude as a single-direction synchronous satellite link. { Even with the somewhat improved low bit rate speech coders noted previously, the transmission delay remains excessive for all of the cellular/high-tier PCS digital technologies. } It should be noted that almost all United States domestic long-distance telephone circuits have been removed from such satellite links, and many international satellite links also are being replaced by undersea fiber links. These long-distance-circuit technology changes are made partially to reduce the perceptual impairment of long transmission delay.

15.7.5 New Technology

New technology, e.g., spread spectrum or CDMA, is sometimes offered as a solution to both the higher-tier cell site capacity and transmitter power issues. As these new technologies are pursued vigorously, however, it becomes increasingly evident that the early projections were considerably overoptimistic, that the base station capacity will be about the same as other technologies [29], 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 [73].

The IS-95 proposal is considerably more technically sophisticated than earlier spread spectrum proposals. It includes fast feedback control of mobile transmitter power, heavy forward error correction, speech detection and speech-encoding rate adjustment to take advantage of speech inactivity, and multiple receiver correlators to latch onto and track resolvable multipath maxima [57]. The spreading sequence rate is 1.23 MHz.

The near–far problem is addressed directly and elegantly on the uplink by a combination of the fast-feedback power control and a technique called soft handoff that permits the instantaneous selection of the best paths between a mobile and two cell sites. Path selection is done on a frame-by-frame basis when paths between a mobile and the two cell sites are within a specified average level (perhaps 6–10 dB) for each other. This soft handoff provides a form of macroscopic diversity [10] between pairs of cell sites when it is advantageous. Increasing capacity by soft handoff requires precise time synchronization (on the order of a microsecond) among all cell sites in a system. An advantage of this proposal is that frequency coordination is not needed among cell sites since all sites can share a frequency channel. Coordination of the absolute time delays of spreading sequences among cell sites is required, however, since these sequence delays are used to distinguish different cell sites for initial access and for soft handoff. Also, handoff from one frequency to another is complicated.

Initially, the projected cell site capacity of this CDMA system, determined by mathematical analysis and computer simulation of simplified versions of the system, was $\times 20$ to $\times 40$ that of the analog AMPS, with a coverage criterion of 99% of the covered area [11]. However, some other early estimates [83] suggested that the factors were more likely to be $\times 6$ to $\times 8$ of AMPS.

A limited experiment was run in San Diego, California, during the fourth quarter of 1991 under the observation of cellular equipment vendors and service providers. This experiment had 42–62 mobile units in fewer than that many vehicles,[10] and four or five cell sites, one with three sectors. Well over half of the mobiles needed to provide the interference environment for system capacity tests were simulated by hardware noise simulation by a method not yet revealed for technical assessment. Estimates of the cell site capacity from this CDMA experiment center around $\times 10$ that of AMPS [12, 54][11] with coverage criteria $<$99%, perhaps 90-95%, and with other capacity estimates ranging between $\times 8$ and $\times 15$.

This experiment did not exercise several potential capacity-reducing factors; the following, for example.

1. Only four cells participated in capacity tests. The test mobiles were all located in a relatively limited area and had limited choices of cell sites with which to communicate for soft handoffs. This excludes the effects of selecting a strong cell-site downlink for soft handoff that does not have the lowest uplink attenuation because of uncorrelated uplink and downlink multipath fading at slow vehicle speeds [3].

[10] Some vehicles contained more than one mobile unit.

[11] AT&T stated that the San Diego data supported a capacity improvement over analog cellular of at least $\times 10$.

2. The distribution of time-dispersed energy in hilly environments like San Diego usually is more concentrated around one or two delays than is the dispersed energy scattered about in heavily built-up urban areas like downtown Manhattan [13, 14], or Chicago. Energy concentrated at one or two delays is more fully captured by the limited number of receiver correlators than is energy more evenly dispersed in time.
3. Network delay in setting up soft handoff channels can result in stronger paths to other cell sites than to the one controlling uplink transmitter power. This effect can be more pronounced when coming out of shadows of tall buildings at intersections in heavily built-up areas. The effect will not occur as frequently in a system with four or five cell sites as it will in a large, many cell site system.

