An evolution toward three large groups of applications and services

Wireless Personal Communications: What Is It?

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

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

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

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

Background and Issues

Mobility and Freedom from Tethers

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

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

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

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

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

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

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

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

There are still other ways in which wireless communications have been segmented in attempts to optimize a technology to satisfy the needs of some particular group. Examples include:
• User location, that can be differentiated by indoors or outdoors, or on an airplane or a train.
• Degree of mobility, that can be differentiated either by speed, e.g., vehicular, pedestrian, or stationary, or by size of area throughout which communications are provided.

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

Communications Portability and Mobility on many different scales:
• Within a house or building (cordless telephone, wireless local area networks (WLANs)).
• Within a campus, a town, or a city (cellular radio, WLANs, wide area wireless data, radio paging, extended cordless telephone).
• Throughout a state or region (cellular radio, wide area wireless data, radio paging, satellite-based wireless).
• Throughout a large country or continent (cellular radio, paging, satellite-based wireless).
• Throughout the world?!!

Communications by many different modes for many different applications:
• Two-way voice.
• Data.
• Messaging.
• Video?

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

Evolution of Technologies, Systems, and Services

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

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

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

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[1] *These ISM technologies either use spread spectrum techniques (direct sequence or frequency hopping), or very low transmitter power ($\lesssim$ 1 mw) as required by the ISM band regulations.*
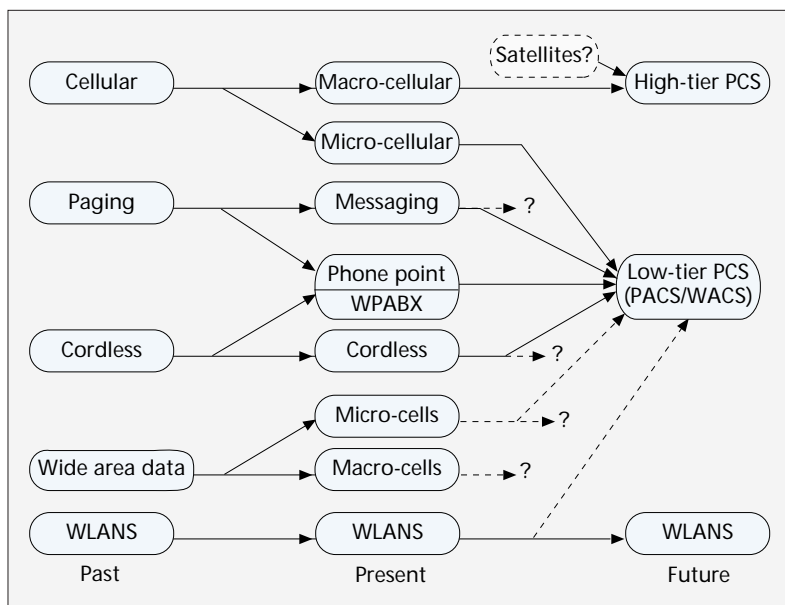
■ Figure 1. *Digital wireless access systems evolution.*

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

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

The compromises accepted in cordless telephone design in order to meet the cost, weight, and talk-time objectives are:
• Few users per MHz.
• Few users per base unit (many link together a particular handset and base unit).
• Large number of base units per unit area; one or more base units per wireline access line (in high-rise apartment buildings the density of base units is very large).
• Short transmission range.

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

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

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

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

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

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

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

| | High Power Systems | | | | Low Power Systems | | | |
	Digital Cellular (High Tier PCS)				Low Tier PCS		Digital Cordless	
System	IS-54	IS-95 (DS)	GSM	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)	1880-1900 (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	π/4 DQPSK	BPSK/QPSK	GMSK	GMSK	π/4 QPSK	π/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 to 2.2 GHz allocated by the FCC for emerging technologies; DS is direct sequence.								

■ **Table 1.** *Wireless PCS technologies.*

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

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

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

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

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

Cellular Mobile Radio Systems

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

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

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

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

Cellular radio at 800 MHz has evolved to digital radio technologies [1-3] in the forms of the deployed systems standards:
- Global Standard for Mobile (GSM) in Europe.
- Japanese or Personal Digital Cellular (JDC or PDC) in Japan.
- U.S. TDMA digital cellular known as USDC or IS-54.

and in the form of the code division multiple access (CDMA) standard, IS-95, which is under development, but not yet deployed. The most significant consideration in the design compromises made for the U.S. digital cellular or high-tier PCS systems was the high cost of cell sites (base stations). A figure often quoted is U.S. $1 million for a cell site. This consideration drove digital system designs to:
- Maximize users per MHz.
- Maximize the users per cell site.

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

Compromises that were accepted while maximizing the above parameters are:
- High transmitter power consumption.
- High user-set complexity, and thus high signal-processing power consumption.
- Low circuit quality.

