WIRELESS COMMUNICATIONS

Andrea Goldsmith

Stanford University

Chapter 1

Overview of Wireless Communications

Wireless communications is, by any measure, the fastest growing segment of the communications industry. As such, it has captured the attention of the media and the imagination of the public. Cellular phones have experienced exponential growth over the last decade, and this growth continues unabated worldwide, with more than a billion worldwide cell phone users projected in the near future. Indeed, cellular phones have become a critical business tool and part of everyday life in most developed countries, and are rapidly supplanting antiquated wireline systems in many developing countries. In addition, wireless local area networks are currently poised to supplement or replace wired networks in many businesses and campuses. Many new applications, including wireless sensor networks, automated highways and factories, smart homes and appliances, and remote telemedicine, are emerging from research ideas to concrete systems. The explosive growth of wireless systems coupled with the proliferation of laptop and palmtop computers indicate a bright future for wireless networks, both as stand-alone systems and as part of the larger networking infrastructure. However, many technical challenges remain in designing robust wireless networks that deliver the performance necessary to support emerging applications. In this introductory chapter we will briefly review the history of wireless networks, from the smoke signals of the Pre-industrial age to the cellular, satellite, and other wireless networks of today. We then discuss the wireless vision in more detail, including the technical challenges that must be overcome to make this vision a reality. We will also describe the current wireless systems in operation today as well as emerging systems and standards. The huge gap between the performance of current systems and the vision for future systems indicates that much research remains to be done to make the wireless vision a reality.

1.1 History of Wireless Communications

The first wireless networks were developed in the Pre-industrial age. These systems transmitted information over line-of-sight distances (later extended by telescopes) using smoke signals, torch signaling, flashing mirrors, signal flares, or semaphore flags. An elaborate set of signal combinations was developed to convey complex messages with these rudimentary signals. Observation stations were built on hilltops and along roads to relay these messages over large distances. These early communication networks were replaced first by the telegraph network (invented by Samuel Morse in 1838) and later by the telephone. In 1895, a few decades after the telephone was invented, Marconi demonstrated the first radio transmission from the Isle of Wight to a tugboat 18 miles away, and radio communications was born. Radio technology advanced rapidly to enable transmissions over larger distances with better quality, less power, and smaller, cheaper devices, thereby enabling public and private radio communications, television, and wireless networking.

Early radio systems transmitted analog signals. Today most radio systems transmit digital signals composed of binary bits, where the bits are obtained directly from a data signal or by digitizing an analog voice or music signal. A digital radio can transmit a continuous bit stream or it can group the bits into packets. The latter type of radio is called a *packet radio* and is characterized by bursty transmissions: the radio is idle except when it transmits a packet. The first network based on packet radio, ALOHANET, was developed at the University of Hawaii in 1971. This network enabled computer sites at seven campuses spread out over four islands to communicate with a central computer on Oahu via radio transmission. The network architecture used a star topology with the central computer at its hub. Any two computers could establish a bi-directional communications link between them by going through the central hub. ALOHANET incorporated the first set of protocols for channel access and routing in packet radio systems, and many of the underlying principles in these protocols are still in use today. The U.S. military was extremely interested in the combination of packet data and broadcast radio inherent to ALOHANET. Throughout the 70's and early 80's the Defense Advanced Research Projects Agency (DARPA) invested significant resources to develop networks using packet radios for tactical communications in the battlefield. The nodes in these ad hoc wireless networks had the ability to self-configure (or reconfigure) into a network without the aid of any established infrastructure. DARPA's investment in ad hoc networks peaked in the mid 1980's, but the resulting networks fell far short of expectations in terms of speed and performance. DARPA has continued work on ad hoc wireless network research for military use, but many technical challenges in terms of performance and robustness remain. Packet radio networks have also found commercial application in supporting wide-area wireless data services. These services, first introduced in the early 1990's, enable wireless data access (including email, file transfer, and web browsing) at fairly low speeds, on the order of 20 Kbps. The market for these wide-area wireless data services is relatively flat, due mainly to their low data rates, high cost, and lack of "killer applications". Next-generation cellular services are slated to provide wireless data in addition to voice, which will provide stiff competition to these data-only services.

The introduction of wired Ethernet technology in the 1970's steered many commercial companies away from radio-based networking. Ethernet's 10 Mbps data rate far exceeded anything available using radio, and companies did not mind running cables within and between their facilities to take advantage of these high rates. In 1985 the Federal Communications Commission (FCC) enabled the commercial development of wireless LANs by authorizing the public use of the Industrial, Scientific, and Medical (ISM) frequency bands for wireless LAN products. The ISM band was very attractive to wireless LAN vendors since they did not need to obtain an FCC license to operate in this band. However, the wireless LAN systems could not interfere with the primary ISM band users, which forced them to use a low power profile and an inefficient signaling scheme. Moreover, the interference from primary users within this frequency band was quite high. As a result these initial LAN systems had very poor performance in terms of data rates and coverage. This poor performance, coupled with concerns about security, lack of standardization, and high cost (the first network adaptors listed for $1,400 as compared to a few hundred dollars for a wired Ethernet card) resulted in weak sales for these initial LAN systems. Few of these systems were actually used for data networking: they were relegated to low-tech applications like inventory control. The current generation of wireless LANS, based on the IEEE 802.11b and 802.11a standards, have better performance, although the data rates are still relatively low (effective data rates on the order of 2 Mbps for 802.11b and around 10 Mbps for 802.11a) and the coverage area is still small (100-500 feet). Wired Ethernets today offer data rates of 100 Mbps, and the performance gap between wired and wireless LANs is likely to increase over time without additional spectrum allocation. Despite the big data rate differences, wireless LANs are becoming the prefered Internet access method in many homes, offices, and campus environments due to their convenience and freedom from wires. However, most wireless LANs support applications that are not bandwidth-intensive (email, file transfer, web browsing) and typically have only one user at a time accessing the system. The challenge for widespread wireless LAN acceptance and use will be for the wireless technology to support many users simultaneously, especially if bandwidth-intensive applications become more prevalent.

By far the most successful application of wireless networking has been the cellular telephone system. Cellular telephones are projected to have a billion subscribers worldwide within the next few years. The convergence of radio and telephony began in 1915, when wireless voice transmission between New York and San Francisco was first established. In 1946 public mobile telephone service was introduced in 25 cities across the United States. These initial systems used a central transmitter to cover an entire metropolitan area. This inefficient use of the radio spectrum coupled with the state of radio technology at that time severely limited the system capacity: thirty years after the introduction of mobile telephone service the New York system could only support 543 users.

A solution to this capacity problem emerged during the 50's and 60's when researchers at AT&T Bell Laboratories developed the cellular concept [1]. Cellular systems exploit the fact that the power of a transmitted signal falls off with distance. Thus, the same frequency channel can be allocated to users at spatially-separate locations with minimal interference between the users. Using this premise, a cellular system divides a geographical area into adjacent, non-overlapping, "cells". Different channel sets are assigned to each cell, and cells that are assigned the same channel set are spaced far enough apart so that interference between the mobiles in these cells is small. Each cell has a centralized transmitter and receiver (called a base station) that communicates with the mobile units in that cell, both for control purposes and as a call relay. All base stations have high-bandwidth connections to a mobile telephone switching office (MTSO), which is itself connected to the public-switched telephone network (PSTN). The handoff of mobile units crossing cell boundaries is typically handled by the MTSO, although in current systems some of this functionality is handled by the base stations and/or mobile units.

The original cellular system design was finalized in the late 60's. However, due to regulatory delays from the FCC, the system was not deployed until the early 80's, by which time much of the original technology was out-of-date. The explosive growth of the cellular industry took most everyone by surprise, especially the original inventors at AT&T, since AT&T basically abandoned the cellular business by the early 80's to focus on fiber optic networks. The first analog cellular system deployed in Chicago in 1983 was already saturated by 1984, at which point the FCC increased the cellular spectral allocation from 40 MHz to 50 MHz. As more and more cities became saturated with demand, the development of digital cellular technology for increased capacity and better performance became essential.

The second generation of cellular systems are digital. In addition to voice communication, these systems provide email, voice mail, and paging services. Unfortunately, the great market potential for cellular phones led to a proliferation of digital cellular standards. Today there are three different digital cellular phone standards in the U.S. alone, and other standards in Europe and Japan, none of which are compatible. The fact that different cities have different incompatible standards makes roaming throughout the U.S. using one digital cellular phone impossible. Most cellular phones today are dual-mode: they incorporate one of the digital standards along with the old analog standard, since only the analog standard provides universal coverage throughout the U.S. More details on today's digital cellular systems will be given in Section 15.

