Adaptation and Mobility in Wireless Information Systems

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Abstract: A confusing array of new wireless "untethered" communications services, for voice and data, in real-time or delayed, interactive or one-way, in-building or out-of-doors, are rapidly becoming available. In this paper, we argue that despite the widely varying issues of engineering that span the creation of these diverse wireless services, the unique underlying aspect is that they must be able to adapt to a constantly changing environment brought on by mobility. Mobile systems must be able to detect their transmission environment and exploit knowledge about its current situation, so-called "situation awareness," to improve the quality of communications. Handoff in cellular phone systems is one example of detection and reaction to the environment. A more pervasive understanding of how to exploit adaptation and situation awareness will be the challenge, especially as systems transition from communications to more general wireless information systems.
Key Words and Phrases: Mobile communications systems, wireless information systems, situation awareness, adaptive systems, diversity.

1. Introduction

> "People and their machines should be able to access information and communicate with each other easily and securely, in any medium or combination of media—voice, data, image, video, or multimedia—any time, anywhere, in a timely, cost-effective way"
> Dr. George H. Heilmeier
> IEEE Communication Magazine
> October 1992

> "Going to war with a rifle in one hand and a laptop computer in the other would have been shocking only a few years ago. [Yet] tomorrow's war-fighter will require global access to information and transparent multilevel security in a laptop system. … Give the battlefield commander access to all of the information needed to win the war … when he wants it, where he wants it, how he wants it."
> Gen. Colin L. Powell
> Byte Magazine
> July 1992

Since the introduction of the cellular telephone over a decade ago, the growth of wireless communications has been rapid. A host of new "untethered" communications systems, under the general heading of Personal Communications Services (PCS), have recently been proposed. These are known by a number of different names, including Personal Communications Networks (PCN), Future Public Land Mobile Telecommunications Services (FPLMNTS), Cellular Phone, Wireless Public Branch Exchanges (PBX), Wireless Local Area Networks, Telepoint phone service, Satellite Communications, location-independent universal phone numbers, and so on [Kobb 93].

This confusing array of alternative services span a very wide range of a frequency allocations, expected data bandwidths, and assumptions about user mobility and location. For example, a high mobility, vehicular (80 meters/second) terminal presents very different engineering challenges than one designed for medium (20 - 40m/s) or low mobility (less than 10 m/s), the latter appropriate mostly for a pedestrian or easily reconfigurable desktop environment. In addition, systems designed for outside use must deal with

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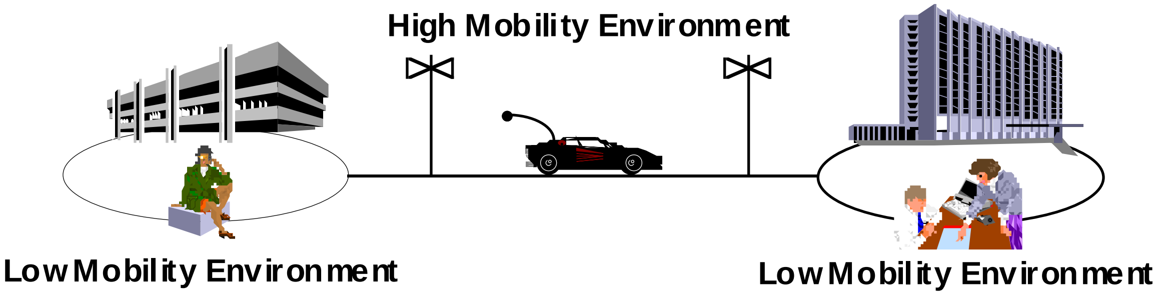

Figure 1: *High vs. Low Mobility Wireless Environments*
Wireless systems must be able to adapt to the different opportunities and constraints of indoor/low mobility environments vs. outdoor/high mobility environments. The former allows higher bandwidth and an easier to control environment, while the latter must exploit as much of the existing infrastructure as possible within the larger cell sizes.

fundamentally different constraints. For example, relatively small frequency allocations are available than those for indoor use, where wider bandwidth allocations are made possible through the use of lower power signals. It appears that any near-term, pervasively wireless communications system is likely to be a hybrid, with high bandwidth “islands” within buildings and public places (like airports) and lower bandwidth in-between spaces (see Figure 1).