All of these effects and others [4] will increase the interference in a large system, similarly to the increase in interference that results from additional mobiles and, thus, will decrease cell site capacity significantly below that estimated in the San Diego trial. Factors like these have been shown to reduce the San Diego estimate of $\times 10$ to an expected CDMA capacity of $\times 5$ or $\times 6$ of analog AMPS [3, 4, 13]. This further reduction in going from a limited experiment to a large-scale system in a large metropolitan area is consistent with the reduction already experienced in going from simplified theoretical estimates to the limited experiment in a restricted environment. { There are many "small" effects that decrease the performance and, thus, the base station capacity of actual mobile CDMA systems compared to calculations of performance based on ideal assumptions — e.g., stationary channel and additive white Gaussian noise analysis. Some of these effects, in addition to those noted above, included inaccuracy in assigning correlators ("fingers") to time varying statistically nonstationary multiple "paths" at different delays when many "paths" exist, and lack of diversity because many environments have delay spreads less than the resolution of correlators. }

The San Diego trial also indicated a higher rate of soft(er) handoffs [54] between antenna sectors at a single cell site than expected for sectors well isolated by antenna patterns. This result suggests a lower realizable sectorization gain because of reflected energy than would be expected from more idealized antennas and locations. This could further reduce the estimated cell site capacity of a large-scale system.

Even considering the aforementioned factors, capacity increases of $\times 5$ or $\times 6$ are significant. These estimates, however, are consistent with the factor of $\times 3$ obtained from low-bit-rate ($<$10-kb/s) speech coding and the $\times 2$ to $\times 2.5$ obtained by taking advantage of speech pauses. These factors result in an expected increase of $\times 6$–7.5, with none of these speech-processing-related contributions being directly attributable to the spread-spectrum processing in CDMA. These results are consistent with the factor of $\times 6$–8 estimate made earlier [83] and are not far from the factor of $\times 8$ quoted recently [86].

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

{ Since the writing for the first edition of this handbook, IS-95 based CDMA systems have been deployed and are providing service in several parts of the world, e.g., the U.S.A., Korea, and Hong Kong. The "high priests" and the "disciples" of CDMA continue to espouse their "belief" in the superiority of their CDMA technology. Good hard data on system performance is still scarce and of questionable reliability. However, there is sufficient evidence from some "usually reliable sources" and from "conversations in the halls" to confirm that, not only does CDMA not perform as well as was originally promised, but also in many places it is likely to be providing performance that is inferior to the other high-tier digital technologies. In spite of the continuing dismal failures of CDMA technology to meet the early claims for it, a significant fraction of the wireless industry appears to be committed to pursuing variations of CDMA for future applications. At this time it is not obvious how many more redesign and reprogramming failures, or perhaps even failures of manufacturing companies and service providers will be needed to overcome the religiously fanatic attachment of a part of the industry to CDMA. It appears that some are heavily committed again to "sweep on to the grand fallacy." Viterbi may even have been over optimistic about CDMA in 1985 [73], but he was correct in the way it attracts advocates.

IS-95 CDMA has failed to satisfy any of the major claims made for it in the late 1980s and early 1990s. The listing in Table 15.7 and the following discussion cites specific claims that have NOT been met now that reality has set in.

TABLE 15.7 CDMA Scoresheet

Early Claim	Reality
Easy to install and expand (no frequency planning)	Many "parameters" to adjust; adjustment is very difficult; many software revisions required
"Capacity" of AMPS $\times 20$ (with high expectation of AMPS $\times 40$)	AMPS $\times 3$ or 4; AMPS $\times$ <3? (at unspecified but likely high call dropping rate) (continuously revised downward over time)
No more dropped calls	More dropped calls than other technologies (some reports say up to 40% dropped calls when system is loaded!)
No problem with interference (CDMA "loves" interference)	Can't live with interference from AMPS or other sources
Greater range and coverage than other technologies	System coverage "breathes" as loading increases; range often is less than other technologies
"Toll quality" 8 kb/s QCELP speech	Original 8 kb/s QCELP speech quality worse than VSELP in TDMA; required change to 13 kb/s coder (change reduced "capacity")