Radio paging systems are another example of an extremely successful wireless data network, with 50 million subscribers in the U.S. alone. However, their popularity is starting to wane with the widespread penetration and competitive cost of cellular telephone systems. Paging systems allow coverage over very wide areas by simultaneously broadcasting the pager message at high power from multiple base stations or satellites. These systems have been around for many years. Early radio paging systems were analog 1 bit messages signaling a user that someone was trying to reach him or her. These systems required callback over the regular telephone system to obtain the phone number of the paging party. Recent advances now allow a short digital message, including a phone number and brief text, to be sent to the pagee as well. In paging systems most of the complexity is built into the transmitters, so that pager receivers are small, lightweight, and have a long battery life. The network protocols are also very simple since broadcasting a message over all base stations requires no routing or handoff. The spectral inefficiency of these simultaneous broadcasts is compensated by limiting each message to be very short. Paging systems continue to evolve to expand their capabilities beyond very low-rate one-way communication. Current systems are attempting to implement "answer-back" capability, i.e. two-way communication. This requires a major change in the pager design, since it must now transmit signals in addition to receiving them, and the transmission distances can be quite large. Recently many of the major paging companies have teamed up with the palmtop computer makers to incorporate paging functions into these devices [2]. This development indicates that short messaging without additional functionality is no longer competitive given other wireless communication options.

Commercial satellite communication systems are now emerging as another major component of the wireless communications infrastructure. Satellite systems can provide broadcast services over very wide areas, and are also necessary to fill the coverage gap between high-density user locations. Satellite mobile communication systems follow the same basic principle as cellular systems, except that the cell base stations are now satellites orbiting the earth. Satellite systems are typically characterized by the height of the satellite orbit, low-earth orbit (LEOs at roughly 2000 Km. altitude), medium-earth orbit (MEOs at roughly 9000 Km. altitude), or geosynchronous orbit (GEOs at roughly 40,000 Km. altitude). The geosynchronous orbits are seen as stationary from the earth, whereas the satellites with other orbits have their coverage area change over time. The disadvantage of high altitude orbits is that it takes a great deal of power to reach the satellite, and the propagation delay is typically too large for delay-constrained applications like voice. However, satellites at these orbits tend to have larger coverage areas, so fewer satellites (and dollars) are necessary to provide wide-area or global coverage.

The concept of using geosynchronous satellites for communications was first suggested by the science fiction writer Arthur C. Clarke in 1945. However, the first deployed satellites, the Soviet Union's Sputnik in 1957 and the Nasa/Bell Laboratories' Echo-1 in 1960, were not geosynchronous due to the difficulty of lifting a satellite into such a high orbit. The first GEO satellite was launched by Hughes and Nasa in 1963 and from then until recently GEOs dominated both commercial and government satellite systems. The trend in current satellite systems is to use lower orbits so that lightweight handheld devices can communicate with the satellite [3]. Inmarsat is the most well-known GEO satellite system today, but most new systems use LEO orbits. These LEOs provide global coverage but the link rates remain low due to power and bandwidth constraints. These systems allow calls any time and anywhere using a single communications device. The services provided by satellite systems include voice, paging, and messaging services, all at fairly low data rates [3, 4]. The LEO satellite systems that have been deployed are not experiencing the growth they had anticipated, and one of the first systems (Iridium) was forced into bankruptcy and went out of business.

A natural area for satellite systems is broadcast entertainment. Direct broadcast satellites operate in the 12 GHz frequency band. These systems offer hundreds of TV channels and are major competitors to cable. Satellite-delivered digital radio is an emerging application in the 2.3 GHz frequency band. These systems offer digital audio broadcasts nationwide at near-CD quality. Digital audio broadcasting is also quite popular in Europe.

1.2 Wireless Vision

The vision of wireless communications supporting information exchange between people or devices is the communications frontier of the next century. This vision will allow people to operate a virtual office anywhere in the world using a small handheld device - with seamless telephone, modem, fax, and computer communications. Wireless networks will also be used to connect together palmtop, laptop, and desktop computers anywhere within an office building or campus, as well as from the corner cafe. In the home these networks will enable a new class of intelligent home electronics that can interact with each other and with the Internet in addition to providing connectivity between computers, phones, and security/monitoring systems. Such smart homes can also help the elderly and disabled with assisted living, patient monitoring, and emergency response. Video teleconferencing will take place between buildings that are blocks or continents apart, and these conferences can include travelers as well, from the salesperson who missed his plane connection to the CEO off sailing in the Caribbean. Wireless video will be used to create remote classrooms, remote training facilities, and remote hospitals anywhere in the world. Wireless sensors have an enormous range of both commercial and military applications. Commercial applications include monitoring of fire hazards, hazardous waste sites, stress and strain in buildings and bridges, or carbon dioxide movement and the spread of chemicals and gasses at a disaster site. These wireless sensors will self-configure into a network to process and interpret sensor measurements and then convey this information to a centralized control location. Military applications include identification and tracking of enemy targets, detection of chemical and biological attacks, and the support of unmanned robotic vehicles. Finally, wireless networks enable distributed control systems, with remote devices, sensors, and actuators linked together via wireless communication channels. Such networks are imperative for coordinating unmanned mobile units and greatly reduce maintenance and reconfiguration costs over distributed control systems with wired communication links, for example in factory automation.

The various applications described above are all components of the wireless vision. So what, exactly, is wireless communications? There are many different ways to segment this complex topic into different applications, systems, or coverage regions. Wireless applications include voice, Internet access, web browsing, paging and short messaging, subscriber information services, file transfer, video teleconferencing, sensing, and distributed control. Systems include cellular telephone systems, wireless LANs, wide-area wireless data systems, satellite systems, and ad hoc wireless networks. Coverage regions include in-building, campus, city, regional, and global. The question of how best to characterize wireless communications along these various segments has resulted in considerable fragmentation in the industry, as evidenced by the many different wireless products, standards, and services being offered or proposed. One reason for this fragmentation is that different wireless applications have different requirements. Voice systems have relatively low data rate requirements (around 20 Kbps) and can tolerate a fairly high probability of bit error (bit error rates, or BERs, of around 10^{-3}), but the total delay must be less than 100 msec or it becomes noticeable to the end user. On the other hand, data systems typically require much higher data rates (1-100 Mbps) and very small BERs (the target BER is 10^{-8} and all bits received in error must be retransmitted) but do not have a fixed delay requirement. Real-time video systems have high data rate requirements coupled with the same delay constraints as voice systems, while paging and short messaging have very low data rate requirements and no delay constraints. These diverse requirements for different applications make it difficult to build one wireless system that can satisfy all these requirements simultaneously. Wired networks are moving towards integrating the diverse requirements of different systems using a single protocol (e.g. ATM or SONET). This integration requires that the most stringent requirements for all applications be met simultaneously. While this is possible on wired networks, with data rates on the order of Gbps and BERs on the order of 10^{-12}, it is not possible on wireless networks, which have much lower data rates and higher BERs. Therefore, at least in the near future, wireless systems will continue to be fragmented, with different protocols tailored to support the requirements of different applications.

Will there be a large demand for all wireless applications, or will some flourish while others vanish? Companies are investing large sums of money to build multimedia wireless systems, yet the only highly profitable wireless application so far is voice. Experts have been predicting a huge market for wireless data services and products for the last 10 years, but the market for these products remains relatively small with sluggish growth. To examine the future of wireless data, it is useful to see the growth of various communication services over the last five years, as shown in Figure 1.1. In this figure we see that cellular and paging subscribers are growing exponentially. This growth is exceeded only by the growing demand for Internet access, driven by web browsing and email exchange. The number of laptop and palmtop computers is also growing steadily. These trends indicate that people want to communicate while on the move. They also want to take their computers wherever they go. It is therefore reasonable to assume that people want the same data communications capabilities on the move as they enjoy in their home or office. Yet the demand for high-speed wireless data has not materialized, except for relatively stationary users accessing the network via a wireless LAN. Why the discrepancy? Perhaps the main reason for the lack of enthusiasm in wireless data for highly mobile users is the high cost and poor performance of today's systems, along with a lack of "killer applications" for mobile users beyond voice and low-rate data.

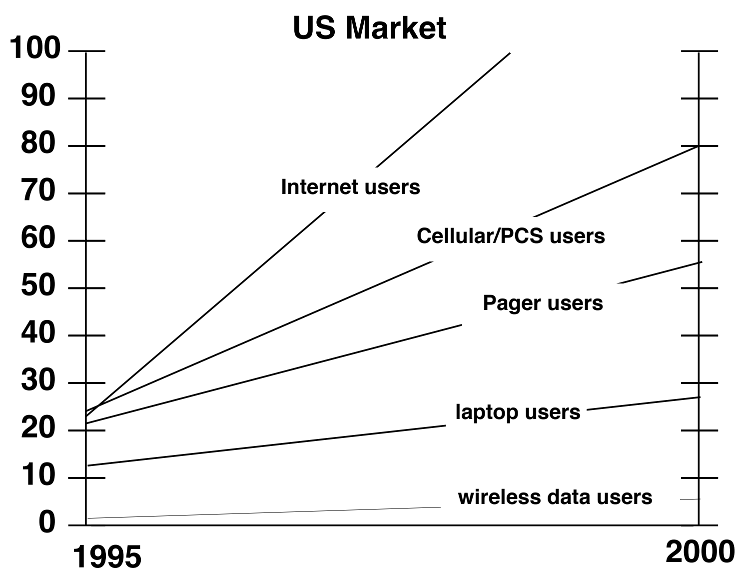

Figure 1.1: Growth of Wireless Communications Markets

Consider the performance gap between wired and wireless networks for both local and wide-area networks, as shown in Figures 1.2 and 1.3. Wired local-area networks have data rates that are two orders of magnitude higher than their wireless counterparts. ATM is promising 100,000 Kbps for wired wide-area networks, while today's wide-area wireless data services provide only tens of Kbps. Moreover, the performance gap between wired and wireless networks appears to be growing. Thus, the most formidable obstacle to the growth of wireless data systems is their performance. Many technical challenges must be overcome to improve wireless network performance such that users will accept this performance in exchange for mobility.