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

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

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

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

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

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

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

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

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

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

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

Wide Area Wireless Data Systems

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

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

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

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

	CDPD	RAM Mobile (Mobitex)	ARDIS (KDT)	Metricom (MDN)
Data rate	19.2 KB/s	8 Kb/s [19.2 Kb/s]	4.8 Kb/s [19.2 Kb/s]	~ 76 Kb/s
Modulation	GMSK BT = 0.5	GMSK	GMSK	GMSK
Frequency	~ 800 MHz	~ 900 MHz	~ 800 MHz	~ 915 MHz
Chan. spacing	30 KHz	12.5 KHz	25 KHz	160 KHz
Status	1994 service	Full service	Full service	In service
Access means	Unused AMPS channels	Slotted Aloha CSMA		FH SS (ISM)
Transmit power			40 watt	1 watt
Note: data in square brackets [ ] indicates proposed. CDPD: Cellular Digital Packet Data MDN: Microcellular Data Network ARDIS: Advanced Radio Data Information Service				

■ **Table 2**. *Wide area wireless packet data systems.*

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

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

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

High-Speed Wireless Local-Area Networks (WLANs)

Wireless local-area data networks (WLANs) can be categorized as providing low-mobility high-speed data communications within a confined region, e.g., a campus or a large building. Coverage range from a wireless data terminal is short, tens to hundreds of feet, like cordless telephones. Coverage is limited to within a room or to several rooms in a building. WLANs have been evolving for a few years, but overall, the situation is chaotic, with many different products being offered by many different vendors [1, 6]. There is no stable definition of the needs or design objectives for WLANs, with data rates ranging from hundreds of kb/s to more than 10 MB/s, and with several products providing one or two MB/s wireless link rates. The best description of the WLAN evolutionary process is: "having severe birth pains." An IEEE standards committee, 802.11, has been attempting to put some order into this topic, but their success has been

Product Company Location	Freq. (MHz)	Link rate	User rate	Protocol(s)	Access	No. of chan. or spread factor	Mod./coding	Power	Network topology
Altair Plus II Motorola Arlington Hts., IL	18-19 GHz	15 Mb/s	5.7 Mb/s	Ethernet			4-level FSK	25 mW peak	Eight devices/ radio; radio to base to Ethernet
WaveLAN NCR/AT&T Dayton, OH	902-928	2 Mb/s	1.6 Mb/s	Ethernet-like	DS SS		DQPSK	250 mW	Peer-to-peer
AirLAN Solectek San Diego, CA	902-928		2 Mb/s	Ethernet	DS SS		DQPSK	250 mW	PCMCIA w/ant; radio to hub
Freeport Windata Inc. Northboro, MA	902-928	16 Mb/s	5.7 Mb/s	Ethernet	DS SS	32 chips/bit	16 PSK trellis coding	650 mW	Hub
Intersect Persoft Inc. Madison, WI	902-928		2 Mb/s	Ethernet, token-ring	DS SS		DQPSK	250 mW	Hub
LAWN O'Neill Comm. Horsham, PA	902-928		38.4 kb/s	AX.25	SS	20 users/chan.; max. 4 chan.		20 mW	Peer-to-peer
WiLAN Wi-LAN Inc. Calgary, Alberta	902-928	20 Mb/s	1.5 Mb/s/ chan.	Ethernet, token ring	CDMA/ TDMA	3 chan. 10-15 links each	"unconventional"	30 mW	Peer-to-peer
RadioPort ALPS Electric USA	902-928		242 kb/s	Ethernet	SS	?/3 channels		100 mW	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
RadioLink Cal. Microwave Sunnyvale, CA	902-928; 2.4 GHz	250 kb/s	64 kb/s		FH SS	250 ms/hop 500 kHz space			Hub
Range LAN Proxim, Inc. Mountain View, CA	902-928		242 kb/s	Ethernet, token ring	DS SS	3 chan.		100 mW	
RangeLAN2 Proxim, Inc. Mountainview, CA	2.4 GHz	1.6 Mb/s	50 kb/s max.	Ethernet, token ring	FH SS	10 chan. @ 5 kb/s; 15 sub-ch. each		100 mW	Peer-to-peer bridge
Netwave Xircom Calabasas, CA	2.4 GHz	1 Mb/s/ adaptor		Ethernet, token ring	FH SS	82 1-MHz chan. or "hops"			Hub
Freelink Cabletron Sys. Rochester, NH	2.4 and 5.8 GHz		5.7 Mb/s	Ethernet	DS SS	32 chips/bit	16 PSK trellis coding	100 mW	Hub

■ **Table 3.** *Partial list of WLAn products.*

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

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

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

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

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

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

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

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

Paging/Messaging Systems

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

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

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

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

Satellite-Based Mobile Systems

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

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

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

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

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

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

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

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

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

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

Wireless Local Area Networks (WLANs)
- Strength: high data rate.
- Limitations: insufficient capacity for voice; limited coverage; no standards; chaos.
- Evolutionary trends: hard to discern from all the churning.

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

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

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

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

Privacy and Security of Communications
- Encrypted radio links.

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

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

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

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

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

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

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

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

•Frequency division duplexing to relax the requirement for synchronizing base station transmissions over a large region.