Much of the original CDMA hype was focused on undefined cell site capacity (see text from original Handbook, particularly this section and the section on "Capacity, Quality, and Complexity.") Information from many sources (e.g., [9], Benjamin and Lusignan, 1997 — Benjamin is with Lucent Technologies; Lusignan with Stanford University; [40, 49, 69], etc.) suggest that with 13 kb/s speech coding, "fully loaded" systems may provide base station capacities on the order of AMPS $\times 3$ or perhaps $\times 4$. However, the meaning of fully loaded is not well defined. If it is taken to be at a very high call dropping rate (sometimes said to be as high as 40%!), perhaps even these low factors are again unrealistically inflated. A usable system loading must provide an acceptable call dropping rate, perhaps 1% or less. If loading is reduced to provide sufficient operating margin to prevent too many dropped calls, perhaps the usable base station capacity may be even significantly less than AMPS $\times 3$. (Note: Publicly presented CDMA claims have been consistently inflated in the past. Why should we be any more inclined to believe them now?) The capacity situation is so bad that the CDMA crowd doesn't even want to discuss this topic anymore. They now attempt to shift attention to the fact that there are operating CDMA systems, and try to brush aside the fact CDMA performance is so very poor. Low capacity has a significant negative impact on the economics of systems; high call dropping rates have a significant negative impact on service quality.

Another big early claim for CDMA was that it was easy to install and expand, that is, that it needed little engineering and planning for installation because it didn't require frequency reuse and power coordination among base stations. In reality, many parameters require adjustment and critical thresholds require setting for a system to provide even the low capacity numbers cited above. Many software revisions have been made in attempts to cope with fundamental problems that keep appearing and reappearing in new deployments and expansions. Deployments and service starts have been consistently late by many months and even years. [40, 69, and others]. A partial list of late CDMA deployments that required many months or even years of "parameter adjustment" and/or "software revisions" and/or "redesign" include those in Seattle, WA, U.S.A. (800 MHz); Los Angeles, CA, U.S.A. (800 MHz); Hong Kong, China (800 MHz); Trenton, NJ, U.S.A.; Seoul, Korea (800 MHz); Houston and Dallas, TX, U.S.A. (1.9 GHz); etc. As these systems were deployed a consistent pattern developed. Announcements would concentrate on a projected future service date, e.g., Seattle, 1Q 1994. When that date approached, news focused on yet another service date elsewhere, e.g., after Seattle was Los Angeles, to divert attention from the deployment problems causing large slips in earlier announcements. Sometimes when service date slips became excessive, sizes of deployed areas were revised downward, and "trials" were substituted for service starts, e.g., Los Angeles. This pattern continued through the early deployments and service eventually was started on systems, even though their performance was significantly below earlier claims. Excuses for slips were often vague, for example: software problems (e.g., Seattle, Hong Kong, and Korea); adjusting parameters (e.g., Seattle, Houston, and Dallas); too much interference from AMPS (e.g., Los Angeles); not enough multipath! (e.g., Seattle). These sound like descriptions of attempts to overcome some of the fundamental problems in mobile CDMA systems. In any event it is obvious that CDMA is not easy to install and is likely more difficult to adjust than other technologies.

The CDMA speech quality issue was discussed earlier in the "Speech Quality Issues" section. It is just another example of unrealistic initial claims.

Throughout the CDMA debate over almost 10 years, when unrealistic claims were questioned and even when sound technical analysis was cited by more conservative members of the wireless technical community, including this author, these members were immediately branded as heretics and their concerns were dismissed with rhetoric by the high priests and their disciples. (In the technical world, "never have so many been misled for so long by so few!") However, as deployments have proceeded and reality set in, even the more conservative initial assessments have, unfortunately, turned out to be somewhat optimistic. Thus, even the conservative heretics in the community now appear to be in the unfortunate position of having also been overoptimistic in their initial estimates of the performance of IS-95 CDMA. }