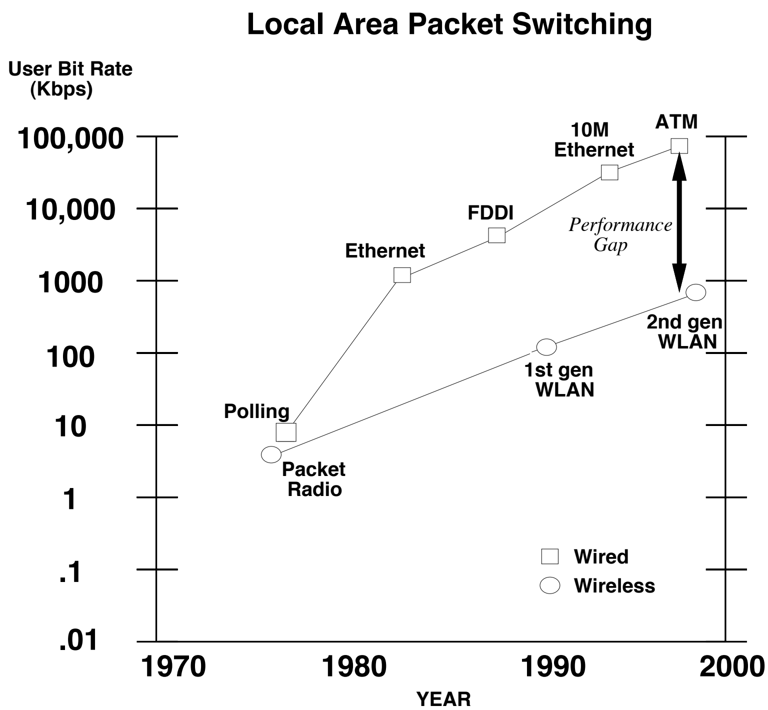

Figure 1.2: Performance Gap for Local Area Networks

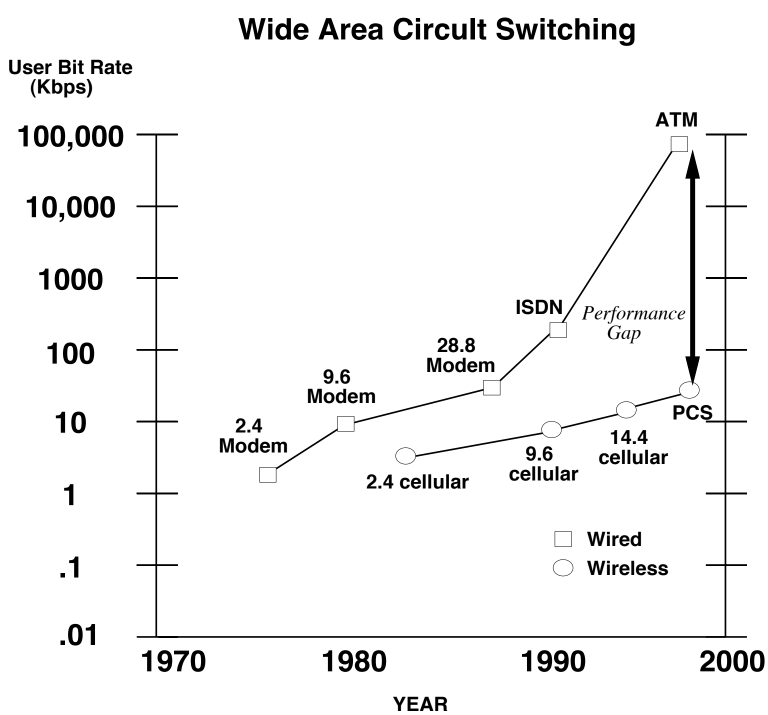

Figure 1.3: Performance Gap for Wide Area Networks

1.3 Technical Issues

The technical problems that must be solved to make the wireless vision a reality extend across all levels of the system design. At the hardware level the terminal must have multiple modes of operation to support the different applications and media. Desktop computers currently have the capability to process voice, image, text, and video data, but breakthroughs in circuit design are required to implement multimode operation in a small, lightweight, handheld device. Since most people don't want to carry around a twenty pound battery, the signal processing and communications hardware of the portable terminal must consume very little power, which will impact higher levels of the system design. Many of the signal processing techniques required for efficient spectral utilization and networking demand much processing power, precluding the use of low power devices. Hardware advances for low power circuits with high processing ability will relieve some of these limitations. However, placing the processing burden on fixed sites with large power resources has and will continue to dominate wireless system designs. The associated bottlenecks and single points-of-failure are clearly undesirable for the overall system. Moreover, in some applications (e.g. sensors) network nodes will not be able to recharge their batteries. In this case the finite battery energy must be allocated efficiently across all layers of the network protocol stack [5]. The finite bandwidth and random variations of the communication channel will also require robust compression schemes which degrade gracefully as the channel degrades.

The wireless communication channel is an unpredictable and difficult communications medium. First of all, the radio spectrum is a scarce resource that must be allocated to many different applications and systems. For this reason spectrum is controlled by regulatory bodies both regionally and globally. In the U.S. spectrum is allocated by the FCC, in Europe the equivalent body is the European Telecommunications Standards Institute (ETSI), and globally spectrum is controlled by the International Telecommunications Union (ITU). A regional or global system operating in a given frequency band must obey the restrictions for that band set forth by the corresponding regulatory body as well as any standards adopted for that spectrum. Spectrum can also be very expensive since in most countries, including the U.S., spectral licenses are now auctioned to the highest bidder. In the 2 GHz spectral auctions of the early 90s, companies spent over nine billion dollars for licenses, and the recent auctions in Europe for 3G spectrum garnered over 100 billion dollars. The spectrum obtained through these auctions must be used extremely efficiently to get a reasonable return on its investment, and it must also be reused over and over in the same geographical area, thus requiring cellular system designs with high capacity and good performance. At frequencies around several Gigahertz wireless radio components with reasonable size, power consumption, and cost are available. However, the spectrum in this frequency range is extremely crowded. Thus, technological breakthroughs to enable higher frequency systems with the same cost and performance would greatly reduce the spectrum shortage, although path loss at these higher frequencies increases, thereby limiting range.

As a signal propagates through a wireless channel, it experiences random fluctuations in time if the transmitter or receiver is moving, due to changing reflections and attenuation. Thus, the characteristics of the channel appear to change randomly with time, which makes it difficult to design reliable systems with guaranteed performance. Security is also more difficult to implement in wireless systems, since the airwaves are susceptible to snooping from anyone with an RF antenna. The analog cellular systems have no security, and you can easily listen in on conversations by scanning the analog cellular frequency band. All digital cellular systems implement some level of encryption. However, with enough knowledge, time and determination most of these encryption methods can be cracked and, indeed, several have been compromised. To support applications like electronic commerce and credit card transactions, the wireless network must be secure against such listeners.

Wireless networking is also a significant challenge [23, 24, 25, 26]. The network must be able to locate a given user wherever it is amongst millions of globally-distributed mobile terminals. It must then route a call to that user as it moves at speeds of up to 100 mph. The finite resources of the network must be allocated in a fair and efficient manner relative to changing user demands and locations. Moreover, there currently exists a tremendous infrastructure of wired networks: the telephone system, the Internet, and fiber optic cable, which should be used to connect wireless systems together into a global network. However, wireless systems with mobile users will never be able to compete with wired systems in terms of data rate and reliability. The design of protocols to interface between wireless and wired networks with vastly different performance capabilities remains a challenging topic of research.

Perhaps the most significant technical challenge in wireless network design is an overhaul of the design process itself. Wired networks are mostly designed according to the layers of the OSI model: each layer is designed independent from the other layers with baseline mechanisms to interface between layers. This methodology greatly simplifies network design, although it leads to some inefficiency and performance loss due to the lack of a global design optimization. However, the large capacity and good reliability of wired network links make it easier to buffer high-level network protocols from the lower level protocols for link transmission and access, and the performance loss resulting from this isolated protocol design is fairly low. However, the situation is very different in a wireless network. Wireless links can exhibit very poor performance, and this performance along with user connectivity and network topology changes over time. In fact, the very notion of a wireless link is somewhat fuzzy due to the nature of radio propagation. The dynamic nature and poor performance of the underlying wireless communication channel indicates that high-performance wireless networks must be optimized for this channel and must adapt to its variations as well as to user mobility. Thus, these networks will require an integrated and adaptive protocol stack across all layers of the OSI model, from the link layer to the application layer.