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

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

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

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

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

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

Parameter	Cellular (high tier)	Low tier PCS	Capacity factor
Speech coding	8 kb/s (MOS 3.4) No tandem coding	32 kb/s (MOS 4.1) 3 or 4 tandem	x 4
Speech activity	Yes (MOS 3.2)	No (MOS 4.1)	x 2.5
Percentage of good areas	90%	99%	x 2
Propagation σ	8 dB	10 dB	x 1.5
Total: trading quality for capacity			x 30

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

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

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

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

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

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

Quality, Capacity, and Economic Issues

*A*lthough the several trajectories toward low-tier PCS discussed in the previous section are clear, it does not fit the existing wireless communications paradigms. Thus, low-tier PCS has attracted less attention than the systems and technologies that are compatible with the existing paradigms. Some examples are cited in the following paragraphs.

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

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

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

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

Capacity, Quality, and Complexity

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

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

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

For the example in Table 4, significant speech and coverage quality has been traded for a factor of x 30 in base station capacity!! While base station capacity affects overall system capacity directly, it should be remembered that overall system capacity can be increased arbitrarily by decreasing the spacing between base stations. Thus, if the PACS low-tier PCS technology were to start with a base station capacity of x 0.5 of AMPS cellular[3] (a much lower figure than the x 0.8 sometimes quoted [12]), and then were degraded in quality as described above to yield the x 30 capacity factor, it would have a resulting capacity of x 15 of AMPS! Thus, it is obvious that making such a base station capacity comparison without including quality is not meaningful.

Economics, System Capacity, and Coverage Area Size

Claims are sometimes made that low-tier PCS cannot be provided economically, even though IT is what the user wants. These claims are often made based on economic estimates from the "cellular paradigm." These include:
- Very low estimates of market penetration, much less than cordless telephones, and often even less than cellular.
- High estimates of base station costs more appropriate to high-complexity high-cost cellular technology than to low-complexity low-cost low-tier technology.

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

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

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System Capacity/Coverage Area Size/Economics
Example 1

Assume channels/MHz are the same for cellular and PCS
    Cell site: spacing = 20,000 ft   cost = $1 M
    PCS port: spacing = 1,000 ft
    PCS system capacity is $(20000/1000)^2$ = 400 x cellular capacity

Then, for the system costs to be the same
    Port cost = ($1M/400) = $2,500, a reasonable figure

If, cell site and port each have 180 channels
    Cellular cost/circuit = $1M/180 = $5,555/circuit
    PCS cost/circuit = $2500/180 = $14/circuit

Example 2

Assume equal cellular and PCS system capacity
    Cell site: spacing = 20,000 ft
    PCS port: spacing = 1,000 ft
If, a cell site has 180 channels

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

Example 3

A Quality/cost trade
    Cell site: Spacing = 20,000 ft   cost = $1 M   channels = 180
    PCS port: Spacing = 1,000 ft   cost = $2,500

Cellular to PCS: base station spacing capacity factor = x 400
    PCS to Cellular "quality" reduction factors:

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

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

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

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

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

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

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

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

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

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

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

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

Other Issues

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

Improvement of Batteries

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

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

New Technology

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

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

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

People Only Want One Handset

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

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

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

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

The approach of using different communications devices for pedestrians than for vehicles is consistent with what has actually happened in other applications of technology in similarly different environments. For example, consider the case of audio cassette tape players. Pedestrians often carry and listen to small portable tape players with lightweight headsets (e.g., a Walkman[6]). When one of these people enters an automobile, he or she often removes the tape from the Walkman and inserts it into a tape player installed in the automobile. The automobile player has speakers that fill the car with sound. The Walkman is optimized for a pedestrian, whereas the vehicular-mounted player is optimized for an automobile. Both use the same tape, but they have separate tape heads, tape transports, audio preamps, etc. They do not attempt to share electronics. In this example, the tape cassette is the information-carrying entity similar to the user identification in the personal communications example discussed earlier. The main points are that the information is shared among different devices, but the devices are optimized for their environments and do not share electronics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Infrastructure Networks

*I*t is beyond the scope of this article to consider the details of PCS network infrastructures. However, there are perhaps as many network issues as there are wireless access issues discussed herein [22, 23, 31, 32]. With the possible exception of the self-organizing WLANS, wireless PCS technologies serve as access technologies to large integrated intelligent fixed communications infrastructure networks.

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

Several other existing networks have some of the capabilities needed to serve as access networks for PCS. Existing networks that could provide fixed base station interconnection include:
- Local exchange networks that could provide interconnection using copper or glass-fiber distribution facilities.
- Cable TV networks that could provide interconnection using new glass-fiber and coaxial-cable distribution facilities.
- Metropolitan fiber digital networks that could provide interconnection in some cities in which they are being deployed.

Networks that contain intelligence, e.g., databases, control processors, and signaling that is suitable, or could be readily adapted, to support PCS access include:
- Local exchange networks that are equipped with signaling system 7 common channel signaling (SS7 CCS), data bases and digital control processors.
- Interexchange networks that are similarly equipped.

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

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

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

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

Conclusion

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

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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.

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Biography

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