Statistical Multiplexing, Speech Activity, CDMA, and TDMA

Factors of $\times$2–2.5 have been projected for the capacity increase possible by taking advantage of pauses in speech. It has been suggested that implementing statistical multiplexing is easier for CDMA systems because it is sometimes thought to be time consuming to negotiate channels for speech spurts for implementation in TDMA systems. The most negative quality-impacting factor in implementing statistical multiplexing for speech, however, is not in obtaining a channel when needed but is in the detection of the onset of speech, particularly in an acoustically noisy environment. The effect of clipping at the onset of speech is evident in the MOS scores noted for the speech-activity implementation in the United States cellular CDMA proposal discussed earlier (i.e., an MOS of 3.4 without statistical multiplexing and of 3.2 with it). The degradation in MOS can be expected to be even greater for encoding that starts with a higher MOS, e.g., 32-kb/s ADPCM.

It was noted earlier that the proposed cellular CDMA implementation was $\times$10 as complex as the proposed WACS wireless access for personal communications TDMA implementation. From earlier discussion, the CDMA round-trip delay approaches 200 ms, whereas the short 2-ms-frame TDMA delay is $<$10-ms round trip. It should be noted that the TDMA architecture could permit negotiation for time slots when speech activity is detected. Since the TDMA frames already have capability for exchange of signalling data, added complexity for statistical multiplexing of voice could readily be added within less than 200 ms of delay and less than $\times$10 in complexity. That TDMA implementation supports 8 circuits at 32 kb/s or 16 circuits at 16 kb/s for each frequency. These are enough circuits to gain benefit from statistical multiplexing. Even more gain could be obtained at radio ports that support two or three frequencies and, thus, have 16–48 circuits over which to multiplex.

A statistical multiplexing protocol for speech and data has been researched at Rutgers WINLAB [39]. The Rutgers packet reservation multiple access (PRMA) protocol has been used to demonstrate the feasibility of increasing capacity on TDMA radio links. These PRMA TDMA radio links are equivalent to slotted ALOHA packet-data networks. Transmission delays of less than 50 ms are realizable. The capacity increase achievable depends on the acceptable packet-dropping ratio. This increase is soft in that a small increase in users causes a small increase in packet-dropping ratio. This is analogous to the soft capacity claimed for CDMA.

Thus, for similar complexity and speech quality, there appears to be no inherent advantage of either CDMA or TDMA for the incorporation of statistical multiplexing. It is not included in the personal communications proposal but is included in cellular proposals because of the different speech-quality/complexity design compromises discussed throughout this chapter, not because of any inherent ease of incorporating it in any particular access technology.

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

{ With widespread and successful deployment of GSM, perhaps an initial dual-mode strategy of GSM and PACS could be desirable. Of all the high-tier and low-tier technologies, GSM and PACS appear most compatible for dual-mode handset and base station implementation. They are considerably more compatible than the dual-mode combinations, e.g., AMPS/IS-54/IS-136 and AMPS/IS-95, already implemented. }

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 chapter. 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 [21, 22, 33]. Two different solutions to the increased delay spread can be employed, one for the downlink and another for the uplink. The PACS radio-link architecture has a specified bit sequence, i.e., a unique word, between each data word on the TDM downlink [7, 28]. 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 [62, 65], 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. The high-tier uplink, however, 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), [58, 70], can be effective for equalizing the PACS uplink. Techniques have been developed for converging the CMA equalizer on the short TDMA data burst.

{ See earlier added section on "Coverage, Range, Speed and Environments." }

The advantages of building a dual-mode high-tier, low-tier PCS system around the low-tier PACS air-interface standard follow.

1. The interface can still support small low-complexity, low-power, high-speech-quality low-tier handsets.
2. Both data and voice can be supported in a PACS personal communicator.
3. 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.
4. 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.