In summary, technological advances in the following areas are needed to implement the wireless vision outlined above:

- Measurements and models for wireless indoor and outdoor channels.
- Hardware for low-power handheld computer and communication terminals.
- Techniques to mitigate wireless channel impairments and to improve the quality and spectral efficiency of communication over wireless channels.
- Better means of sharing the limited spectrum to accommodate the different wireless applications.
- Protocols for routing and mobility management which support users on the move.
- An architecture to connect the various wireless subnetworks together and to the backbone wireline network.
- An integrated and adaptive protocol stack for wireless networks that extends across all layers of the OSI model.

Given these requirements, the field of wireless communications draws from many areas of expertise, including physics, communications, signal processing, network theory and design, software design, and hardware design. Moreover, given the fundamental limitations of the wireless channels and the explosive demand for its utilization, communication between these interdisciplinary groups is necessary to implement the most rudimentary shell of the wireless vision depicted above.

We now give an overview of the wireless systems in operation today. It will be clear from this overview that the wireless vision remains a distant goal, with many challenges remaining before it will be realized. Many of these challenges will be examined in detail in later chapters.

1.4 Current Wireless Systems

1.4.1 Cellular Telephone Systems

Cellular telephone systems, also referred to as Personal Communication Systems (PCS), are extremely popular and lucrative worldwide: these systems have sparked much of the optimism about the future of wireless networks. Cellular telephone systems are designed to provide two-way voice communication at vehicle speeds with regional or national coverage. Cellular systems were initially designed for mobile terminals inside vehicles with antennas mounted on the vehicle roof. Today these systems have evolved to support lightweight handheld mobile terminals operating inside and outside buildings at both pedestrian and vehicle speeds.

The basic premise behind cellular system design is frequency reuse, which exploits path loss to reuse the same frequency spectrum at spatially-separated locations. Specifically, the coverage area of a cellular system is divided into nonoverlapping *cells* where some set of channels is assigned to each cell. This same channel set is used in another cell some distance away, as shown in Figure 1.4, where f_i denotes the channel set used in a particular cell. Operation within a cell is controlled by a centralized base station, as described in more detail below. The interference caused by users in different cells operating on the same channel set is called intercell interference. The spatial separation of cells that reuse the same channel set, the *reuse distance*, should be as small as possible to maximize the spectral efficiency obtained by frequency reuse. However, as the reuse distance decreases, intercell interference increases, due to the smaller propagation distance between interfering cells. Since intercell interference must remain below a given threshold for acceptable system performance, reuse distance cannot be reduced below some minimum value. In practice it is quite difficult to determine this minimum value since both the transmitting and interfering signals experience random power variations due to path loss, shadowing, and multipath. In order to determine the best reuse distance and base station placement, an accurate characterization of signal propagation within the cells is needed. This characterization is usually obtained using detailed analytical models, sophisticated computer-aided modeling, or empirical measurements.

Initial cellular system designs were mainly driven by the high cost of base stations, approximately one million dollars apiece. For this reason early cellular systems used a relatively small number of cells to cover an entire city or region. The cell base stations were placed on tall buildings or mountains and transmitted at very high power with cell coverage areas of several square miles. These large cells are called macrocells. Signals propagated out from base stations uniformly in all directions, so a mobile moving in a circle around the base station would have approximately constant received power. This circular contour of constant power yields a hexagonal cell shape for the system, since a hexagon is the closest shape to a circle that can cover a given area with multiple nonoverlapping cells.

Cellular telephone systems are now evolving to smaller cells with base stations close to street level or inside buildings transmitting at much lower power. These smaller cells are called microcells or picocells, depending on their size. This evolution is driven by two factors: the need for higher capacity in areas with high user density and the reduced size and cost of base station electronics. A cell of any size can support roughly the same number of users if the system is scaled accordingly. Thus, for a given coverage area a system with many microcells has a higher number of users per unit area than a system with just a few macrocells. Small cells also have better propagation conditions since the lower base stations have reduced shadowing and multipath. In addition, less power is required at the mobile terminals in microcellular systems, since the terminals are closer to the base stations. However, the evolution to smaller cells has complicated network design. Mobiles traverse a small cell more quickly than a large cell, and therefore handoffs must be processed more quickly. In addition, location management becomes more complicated, since there are more cells within a given city where a mobile may be located. It is also harder to develop

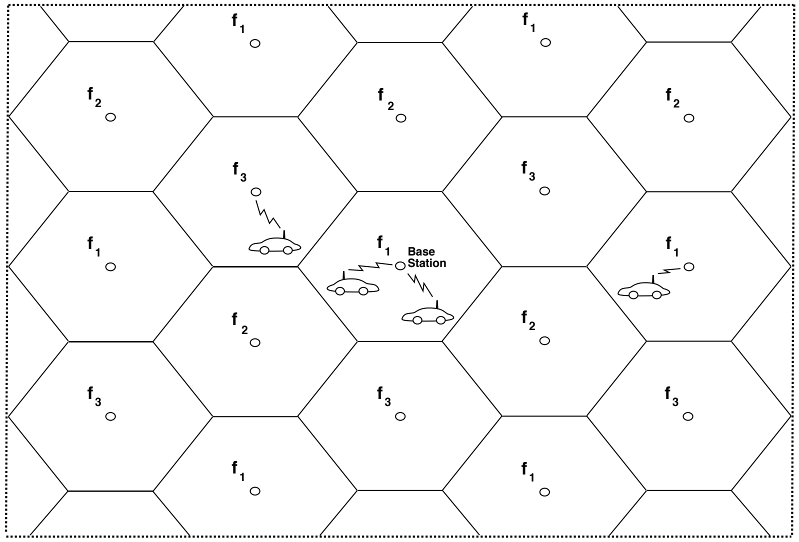

Figure 1.4: Cellular Systems.

general propagation models for small cells, since signal propagation in these cells is highly dependent on base station placement and the geometry of the surrounding reflectors. In particular, a hexagonal cell shape is not a good approximation to signal propagation in microcells. Microcellular systems are often designed using square or triangular cell shapes, but these shapes have a large margin of error in their approximation to microcell signal propagation [7].

All base stations in a city are connected via a high-speed communications link to a mobile telephone switching office (MTSO), as shown in Figure 1.5. The MTSO acts as a central controller for the network, allocating channels within each cell, coordinating handoffs between cells when a mobile traverses a cell boundary, and routing calls to and from mobile users in conjunction with the public switched telephone network (PSTN). A new user located in a given cell requests a channel by sending a call request to the cell's base station over a separate control channel. The request is relayed to the MTSO, which accepts the call request if a channel is available in that cell. If no channels are available then the call request is rejected. A call handoff is initiated when the base station or the mobile in a given cell detects that the received signal power for that call is approaching a given minimum threshold. In this case the base station informs the MTSO that the mobile requires a handoff, and the MTSO then queries surrounding base stations to determine if one of these stations can detect that mobile's signal. If so then the MTSO coordinates a handoff between the original base station and the new base station. If no channels are available in the cell with the new base station then the handoff fails and the call is terminated. False handoffs may also be initiated if a mobile is in a deep fade, causing its received signal power to drop below the minimum threshold even though it may be nowhere near a cell boundary.

Cellular telephone systems have recently moved from analog to digital technology. Digital technology has many advantages over analog. The components are cheaper, faster, smaller, and require less power. Voice quality is improved due to error correction coding. Digital systems also have higher capacity than analog systems since they are not limited to frequency division for multiple access, and they can take advantage of advanced compression techniques and voice activity factors. In addition, encryption

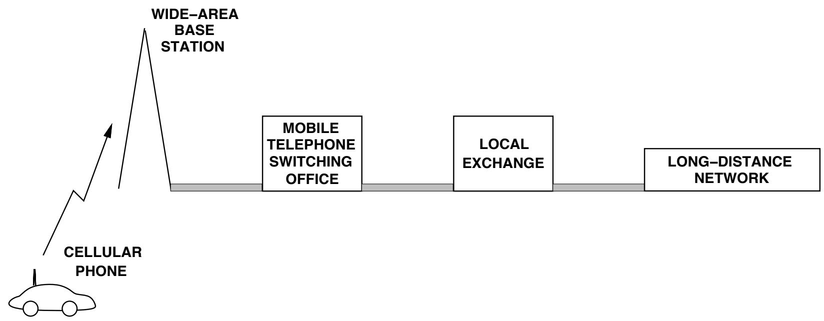

Figure 1.5: Current Cellular Network Architecture

techniques can be used to secure digital signals against eavesdropping. All cellular systems being deployed today are digital, and these systems provide voice mail, paging, and email services in addition to voice. Due to their lower cost and higher efficiency, service providers have used aggressive pricing tactics to encourage user migration from analog to digital systems. Since they are relatively new, digital systems do not always work as well as the old analog ones. Users experience poor voice quality, frequent call dropping, short battery life, and spotty coverage in certain areas. System performance will certainly improve as the technology and networks mature. However, it is unlikely that cellular phones will provide the same quality as wireline service any time soon. The great popularity of cellular systems indicates that users are willing to tolerate inferior voice communications in exchange for mobility.