As computing devices have shrunk in size, weight, and power, untethering the communications link will make possible the next step in the evolution of computer environments. This is one in which computing resources can be used more flexibly, because users can be freed from being physically connected to the underlying network. Yet a key challenge is to build the underlying infrastructure to support wireless communications. While it is possible to transmit data over a modem-equipped cellular phone, the solution is expensive and the effective bandwidth is disappointing because of the limitations of the existing analog cellular telephone system.

The distinction between communications and computing will continue to blur, leading to the new field of *telecomputing*. For example, a variety of popular wireless electronic mail systems have recently appeared, exploiting their own radio infrastructures. These include ARDIS, EMBARC, and RAM Mobile Data [Mello 93]. However, in this paper, our focus is on the challenges of providing high quality communications to computing systems in a mobile environment. The key issue is not so much that the communications medium is wireless, but rather that the system must deliver information in the face of a constantly changing environment precisely because it is on the move. For these kinds of systems, perhaps the term *adaptive* communications is more appropriate than wireless communications.

One problem facing the wireless communications infrastructure is the lack of an adequate strategy for high bandwidth data communications on the move. Even the emerging digital cellular telephone standards continue to focus on narrow bandwidth voice channels, not on higher bandwidth data communications. The engineering tradeoffs are not always the same. Voice communication is connection-oriented, requiring rigorous controls on latency, while data communication is more bursty and is well-suited to packetization. Even attempts to layer data communications onto the latest generation digital spread spectrum cellular systems have not yielded very high data bandwidth [Karn 93]. All too often Personal Communications Systems is synonymous with little more than ubiquitous cordless phones.

Computer companies have not solved this problem either. They continue to focus on developing ingenious handheld devices, like the EO pad or the Apple Newton, but not on the ubiquitous wireless networks to support them. There exists no “global vision” of an integrated wireless/wireline network architecture. And while wireless electronic mail is an obviously attractive application (and relatively easy to implement because of the low data rates required—at least until the arrival of multimedia electronic mail), innovative applications for decoupled access and location-dependent information services remain to be demonstrated.

Mobility requires *adaptability*. By this we mean that systems must be location and situation-aware, and must take advantage of this information to dynamically configure themselves in a distributed fashion.

The challenges that must be faced span a wide range of considerations and technical expertise. These include the architecture of the communications and information service infrastructure (base stations, network protocols, servers) necessary to support mobile communications, the demonstration of new and innovative infrastructure elements and services, the development of new design methods for power-sensitive, mobile, real-time, network-attached computer systems, and the integration of wireless communications into the emerging National Information Infrastructure.

The rest of this paper is organized as follows. In Section 2, we provide some background, defining key terms and showing how wireless information systems can be viewed as a natural evolution of computing's relentless march towards greater distribution and ubiquity of access. Section 3 details the research issues faced by designers of wireless information systems, and lays out some large scale engineering challenges for such designers. Section 4 compares the existing cellular system architecture, evolved from telephony, with an alternative architecture more closely integrated with a computer networking view of wireless systems. We review existing wireless systems in Section 5. Section 6 contains our summary and conclusions, and charts the future of wireless information systems.

2. Background and Motivation

2.1. Definitions

Wireless information systems are computing systems that provide the ability to compute, communicate, and collaborate anywhere and anytime. A number of terms have been used in the literature to describe such systems, including wireless computing, ubiquitous computing, nomadic computing and decoupled computing. While no clear cut consensus exists for their definition, for the purposes of this paper we suggest some definitions here.

Wireless computing refers to computing systems that are connected to their working environment via wireless links, such as radio frequency (RF) or infrared (IR). In general, this term is applied to the computing devices participating in a wireless local area network, with gateways to more traditional wired networks. The key concept is the ability to participate in a work group, that is, a collection of computing devices and servers for sharing data and information. This implies relatively symmetric bandwidth between the wireless node and the network, and a general desire for as high a bandwidth as possible, possibly approaching Ethernet speeds. Under this definition, wireless email is a particularly primitive form of wireless computing.