15.8 Infrastructure Networks

It is beyond the scope of this chapter to consider the details of PCS network infrastructures. There are, however, perhaps as many network issues as there are wireless access issues discussed herein [26, 32, 43, 81]. 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., database storage, signalling, 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, databases, and control processors. Of course, existing cellular mobile networks now contain or are incorporating these infrastructure network capabilities. Existing cellular networks, however, 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 signalling that is suitable or could be readily adapted to support PCS access include:

- Local exchange networks that are equipped with signalling system 7 common channel signalling (SS7 CCS), databases, 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 they do 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 signalling, control processing, and database 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. When viewed from a cordless telephone paradigm of a base unit for every handset and, perhaps, several base units per wireline, however, the requirement is much less fixed interconnection because of the concentration of users and trunking that occurs at the multiuser 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!

15.9 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 chapter, along with techniques for using that technology in high-tier PCS systems.

References

[1] Afrashteh, A., Sollenberg, N.R., and Chukurov, D.D., Signal to interference performance for a TDMA portable radio link. *IEEE VTC'91*, St. Louis, MO, 19–22, May, 1991.

[2] {Andrews, E.L., "When Digital Doesn't Always Mean Clear," *New York Times*, p. C1, 4, Jun. 26, 1995.}

[3] Ariyavisitakul, S., SIR-based power control in a CDMA system. *IEEE GLOBECOM'92*, Orlando, FL, Paper 26.3, Dec. 6–9, to be published in *IEEE Trans. Comm.*, 1992.

[4] Ariyavisitakul, S., et al., private communications.
[5] {Baugh, C.R., Wireless quality: a ticking time bomb, *Telephony,* 232(9), 50–58, Mar. 3, 1997.}
[6] {Baugh, C.R., Laborde, E., Pandey, V., and Varma, V., Personal access communications system: fixed wireless local loop and mobile configurations and services, *Proc. IEEE,* 1498–1506, July, 1998. }
[7] Bellcore Technical Advisories. Generic framework criteria for universal digital personal communications systems (PCS). FA-TSY-001013(1) March and FA-NWT-001013(2) Dec., and Tech. Ref. 1993. Generic criteria for version 0.1 wireless access communications systems (WACS). (1) Oct. rev. 1, Jun. 1994.
[8] BellSouth Services Inc., Quarterly progress report number 3 for experimental licenses KF2XFO and KF2XFN. To the Federal Communications Commission, Nov. 25, 1991.
[9] { Benjamin, B. and Lusignan, B., CDMA vs. TDMA, Stanford Univ. Center for Telecom. Symposium, The Acceleration of World Wide Wireless Communication, May 21, 1997.}
[10] Bernhardt, R.C., Macroscopic diversity in frequency reuse radio systems. *IEEE J. Sel. Areas in Comm.,* SAC-5, 862–870, Jun. 1987.
[11] Cellular Telecommunications Industries Association. CDMA digital cellular technology open forum. Jun. 6, 1989.
[12] Cellular Telecommunications Industries Association. CTIA Meeting, Washington, D.C., 5–6, Dec. 1991.
[13] Chang, L.F., Dispersive fading effects in CDMA radio systems. *Elect. Lett.,* 28(19), 1801–1802, 1992.
[14] Chang, L.F. and Ariyavisitakul, S., Performance of a CDMA radio communications system with feed-back power control and multipath dispersion. *IEEE GLOBECOM'91,* Phoenix, AZ, 1017–1021, Dec. 1991.
[15] Chuang, J.C.-I., Performance issues and algorithms for dynamic channel assignment. *IEEE JSAC,* Aug. 1993.
[16] Chuang, J.C.-I., Performance limitations of TDD wireless personal communications with asynchronous radio ports. *Electron. Lett.,* 28, 532–533, Mar. 1992.
[17] Chuang, J.C.-I., Comparison of coherent and differential detection of BPSK and QPSK in a quasistatic fading channel. *IEEE Trans. Comm.,* 565–576, May 1990.
[18] Chuang, J.C.-I. and Sollenberger, N.R., Burst coherent detection with robust frequency and timing estimation for portable radio communications. *IEEE GLOBECOM'88,* Hollywood, FL, 28–30, Nov. 1988.
[19] Chuang, J.C.-I., Sollenberger, N.R., and Cox, D.C., A pilot based dynamic channel assignment scheme for wireless access TDMA/FDMA systems. *Proc. IEEE ICUPC'93,* Ottawa, Canada, Oct. 12–15, 706–712, 1994. *Intl. J. Wireless Inf. Net.,* 1(1), 37–48, 1993.
[20] Cook, C.I., Development of air interface standards for PCS. *IEEE Personal Comm.,* 4th Quarter, 30–34, 1994.
[21] Cox, D.C., Delay-Doppler characteristics of multipath propagation at 910 MHz in a suburban mobile radio environment. *IEEE Trans. on Antennas and Propagation,* 625–635, Sep. 1972.
[22] Cox, D.C., Multipath delay spread and path loss correlation for 910 MHz urban mobile radio propagation. *IEEE Trans. on Veh. Tech.,* 340–344, Nov. 1977.
[23] Cox, D.C., Universal portable radio communications. *IEEE Trans. on Veh. Tech.,* 117–121, Aug. 1985.
[24] Cox, D.C., Research toward a wireless digital loop. *Bellcore Exchange*, 2, 2–7, Nov./Dec. 1986.