Spectral sharing in digital cellular can be done using frequency-division, time-division, code-division (spread spectrum), or hybrid combinations of these techniques (see Chapter 14). In time-division the signal occupies the entire frequency band, and is divided into time slots t_i which are reused in distant cells [8]. Time division is depicted by Figure 1.4 if the f_is are replaced by t_is. Time-division is more difficult to implement than frequency-division since the users must be time-synchronized. However, it is easier to accommodate multiple data rates with time-division since multiple timeslots can be assigned to a given user. Spectral sharing can also be done using code division, which is commonly implemented using either direct-sequence or frequency-hopping spread spectrum [9]. In direct-sequence each user modulates its data sequence by a different pseudorandom chip sequence which is much faster than the data sequence. In the frequency domain, the narrowband data signal is convolved with the wideband chip signal, resulting in a signal with a much wider bandwidth than the original data signal - hence the name spread spectrum. In frequency hopping the carrier frequency used to modulate the narrowband data signal is varied by a pseudorandom chip sequence which may be faster or slower than the data sequence. Since the carrier frequency is hopped over a large signal bandwidth, frequency-hopping also spreads the data signal to a much wider bandwidth. Typically spread spectrum signals are superimposed onto each other within the same signal bandwidth. A spread spectrum receiver can separate each of the distinct signals by separately decoding each spreading sequence. However, since the codes are semi-orthogonal, the users within a cell interfere with each other (intracell interference), and codes that are reused in other cells also cause interference (intercell interference). Both the intracell and intercell interference power is reduced by the spreading gain of the code. Moreover, interference in spread spectrum systems can be further reduced through multiuser detection and interference cancellation.

In the U.S. the standards activities surrounding the second generation of digital cellular systems provoked a raging debate on multiple access for these systems, resulting in several incompatible standards [10, 11, 12]. In particular, there are two standards in the 900 MHz (cellular) frequency band: IS-54, which uses a combination of TDMA and FDMA, and IS-95, which uses semi-orthogonal CDMA [13, 14]. The spectrum for digital cellular in the 2 GHz (PCS) frequency band was auctioned off, so service providers could use an existing standard or develop proprietary systems for their purchased spectrum. The end result has been three different digital cellular standards for this frequency band: IS-136 (which is basically the same as IS-54 at a higher frequency), IS-95, and the European digital cellular standard GSM, which uses a combination of TDMA and slow frequency-hopping. The digital cellular standard in Japan is similar to IS-54 and IS-136 but in a different frequency band, and the GSM system in Europe is at a different frequency than the GSM systems in the U.S. This proliferation of incompatible standards in the U.S. and abroad makes it impossible to roam between systems nationwide or globally without using multiple phones (and phone numbers).

All of the second generation digital cellular standards have been enhanced to support high rate packet data services [15]. GSM systems provide data rates of up to 100 Kbps by aggregating all timeslots together for a single user. This enhancement was called GPRS. A more fundamental enhancement, called Enhanced Data Services for GSM Evolution (EDGE), further increases data rates using a high-level modulation format combined with FEC coding. This modulation is more sensitive to fading effects, and EDGE uses adaptive modulation and coding to mitigate this problem. Specifically, EDGE defines six different modulation and coding combinations, each optimized to a different value of received SNR. The received SNR is measured at the receiver and fed back to the transmitter, and the best modulation and coding combination for this SNR value is used. The IS-54 and IS-136 systems currently provide data rates of 40-60 Kbps by aggregating time slots and using high-level modulation. This new TDMA standard is referred to as IS-136HS (high-speed). Many of these time-division systems are moving toward GSM, and their corresponding enhancements to support high speed data. The IS-95 systems support higher data using a time-division technique called high data rate (HDR)[16].

The third generation of cellular phones is based on a wideband CDMA standard developed within the auspices of the International Telecommunications Union (ITU) [15]. The standard, initially called International Mobile Telecommunications 2000 (IMT-2000), provides different data rates depending on mobility and location, from 384 Kbps for pedestrian use to 144 Kbps for vehicular use to 2 Mbps for indoor office use. The 3G standard is incompatible with 2G systems, so service providers must invest in a new infrastructure before they can provide 3G service. The first 3G systems were deployed in Japan, where they have experienced limited success with a somewhat slower growth than expected. One reason that 3G services came out first in Japan is the process of 3G spectrum allocation, which in Japan was awarded without much up-front cost. The 3G spectrum in both Europe and the U.S. is allocated based on auctioning, thereby requiring a huge initial investment for any company wishing to provide 3G service. European companies collectively paid over 100 billion dollars in their 3G spectrum auctions. There has been much controversy over the 3G auction process in Europe, with companies charging that the nature of the auctions caused enormous overbidding and that it will be very difficult if not impossible to reap a profit on this spectrum. A few of the companies have already decided to write off their investment in 3G spectrum and not pursue system buildout. In fact 3G systems have not yet come online in Europe, and it appears that data enhancements to 2G systems may suffice to satisfy user demands. However, the 2G spectrum in Europe is severely overcrowded, so users will either eventually migrate to 3G or regulations will change so that 3G bandwidth can be used for 2G services (which is not currently allowed in Europe). 3G development in the U.S. has lagged far behind that of Europe. The available 3G spectrum in the U.S. in only about half that available in Europe. Due to wrangling about which parts of the spectrum will be used, the spectral auctions have been delayed. However, the U.S. does allow the 1G and 2G spectrum to be used for 3G, and this flexibility may allow a more gradual rollout and investment than the more restrictive 3G requirements in Europe. It appears that delaying 3G in the U.S. will allow U.S. service providers to learn from the mistakes and successes in Europe and Japan.

Efficient cellular system designs are *interference-limited*, i.e. the interference dominates the noise floor since otherwise more users could be added to the system. As a result, any technique to reduce interference in cellular systems leads directly to an increase in system capacity and performance. Some methods for interference reduction in use today or proposed for future systems include cell sectorization [6], directional and smart antennas [19], multiuser detection [20], and dynamic channel and resource allocation [21, 22].

1.4.2 Cordless Phones

Cordless telephones first appeared in the late 1970's and have experienced spectacular growth ever since. Roughly half of the phones in U.S. homes today are cordless. Cordless phones were originally designed to provide a low-cost low-mobility wireless connection to the PSTN, i.e. a short wireless link to replace the cord connecting a telephone base unit and its handset. Since cordless phones compete with wired handsets, their voice quality must be similar: initial cordless phones had poor voice quality and were quickly discarded by users. The first cordless systems allowed only one phone handset to connect to each base unit, and coverage was limited to a few rooms of a house or office. This is still the main premise behind cordless telephones in the U.S. today, although these phones now use digital technology instead of analog. In Europe and the Far East digital cordless phone systems have evolved to provide coverage over much wider areas, both in and away from home, and are similar in many ways to today's cellular telephone systems.

Digital cordless phone systems in the U.S. today consist of a wireless handset connected to a single base unit which in turn is connected to the PSTN. These cordless phones impose no added complexity on the telephone network, since the cordless base unit acts just like a wireline telephone for networking purposes. The movement of these cordless handsets is extremely limited: a handset must remain within range of its base unit. There is no coordination with other cordless phone systems, so a high density of these systems in a small area, e.g. an apartment building, can result in significant interference between systems. For this reason cordless phones today have multiple voice channels and scan between these channels to find the one with minimal interference. Spread spectrum cordless phones have also been introduced to reduce interference from other systems and narrowband interference.

In Europe and the Far East the second generation of digital cordless phones (CT-2, for cordless telephone, second generation) have an extended range of use beyond a single residence or office. Within a home these systems operate as conventional cordless phones. To extend the range beyond the home base stations, also called *phone-points* or *telepoints*, are mounted in places where people congregate, like shopping malls, busy streets, train stations, and airports. Cordless phones registered with the telepoint provider can place calls whenever they are in range of a telepoint. Calls cannot be received from the telepoint since the network has no routing support for mobile users, although some newer CT-2 handsets have built-in pagers to compensate for this deficiency. These systems also do not handoff calls if a user moves between different telepoints, so a user must remain within range of the telepoint where his call was initiated for the duration of the call. Telepoint service was introduced twice in the United Kingdom and failed both times, but these systems grew rapidly in Hong Kong and Singapore through the mid 1990's. This rapid growth deteriorated quickly after the first few years, as cellular phone operators cut prices to compete with telepoint service. The main complaint about telepoint service was the incomplete radio coverage and lack of handoff. Since cellular systems avoid these problems, as long as prices were competitive there was little reason for people to use telepoint services. Most of these services have now disappeared.

Another evolution of the cordless telephone designed primarily for office buildings is the European DECT system. The main function of DECT is to provide local mobility support for users in an in-building private branch exchange (PBX). In DECT systems base units are mounted throughout a building, and each base station is attached through a controller to the PBX of the building. Handsets communicate to the nearest base station in the building, and calls are handed off as a user walks between base stations. DECT can also ring handsets from the closest base station. The DECT standard also supports telepoint services, although this application has not received much attention, probably due to the failure of CT-2 services. There are currently around 7 million DECT users in Europe, but the standard has not yet spread to other countries.

The most recent advance in cordless telephone system design is the Personal Handyphone System (PHS) in Japan. The PHS system is quite similar to a cellular system, with widespread base station deployment supporting handoff and call routing between base stations. With these capabilities PHS does not suffer from the main limitations of the CT-2 system. Initially PHS systems enjoyed one of the fastest growth rates ever for a new technology. In 1997, two years after its introduction, PHS subscribers peaked at about 7 million users, and has declined slightly since then due mainly to sharp price cutting by cellular providers. The main difference between a PHS system and a cellular system is that PHS cannot support call handoff at vehicle speeds. This deficiency is mainly due to the dynamic channel allocation procedure used in PHS. Dynamic channel allocation greatly increases the number of handsets that can be serviced by a single base station, thereby lowering the system cost, but it also complicates the handoff procedure. It is too soon to tell if PHS systems will go the same route as CT-2. However, it is clear from the recent history of cordless phone systems that to extend the range of these systems beyond the home requires either the same functionality as cellular systems or a significantly reduced cost.

1.4.3 Wireless LANs

Wireless LANs provide high-speed data within a small region, e.g. a campus or small building, as users move from place to place. Wireless devices that access these LANs are typically stationary or moving at pedestrian speeds. Nearly all wireless LANs in the United States use one of the ISM frequency bands. The appeal of these frequency bands, located at 900 MHz, 2.4 GHz, and 5.8 GHz, is that an FCC license is not required to operate in these bands. However, this advantage is a double-edged sword, since many other systems operate in these bands for the same reason, causing a great deal of interference between systems. The FCC mitigates this interference problem by setting a limit on the power per unit bandwidth for ISM-band systems. Wireless LANs can have either a star architecture, with wireless access points or hubs placed throughout the coverage region, or a peer-to-peer architecture, where the wireless terminals self-configure into a network.

Dozens of wireless LAN companies and products appeared in the early 1990's to capitalize on the "pent-up demand" for high-speed wireless data. These first generation wireless LANs were based on proprietary and incompatible protocols, although most operated in the 900 MHz ISM band using direct sequence spread spectrum with data rates on the order of 1-2 Mbps. Both star and peer-to-peer architectures were used. The lack of standardization for these products led to high development costs, low-volume production, and small markets for each individual product. Of these original products only a handful were even mildly successful. Only one of the first generation wireless LANs, Motorola's Altair, operated outside the 900 MHz ISM band. This system, operating in the licensed 18 GHz band, had data rates on the order of 6 Mbps. However, performance of Altair was hampered by the high cost of components and the increased path loss at 18 GHz, and Altair was discontinued within a few years of its release.

The second generation of wireless LANs in the United States operate in the 2.4 GHz ISM band. A wireless LAN standard for this frequency band, the IEEE 802.11b standard, was developed to avoid some of the problems with the proprietary first generation systems. The standard specifies frequency hopped spread spectrum with data rates of around 1.6 Mbps (raw data rates of 11 Mbps) and a range of approximately 500 ft. The network architecture can be either star or peer-to-peer. Many companies have developed products based on the 802.11b standard, and these products are constantly evolving to provide higher data rates and better coverage at very low cost. The market for 802.11b wireless LANs is growing, and computer manufacturers have begun integrating the cards directly into their laptops. Many companies and universities have installed 802.11b base stations throughout their locations, and even local coffee houses are installing these base stations to offer wireless access to customers. Optimism is high that the wireless LAN market is poised to take off (although this prediction has been made every year since the inception of wireless LANs).

Perhaps the main impediment to the ultimate success of the 802.11b wireless LANs is the newest wireless LAN standard, IEEE 802.11a. This wireless LAN operates in the 5 GHz unlicensed band, which has much more spectrum and less interference than the 2.4 GHz band. The 802.11a standard is based on OFDM modulation and provides on the order of 50 Mbps data rates. There was some initial concern that 802.11a systems would be significantly more expensive than 802.11b systems, but in fact they are becoming quite competitive in price.

In Europe wireless LAN development revolves around the HIPERLAN (high performance radio LAN) standards. The first HIPERLAN standard, HIPERLAN Type 1, is similar to the IEEE 802.11a wireless LAN standard and promises data rates of 20 Mbps at a range of 50 meters (150 feet). This system operates in the 5 GHz band. Its network architecture is peer-to-peer, and the channel access mechanism uses a variation of ALOHA with prioritization based on the lifetime of packets. The next generation of HIPERLAN, HIPERLAN Type 2, is still under development, but the goal is to provide data rates on the order of 54 Mbps with a similar range, and also to support access to cellular, ATM, and IP networks. HIPERLAN Type 2 is also supposed to include support for Quality-of-Service (QoS), however it is not yet clear how and to what extent this will be done.

1.4.4 Wide Area Wireless Data Services

Wide area wireless data services provide low rate wireless data to high-mobility users over a very large coverage area. In these systems a given geographical region is serviced by base stations mounted on towers, rooftops, or mountains. The base stations can be connected to a backbone wired network or form a multihop ad hoc network. Initial data rates for these systems were below 10 Kbps but gradually increased to 20 Kbps. There are two main players in wide area wireless data services: Motient and Bell South Mobile Data (formerly RAM Mobile Data). Metricom provided a similar service with a network architecture consisting of a large network of small inexpensive base stations with small coverage areas. The increased efficiency of the small coverage areas allowed for higher data rates in Metricom, 76 Kbps, than in the other wide-area wireless data systems. However, the high infrastructure cost for Metricom eventually forced it into bankruptcy, and the system was shut down. Some of the infrastructure was bought and is operating in a few araas as Ricochet.

The cellular digital packet data (CDPD) system is a wide area wireless data service overlayed on the analog cellular telephone network. CDPD shares the FDMA voice channels of the analog systems, since many of these channels are idle due to the growth of digital cellular. The CDPD service provides packet data transmission at rates of 19.2 Kbps, and is available throughout the U.S. However, since newer generations of cellular systems also provide data services, CDPD will likely be replaced by these newer services.

All of these wireless data services have failed to grow as rapidly or to attract as many subscribers as initially predicted, especially in comparison with the rousing success of wireless voice systems. There is disagreement on why these systems have experienced such anemic growth. Data rates for these systems are clearly low, especially in comparison with their wireline counterparts. Pricing for these services also remains high. There is a perceived lack of "killer applications" for wireless data: while voice communication on the move seems essential for a large part of the population, most people can wait until they have access to a phone line or wired network for data exchange. This may change with the proliferation of laptop and palmtop computers and the explosive demand for constant Internet access and email exchange. Optimists point to these factors as the drivers for wireless data but, as with wireless LANs, wide area wireless data services have been the pot of gold around the corner for many years yet have so far failed to deliver on these high expectations.

1.4.5 Fixed Wireless Access

Fixed wireless access provides wireless communications between a fixed access point and multiple terminals. These systems were initially proposed to support interactive video service to the home, but the application emphasis has now shifted to providing high speed data access (tens of Mbps) to the Internet, the WWW, and to high speed data networks for both homes and businesses. In the U.S. two frequency bands have been set aside for these systems: part of the 28 GHz spectrum is allocated for local distribution systems (local multipoint distribution systems or LMDS) and a band in the 2 GHz spectrum is allocated for metropolitan distribution systems (multichannel multipoint distribution services or MMDS). LMDS represents a quick means for new service providers to enter the already stiff competition among wireless and wireline broadband service providers. MMDS is a television and telecommunication delivery system with transmission ranges of 30-50 Km. MMDS has the capability to deliver over one hundred digital video TV channels along with telephony and access to emerging interactive services such as the Internet. MMDS will mainly compete with existing cable and satellite systems. Europe is developing a standard similar to MMDS called Hiperaccess.

1.4.6 Paging Systems

Paging systems provide very low rate one-way data services to highly mobile users over a very wide coverage area. Paging systems have experienced steady growth for many years and currently serve about 56 million customers in the United States. However, the popularity of paging systems is declining as cellular systems become cheaper and more ubiquitous. In order to remain competitive paging companies have slashed prices, and few of these companies are currently profitable. To reverse their declining fortunes, a consortium of paging service providers have recently teamed up with Microsoft and Compaq to incorporate paging functionality and Internet access into palmtop computers [2].

Paging systems broadcast a short paging message simultaneously from many tall base stations or satellites transmitting at very high power (hundreds of watts to kilowatts). Systems with terrestrial transmitters are typically localized to a particular geographic area, such as a city or metropolitan region, while geosynchronous satellite transmitters provide national or international coverage. In both types of systems no location management or routing functions are needed, since the paging message is broadcast over the entire coverage area. The high complexity and power of the paging transmitters allows low-complexity, low-power, pocket paging receivers with a long usage time from small and lightweight batteries. In addition, the high transmit power allows paging signals to easily penetrate building walls. Paging service also costs less than cellular service, both for the initial device and for the monthly usage charge, although this price advantage has declined considerably in recent years. The low cost, small and lightweight handsets, long battery life, and ability of paging devices to work almost anywhere indoors or outdoors are the main reasons for their appeal.