[25] Cox, D.C., Universal digital portable radio communications. *Proc. IEEE*, 75, 436–477, Apr. 1987.
[26] Cox, D.C., Portable digital radio communications—An approach to tetherless access. *IEEE Comm. Mag.*, 30–40, Jul. 1989.
[27] Cox, D.C., Personal communications—A viewpoint. *IEEE Comm. Mag.*, 8–20, Nov. 1990.
[28] Cox, D.C., A radio system proposal for widespread low-power tetherless communications. *IEEE Trans. on Comm.*, 324–335, Feb. 1991.
[29] Cox, D.C., Wireless network access for personal communications. *IEEE Comm. Mag.*, 96–115, Dec. 1992.
[30] {Cox, D.C., Wireless loops: what are they. *Intl. J. Wireless Inf. Net.*, 3(3), Plenum Press, 1996.}
[31] Cox, D.C., Arnold, H.W., and Porter, P.T., Universal digital portable communications—a system perspective. *IEEE JSAC*, JSAC-5, 764–773, Jun. 1987.
[32] Cox, D.C., Gifford, W.G., and Sherry, H., Low-power digital radio as a ubiquitous subscriber loop. *IEEE Comm. Mag.*, 92–95, Mar. 1991.
[33] {Devasirvatham, D.M.J., Radio propagation studies in a small city for universal portable communications. *IEEE VTC'88*, Conference Record. Philadelphia, PA, 100–104, Jun. 15–17, 1988.}
[34] {Devasirvatham, D.M.J., Radio propagation studies in a small city for universal portable communications, *IEEE VTC'88*, Philadelphia, PA, 100–104, Jun. 15–17, 1988.}
[35] Devasirvatham, D.M.J., et al., Radio propagation measurements at 850 MHz, 1.7 GHz and 4 GHz inside two dissimilar office buildings. *Elect. Lett.*, 26(7), 445–447, 1990a.
[36] Devasirvatham, D.M.J., et al., Multi-frequency radiowave propagation measurements in the portable radio environment. *IEEE ICC'90*, 1334–1340, Apr. 1990b.
[37] {Devasirvatham, D.M.J., Murray, R.R., Arnold, H.W., and Cox, D.C., Four-frequency CW measurements in residential environments for personal communications, symposium on personal indoor and mobile radio communications (PIMRC'93), Yokohama, Japan, 201–205, Sep. 9–11, 1993.}
[38] {Goldhirsh, J. and Vogel, W., Mobile satellite system fade and statistics for shadowing and multipath from roadside trees at UFH and L-band, *IEEE Transactions on Antennas and Propagation*, 37, Apr. 1989.}
[39] Goodman, D.J., Trends in cellular and cordless communications. *IEEE Comm. Mag.*, 31–40, Jun. 1991.
[40] {Hardy, Q., Jacob's Patter, The Wall Street Journal, Friday, Sep. 6, 1996.}
[41] {Hattori, T., PHS system deployment success story, Stanford Univ. Center for Telecom. Symposium, May 21, 1997.}
[42] Hinderling, J., et al., CDMA mobile station modem ASIC. *IEEE CICC 92*, Boston, MA, May. *Intl. J. Wireless Info. Net.*, 1(1), 37–48, Jan. 1994.
[43] Jabbari, B., et al., Network issues for wireless personal communications. *IEEE Comm. Mag.*, 88–98, Jan. 1995.
[44] Katz, R.H., Adaptation and mobility in wireless information systems. *IEEE Personal Comm.*, 1st Quarter, 6–17, 1994.
[45] {Kim, B.-J. and Cox, D.C., Blind equalization for short burst communications over frequency selective wireless channels, 1997 *IEEE VTC'97*, Phoenix, AZ, 2, 544–548, May 4–7, 1997a.}
[46] {Kim, B.-J. and Cox, D.C., Blind sequence estimation for short burst communications over time-varying wireless channels, *IEEE ICUPC'97*, San Diego, CA, 2, 713–717, Oct. 12–16, 1997b.}