Some paging services today offer rudimentary (1 bit) answer-back capabilities from the handheld paging device. However, the requirement for two-way communication destroys the asymmetrical link advantage so well exploited in paging system design. A paging handset with answer-back capability requires a modulator and transmitter with sufficient power to reach the distant base station. These requirements significantly increase the size and weight and reduce the usage time of the handheld pager. This is especially true for paging systems with satellite base stations, unless terrestrial relays are used.

1.4.7 Satellite Networks

Satellite systems provide voice, data, and broadcast services with widespread, often global, coverage to high-mobility users as well as to fixed sites. Satellite systems have the same basic architecture as cellular systems, except that the cell base-stations are satellites orbiting the earth. Satellites are characterized by their orbit distance from the earth. There are three main types of satellite orbits: low-earth orbit (LEOs) at 500-2000 Kms, medium-earth orbit (MEO) at 10,000 Kms, and geosynchronous orbit (GEO) at 35,800 Kms. A geosynchronous satellite has a large coverage area that is stationary over time, since the earth and satellite orbits are synchronous. Satellites with lower orbits have smaller coverage areas, and these coverage areas change over time so that satellite handoff is needed for stationary users or fixed point service.

Since geosynchronous satellites have such large coverage areas just a handful of satellites are needed for global coverage. However, geosynchronous systems have several disadvantages for two-way communication. It takes a great deal of power to reach these satellites, so handsets are typically large and bulky. In addition, there is a large round-trip propagation delay: this delay is quite noticeable in two-way voice communication. Recall also from Section 15 that high-capacity cellular systems require small cell sizes. Since geosynchronous satellites have very large cells, these systems have small capacity, high cost, and low data rates, less than 10 Kbps. The main geosynchronous systems in operation today are the global Inmarsat system, MSAT in North America, Mobilesat in Australia, and EMS and LLM in Europe.

The trend in current satellite systems is to use the lower LEO orbits so that lightweight handheld devices can communicate with the satellites and propagation delay does not degrade voice quality. The best known of these new LEO systems are Globalstar and Teledesic. Globalstar provides voice and data services to globally-roaming mobile users at data rates under 10 Kbps. The system requires roughly 50 satellites to maintain global coverage. Teledesic uses 288 satellites to provide global coverage to fixed-point users at data rates up to 2 Mbps. Teledesic is set to be deployed in 2005. The cell size for each satellite in a LEO system is much larger than terrestrial macrocells or microcells, with the corresponding decrease in capacity associated with large cells. Cost of these satellites, to build, to launch, and to maintain, is also much higher than that of terrestrial base stations, so these new LEO systems are unlikely to be cost-competitive with terrestrial cellular and wireless data services. Although these LEO systems can certainly complement these terrestrial systems in low-population areas, and are also appealing to travelers desiring just one handset and phone number for global roaming, it remains to be seen if there are enough such users willing to pay the high cost of satellite services to make these systems economically viable. In fact, Iridium, the largest and best-known of the LEO systems, was forced into bankruptcy and disbanded.

1.4.8 Bluetooth

Bluetooth is a cable-replacement RF technology for short range connections between wireless devices. The Bluetooth standard is based on a tiny microchip incorporating a radio transceiver that is built into digital devices. The transceiver takes the place of a connecting cable for devices such as cell phones, laptop and palmtop computers, portable printers and projectors, and network access points. Bluetooth is mainly for short range communications, e.g. from a laptop to a nearby printer or from a cell phone to a wireless headset. Its normal range of operation is 10 m (at 1 mW transmit power), and this range can be increased to 100 m by increasing the transmit power to 100 mW. The system operates in the unregulated 2.4 GHz frequency band, hence it can be used worldwide without any licensing issues. The Bluetooth standard provides 1 data channel at 721 Kbps and up to three voice channels at 56 Kbps for an aggregate bit rate of 1 Mbps. Networking is done via a packet switching protocol based on frequency hopping at 1600 hops per second.

The Bluetooth standard was developed jointly by 3 Com, Ericsson, Intel, IBM, Lucent, Microsoft, Motorola, Nokia, and Toshiba. The standard has now been adopted by over 1300 manufacturers, and products compatible with Bluetooth are starting to appear on the market now. Specifically, the following products all use Bluetooth technology: a wireless headset for cell phones (Ericsson), a wireless USB or RS232 connector (RTX Telecom, Adayma), wireless PCMCIA cards (IBM), and wireless settop boxes (Eagle Wireless), to name just a few. More details on Bluetooth, including Bluetooth products currently available or under development, can be found at the website http://www.bluetooth.com.

1.4.9 HomeRF

HomeRF is a working group developing an open industry standard for wireless digital communication between PCs, PDAs, intelligent home appliances and consumer electronic devices anywhere in and around the home. The working group was initiated by Intel, HP, Microsoft, Compaq, and IBM. The main component of the HomeRF protocol is its Shared Wireless Access Protocol (SWAP), which operates in the unregulated 2.4 GHz frequency band (same band as Bluetooth).

The SWAP protocol is designed to carry both voice and data traffic and to interoperate with the PSTN and the Internet. The bandwidth sharing is enabled by frequency hopped spread spectrum at 50 hops/sec, however it also supports a TDMA service for delivery of interactive voice and other time-critical services, and a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) service for high speed packet data. The transmit power for HomeRF is specified at 100 mW which provides a data rate of 1-2 Mbps. However, in August 2000 the FCC okayed a five-fold increase in the HomeRF bandwidth, which will increase data rates to 10 Mbps. The range of HomeRF covers a typical home and backyard. Compaq and Intel released products in the spring of 2000 based on HomeRF in the $100 range, and other products in this price range are expected soon. More details on HomeRF can be found at http://www.homerf.org.

1.4.10 Other Wireless Systems and Applications

Many other commercial systems using wireless technology are on the market today. Remote sensor networks that collect data from unattended sensors and transmit this data back to a central processing location are being used for both indoor (equipment monitoring, climate control) and outdoor (earthquake sensing, remote data collection) applications. Satellite systems that provide vehicle tracking and dispatching (OMNITRACs) are very successful. Satellite navigation systems (the Global Positioning System or GPS) are also widely used for both military and commercial purposes. A wireless system for Digital Audio Broadcasting (DAB) has been available in Europe for quite some time and has recently been introduced in the U.S. as satellite radio. New systems and standards are constantly being developed and introduced, and this trend seems to be accelerating.

1.5 The Wireless Spectrum

1.5.1 Methods for Spectrum Allocation

Most countries have government agencies responsible for allocating and controlling the use of the radio spectrum. In the United States spectrum allocation is controlled by the Federal Communications Commission (FCC) for commercial use and by the Office of Spectral Management (OSM) for military use. The government decides how much spectrum to allocate between commercial and military use. Historically the FCC allocated spectral blocks for specific uses and assigned licenses to use these blocks to specific groups or companies. For example, in the 1980s the FCC allocated frequencies in the 800 MHz band for analog cellular phone service, and provided spectral licenses to two companies in each geographical area based on a number of criteria. While the FCC still typically allocates spectral blocks for specific purposes, over the last decade they have turned to spectral auctions for assigning licenses in each block to the highest bidder. While some argue that this market-based method is the fairest way for the government to allocate the limited spectral resource, and it provides significant revenue to the government besides, there are others who believe that this mechanism stifles innovation, limits competition, and hurts technology adoption. Specifically, the high cost of spectrum dictates that only large conglomerates can purchase it. Moreover, the large investment required to obtain spectrum delays the ability to invest in infrastructure for system rollout and results in very high initial prices for the end user. The 3G spectral auctions in Europe, in which several companies have already defaulted, have provided fuel to the fire against spectral auctions.

In addition to spectral auctions, the FCC also sets aside specific frequency bands that are free to use according to a specific set of etiquette rules. The rules may correspond to a specific communications standard, power levels, etc. The purpose of these "free bands" is to encourage innovation and low-cost implementation. Two of the most important emerging wireless systems, 802.11b wireless LANs and Bluetooth, co-exist in the free National Information Highway (NIH) band set aside at 2.5 GHz. However, one difficulty with free bands is that they can be killed by their own success: if a given system is widely used in a given band, it will generate much interference to other users colocated in that band. Satellite systems cover large areas spanning many countries and sometimes the globe. For wireless systems that span multiple countries, spectrum is allocated by the International Telecommunications Union Radio Communications group (ITU-R). The standards arm of this body, ITU-T, adopts telecommunication standards for global systems that must interoperate with each other across national boundaries.

1.5.2 Spectrum Allocations for Existing Systems

Most wireless applications reside in the radio spectrum between 30 MHz and 30 GHz. These frequencies are natural for wireless systems since they are not affected by the earth's curvature, require only moderately sized antennas, and can penetrate the ionosphere. Note that the required antenna size for good reception is inversely proportional to the signal frequency, so moving systems to a higher frequency allows for more compact antennas. However, received signal power is proportional to the inverse of frequency squared, so it is harder to cover large distances with higher frequency signals. These tradeoffs will be examined in more detail in later chapters.

As discussed in the previous section, spectrum is allocated either in licensed bands (which the FCC assigns to specific operators) or in unlicensed bands (which can be used by any operator subject to certain operational requirements). The following table shows the licensed spectrum allocated to major commercial wireless systems in the U.S. today.