[47] {Kim, B.-J. and Cox, D.C., Blind diversity combining equalization for short burst wireless communications, *IEEE Globecom'97,* Phoenix, AZ, 3, 1163–1167, Nov. 3–8, 1997c.}
[48] {Kim, B.-J., Blind equalization for short burst wireless communications, Stanford University Ph.D. Thesis, Jan. 1998.}
[49] {Korea Mobile Telecom, Article on CDMA, Mobile Communications International, Feb. 1997.}
[50] Padgett, J.E., Hattori, T., and Gunther, C., Overview of wireless personal communications. *IEEE Comm. Mag.,* 28–41, Jan. 1995.
[51] {Patel, V., Personal Access Communications System, Stanford Univ. Center for Telecom. Symposium, May 21, 1997.}
[52] {Phillips, B.W., Broadband in the Local Loop, Telecommunications, 37–42, Nov. 1994.}
[53] {PHS, World Congress, Singapore, Nov. 18–20, 1996.}
[54] Qualcomm Technology Forum, Open meeting on status of CDMA technology and review of San Diego experiment. San Diego, CA, Jan. 16–17, 1992.
[55] {Ranade, A., Local access radio interference due to building reflections, *IEEE Transaction on Communications,* 70–74, Jan. 1989.}
[56] {Rizzo, J.F. and Sollenberger, N.R., Multiuser Wireless Access, *IEEE Personal Communications Magazine,* 18–30, Jun. 1995.}
[57] Salmasi, A. and Gilhousen, K.S., On the system design aspects of code division multiple access (CDMA) applied to digital cellular and personal communications networks. *IEEE VTC'91,* St. Louis, MO, 57–62, May 1991.
[58] Sato, Y., A method of self-recovering equalization for multilevel amplitude modulation systems. *IEEE Trans. on Comm.,* 679–682, Jun. 1975.
[59] Schneideman, R., Spread spectrum gains wireless applications. *Microwaves and RF,* 31–42, May 1992.
[60] {Seidel, S.Y. and Arnold, H.W., Propagation measurements of 28 GHz to investigate the performance of local multipoint distribution services (LMDS), *IEEE Globecom'95,* 1995.}
[61] Sollenberger, N.R. and Chuang, J.C-I., Low overhead symbol timing and carrier recovery for TDMA portable radio systems. Third nordic sem. digital land mobile radio comm., Copenhagen, Denmark, 13–15, Sep. 1988.
[62] Sollenberger, N.R., An experimental VLSI implementation of low-overhead symbol timing and frequency offset estimation for TDMA portable radio applications. *IEEE Globecom'90,* San Diego, CA, 1701–1711, Dec. 1990.
[63] Sollenberger, N.R., An experimental TDMA modulation/demodulation CMOS VLSI chipset. *IEEE CICC'91,* San Diego, CA, May 12–15, 1991.
[64] Sollenberger, N.R. and Afrashteh, A., An experimental low-delay TDMA portable radio link. *Wireless'91,* Calgary, Canada, Jul. 8–10, 1991.
[65] Sollenberger, N.R. and Chuang, J.C.-I., Low-overhead symbol timing and carrier recovery for TDMA portable radio systems. *IEEE Trans. on Comm.*, 1886–1892, Oct. 1990.
[66] Sollenberger, N.R., et al., Architecture and implementation of an efficient and robust TDMA frame structure for digital portable communications. *IEEE Trans. Veh. Tech.,* 40, 250–260, Feb. 1991.
[67] Steele, R., Deploying personal communications networks. *IEEE Comm. Mag.,* 12–15, Sep. 1990.
[68] Steer, D.G., Coexistence and access etiquette in the United States unlicensed PCS band. *IEEE Personal Comm. Mag.,* 4th Quarter, 36–43, 1994.
[69] {Titch, S., Blind Faith, Telephony, Sep. 8, 1997 and Global Telephony, Intertec Publishing Corp., Oct. 30, 1997.}

[70] Treichler, J.R. and Agee, B.G., A new approach to multipath correction of constant modulus signals, *IEEE Trans. on Acoustics, Speech and Signal Processing*, 459–472, Apr. 1983.

[71] Tuthill, J.P., Granger, B.S., and Wurtz, J.L., Request for a pioneer's preference. Before the Federal Communications Commission, Pacific Bell submission for FCC General Docket No. 90–314, RM-7140, and RM-7175, May 4, 1992.

[72] Varma, V.K., et al., Performance of sub-band and RPE coders in the portable communication environment. *Fourth Intl. Conf. on Land Mobile Radio*, Coventry, UK, 221–227, Dec. 14–17, 1987.

[73] Viterbi, A.J., When not to spread spectrum—A sequel. *IEEE Comm. Mag.*, 12–17, Apr. 1985.

[74] {Weseloh, C., Solutions for Wireless Communications, Stanford University Center for Telecommunications, Symposium, Stanford, CA, May 16, 1995.}

[75] Wong, A., Regulating public wireless networks. Workshop on lightwave, wireless and networking technologies, Chinese Univ. of Hong Kong, Hong Kong, Aug. 24, 1994.

[76] {Wong, P., Low-power, low-complexity diversity combining algorithm and VLSI circuit chip for hand-held PCS receivers, Stanford University Ph.D. Thesis, Apr. 1997.}

[77] {Wong, P. and Cox, D.C., Low-complexity cochannel interference cancellation and macroscopic diversity for high capacity PCS, *IEEE ICC'95 Digest*, Seattle, WA, 852–857, Jun. 19–22, 1995.}

[78] {Wong, P. and Cox, D.C., Low-complexity diversity combining algorithms and circuit architectures for cochannel interference cancellation and frequency selective fading mitigation, *IEEE ICC'96 Digest*, Dallas TX, Jun. 23–27, 1996a.}

[79] {Wong, P. and Cox, D.C., Low-complexity diversity combining algorithms and circuit architectures for cochannel interference cancellation and frequency-selective fading mitigation, *IEEE Trans. on Comm.*, 44(9), 1107–1116, Sep. 1996b.}

[80] {Wong, P. and Cox, D.C., Low-complexity interference cancellation and macroscopic diversity for high capacity PCS, *IEEE Trans. on Veh. Tech.*, 124–132, Feb. 1998.}

[81] Zaid, M., Personal mobility in PCS. *IEEE Personal Comm.*, 4th Quarter, 12–16, 1994.

[82] Special issue on advanced mobile phone service (AMPS). *Bell System Tech. J.*, (BSTS). 58, Jan. 1979.

[83] CDMA capacity seen as less than advertised. *Adv. Wireless Comm.*, (AWC). 1–2, Feb. 6, 1991.

[84] Bellcore's Wireless Prototype. *Microcell News*, (MN). 5–6, Jan. 25, 1992.

[85] Bellcore PCS phone shines in Bellsouth test; others fall short. *Adv. Wireless Comm.*, (AWC). 2–3, Feb. 19, 1992a.

[86] TDMA accelerates, but CDMA could still be second standard. *Adv. Wireless Comm.*, (AWC). 6, Mar. 4, 1992b.

[87] Special issue on wireless personal communications. *IEEE Comm. Mag.*, Jan. 1995.