AM Radio	535-1605 KHz
FM Radio	88-108 MHz
Broadcast TV (Channels 2-6)	54-88 MHz
Broadcast TV (Channels 7-13)	174-216 MHz
Broadcast TV (UHF)	470-806 MHz
3G Broadband Wireless	746-764 MHz, 776-794 MHz
3G Broadband Wireless	1.7-1.85 MHz, 2.5-2.69 MHz
Analog and 2G Digital Cellular Phones	806-902 MHz
Personal Communications Service (2G Cell Phones)	1.85-1.99 GHz
Wireless Communications Service	2.305-2.32 GHz, 2.345-2.36 GHz
Satellite Digital Radio	2.32-2.325 GHz
Multichannel Multipoint Distribution Service (MMDS)	2.15-2.68 GHz
Digital Broadcast Satellite (Satellite TV)	12.2-12.7 GHz
Digital Electronic Message Service (DEMS)	24.25-24.45 GHz, 25.05-25.25 GHz
Teledesic	18.8-19.3 GHz, 28.6-29.1 GHz
Local Multipoint Distribution Service (LMDS)	27.5-29.5 GHz, 31-31.3 GHz
Fixed Wireless Services	38.6-40 GHz

Note that digital TV is slated for the same bands as broadcast TV. By 2006 all broadcasters are expected to switch from analog to digital transmission. Also, the 3G broadband wireless spectrum is currently allocated to UHF TV stations 60-69, but is slated to be reallocated for 3G. Both analog and 2G digital cellular services occupy the same cellular band at 800 MHz, and the cellular service providers decide how much of the band to allocate between digital and analog service.

Unlicensed spectrum is allocated by the governing body within a given country. Often countries try to match their frequency allocation for unlicensed use so that technology developed for that spectrum is compatible worldwide. The following table shows the unlicensed spectrum allocations in the U.S.

ISM Band I (Cordless phones, 1G WLANs)	902-928 MHz
ISM Band II (Bluetooth, 802.11b WLANs)	2.4-2.4835 GHz
ISM Band III (Wireless PBX)	5.725-5.85 GHz
NII Band I (Indoor systems, 802.11a WLANs)	5.15-5.25 GHz
NII Band II (short outdoor and campus applications)	5.25-5.35 GHz
NII Band III (long outdoor and point-to-point links)	5.725-5.825 GHz

ISM Band I has licensed users transmitting at high power that interfere with the unlicensed users. Therefore, the requirements for unlicensed use of this band is highly restrictive and performance is somewhat poor. The NII bands were set aside recently to provide a total of 300 MHz of spectrum with very few restrictions. It is expected that many new applications will take advantage of this large amount of unlicensed spectrum.

1.6 Standards

Communication systems that interact with each other require standardization. Standards are typically decided on by national or international committees: in the U.S. the TIA plays this role. These committees adopt standards that are developed by other organizations. The IEEE is the major player for standards development in the United States, while ETSI plays this role in Europe. Both groups follow a lengthy process for standards development which entails input from companies and other interested parties, and a long and detailed review process. The standards process is a large time investment, but companies participate since if they can incorporate their ideas into the standard, this gives them an advantage in developing the resulting system. In general standards do not include all the details on all aspects of the system design. This allows companies to innovate and differentiate their products from other standardized systems. The main goal of standardization is for systems to interoperate with other systems following the same standard.

In addition to insuring interoperability, standards also enable economies of scale and pressure prices lower. For example, wireless LANs typically operate in the unlicensed spectral bands, so they are not required to follow a specific standard. The first generation of wireless LANs were not standardized, so specialized components were needed for many systems, leading to excessively high cost which, coupled with poor performance, led to very limited adoption. This experience led to a strong push to standardize the next wireless LAN generation, which resulted in the highly successful IEEE 802.11b standard widely used today. Future generations of wireless LANs are expected to be standardized, including the now emerging IEEE 802.11a standard in the 5 GHz band.

There are, of course, disadvantages to standardization. The standards process is not perfect, as company participants often have their own agenda which does not always coincide with the best technology or best interests of the consumers. In addition, the standards process must be completed at some point, after which time it becomes more difficult to add new innovations and improvements to an existing standard. Finally, the standards process can become very politicized. This happened with the second generation of cellular phones in the U.S., which ultimately led to the adoption of two different standards, a bit of an oxymoron. The resulting delays and technology split put the U.S. well behind Europe in the development of 2nd generation cellular systems. Despite its flaws, standardization is clearly a necessary and often beneficial component of wireless system design and operation. However, it would benefit everyone in the wireless technology industry if some of the disadvantages in the standardization process could be mitigated.

Bibliography

[1] V.H. McDonald, "The Cellular Concept," *Bell System Tech. J*, pp. 15-49, Jan. 1979.

[2] S. Schiesel. Paging allies focus strategy on the Internet. *New York Times*, April 19, 1999.

[3] F. Abrishamkar and Z. Siveski, "PCS global mobile satellites," *IEEE Commun. Mag.,*, pp. 132-136, Sep. 1996.

[4] R. Ananasso and F. D. Priscoli, "The role of satellites in personal communication services," Issue on Mobile Satellite Communications for Seamless PCS, *IEEE J. Sel. Areas Commun.,* pp. 180-196, Feb. 1995.

[5] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," IEEE Wireless Communications Magazine, Aug. 2002.

[6] T. S. Rappaport. *Wireless Communications: Principles and Practice*, 2nd ed. Prentice Hall, 2002.

[7] A. J. Goldsmith and L.J. Greenstein. A measurement-based model for predicting coverage areas of urban microcells. *IEEE Journal on Selected Areas in Communication*, pages 1013–1023, September 1993.

[8] D. D. Falconer, F. Adachi, B. Gudmundson, "Time division multiple access methods for wireless personal communications," *IEEE Commun. Mag.*, pp.50-57, Jan. 1995.

[9] A. J. Viterbi, *CDMA Principles of Spread Spectrum Communications,* Addison-Wesley, 1995.

[10] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, Jr., and C. E. Wheatley III, "On the capacity of a cellular CDMA system," *IEEE Trans. Veh. Tech.,* pp. 303–312, May 1991.

[11] K. Rath and J. Uddenfeldt, "Capacity of digital cellular TDMA systems," *IEEE Trans. Veh. Tech.,* pp. 323-332, May 1991.

[12] Q. Hardy, "Are claims hope or hype?," *Wall Street Journal*, p. A1, Sep. 6, 1996.

[13] A. Mehrotra, *Cellular Radio: Analog and Digital Systems,* Artech House, 1994.

[14] J. E. Padgett, C. G. Gunther, and T. Hattori, "Overview of wireless personal communications," Special Issue on Wireless Personal Communications, *IEEE Commun. Mag.,* pp. 28–41, Jan. 1995.

[15] J. D. Vriendt, P. Laine, C. Lerouge, X. Xu, "Mobile network evolution: a revolution on the move," *IEEE Commun. Mag.,* pp. 104-111, April 2002.

[16] P. Bender, P. Black, M. Grob, R. Padovani, N. Sundhushayana, A. Viterbi, "CDMA/HDR: A bandwidth efficient high speed wireless data service for nomadic users," *IEEE Commun. Mag.*, July 2000.

[17] *IEEE Personal Communications Magazine: Special Issue on Wireless ATM*, August 1996.

[18] K. Pahlavan and A. H. Levesque. *Wireless Information Networks*. New York, NY: John Wiley & Sons, Inc., 1995.

[19] *IEEE Pers. Commun. Mag: Special Issue on Smart Antennas*, February 1998.

[20] S. Verdú. *Multiuser Detection*. Cambridge, U.K.: Cambridge University Press, 1998.

[21] I. Katzela and M. Naghshineh. Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey. *IEEE Pers. Commun. Mag.*, pages 10–22, June 1996.

[22] G. Pottie. System design choices in personal communications. *IEEE Pers. Commun. Mag.*, pages 50–67, October 1995.

[23] P. Bhagwat, C. Perkins, and S. Tripathi, "Network layer mobility: an architecture and survey," *IEEE Pers. Commun. Mag.,* pp. 54-64, June 1996.

[24] A. Nakajima, "Intelligent network architecture for mobile multimedia communication," *IEICE Trans. Commun.,* pp. 1073-1082, Sep. 1994.

[25] D. Raychaudhuri, "Wireless ATM networks: architecture, system design and prototyping," *IEEE Pers. Commun. Mag.,* pp. 42-49, August 1996.

[26] E. Ayanoglu, K. Y. Eng, and M. J. Karol, "Wireless ATM: limits, challenges, and proposals," *IEEE Pers. Commun. Mag.,* pp. 18-34, Aug. 1996.

[27] D. C. Cox, "Wireless personal communications: what is it?," *IEEE Pers. Commun. Mag.,* pp. 20-35, April 1995.

[28] R. Kohno, R. Meidan, and L. B. Milstein, "Spread spectrum access methods for wireless communications," *IEEE Commun. Mag.,* pp. 58–67, Jan. 1995.