Ubiquitous computing, as defined by Weiser [Weiser 91, Weiser 93], envisions an environment in which computing devices are so inexpensive and so readily available that there are hundreds or even thousands in a typical office. With such a large number of devices, any attempt to interconnect them with traditional wired networks is impossible, and so wireless communications is a necessary part of their infrastructure. Unlike wireless computing based on a more conventional extension of networked computing, ubiquitous devices individually demand relatively modest bandwidth (e.g., 64Kbps or less), although the aggregate within the volume of a typical office (bps/cubic inch) may be very high.

Nomadic computing refers to the ability to compute as the user relocates from one support environment to another. This is the wireless analog of permitting a non-local user to use a local machine to make remote terminal connections over a network to his/her home system. In this model, it is expected that individual organizations will construct their own wireless infrastructures that are linked across organizations by wired internetworks. Yet a user would like to be able to use his or her device even within a foreign organization's wireless infrastructure. System support for nomadic computing must address the issues of trust, security, and privacy as wireless computing devices move between such organizational infrastructures. The host infrastructure must retain security against the nomad, while the operations of the nomad must be kept private from the owners of the host infrastructure.

Decoupled computing refers to the ability to compute when detached from the existing computing and communications infrastructure. If the wireless computing devices are full function computers in their own right, such as modern notebook computers, then decoupled computing makes it possible to perform some operations, like file access from servers, in a transparent fashion even when disconnected from the file server. Using techniques like file caching in the wireless device, it is possible for the user to update the file even when disconnected. When he or she reestablishes connection, the cached files are automatically resynchronized with the copies on the server. Successful decoupled applications include Eudora email, which allows the user to read and compose mail on a laptop computer, connect to a network server over phone lines, transfer mail, and then disconnect from the server. Decoupled computing is an important element of the more general wireless computing milieu, because the support infrastructure for wireless will not be universally available for many years to come. In addition, the techniques developed for decoupled computing will form the foundation for hybrid bandwidths in the network, gracefully spanning between 0 and high bandwidth.

Applications that require untethered access, in real-time, to multimedia information sources are made possible by wireless information systems. These include: support for decision makers in the field, crisis management and response, law enforcement, training in remote locations (such as support for troubleshooting and repair on the tarmac), the first mile of the global communications grid, transportation, mapping, and location finding, and education and entertainment applications.

To see the diversity of wireless communications in a typical crisis management application, consider a multimedia terminal for a firefighter. He or she might need access to (1) maps to plan a route from the firehouse to the scene of the fire, (2) architectural blueprints to plan a strategy for fighting the fire, (3) a database of local fire hydrants as well as unusual fire hazards like chemical plants in the affected area, (4) a locator system, so the firefighting team can be tracked as they move through the building, and (5) general purpose voice and data communications to other firefighters and engine companies, as well as police and other law enforcement entities. The dynamic nature of information clearly demonstrates that all of the data cannot be carried within the mobile device, that a wide range of data rates must be supported, and that some applications can be supported by one-way communications while others require interactive, two-way communications. For example, communications with other users demands symmetric transmission, while downloading maps or blueprints can be supported by asymmetric methods, with greater download bandwidth than uplink bandwidth. Location and tracking systems based on global position sensing (GPS) are essentially one way.

2.2. Natural Evolution of Computing

Wireless information systems represent the next logical step in the natural evolution of computing systems. Over time, the user has been freed from the need to be collocated in time and space with the computing system he or she will use. Early computers were mammoth machines that required the user to be physically located at the machine to use it, As these early machines only ran a single user operating system, not only did the user need to be collocated in space, but also in time. In effect, the computing resource could not be effectively used by more than on user at a time. As usage restrictions are reduced, multiuser collaborative activities are better enabled.

Over time, the evolution of computing has decreased the tight coupling between the user and his or her computing resource and environment (see Figure 2). Batch processing freed the user in time. That is, the user didn’t need to wait until the computer became free to submit his or her work. However this still required the user to be located with the computer to use it. Time sharing allowed the computer resource to be simultaneously shared among many users, while adding an element of physical dispersal from the actual machine. Conventional networking of distributed timesharing systems extended this dispersion across a geographically wider area. But this still limited the ease with which the interconnected computing resources could be shared among users.

Local area networks and workstations eased this restriction. This kind of environment consists of user dedicated resources, in the form of dedicated workstations, and shared resources like servers and printers, dispersed over a relatively wide area such as a college campus. In its most advanced form, the users share a single system image, making it possible for them to use any available workstation yet still access what appears to be their dedicated computing environment.

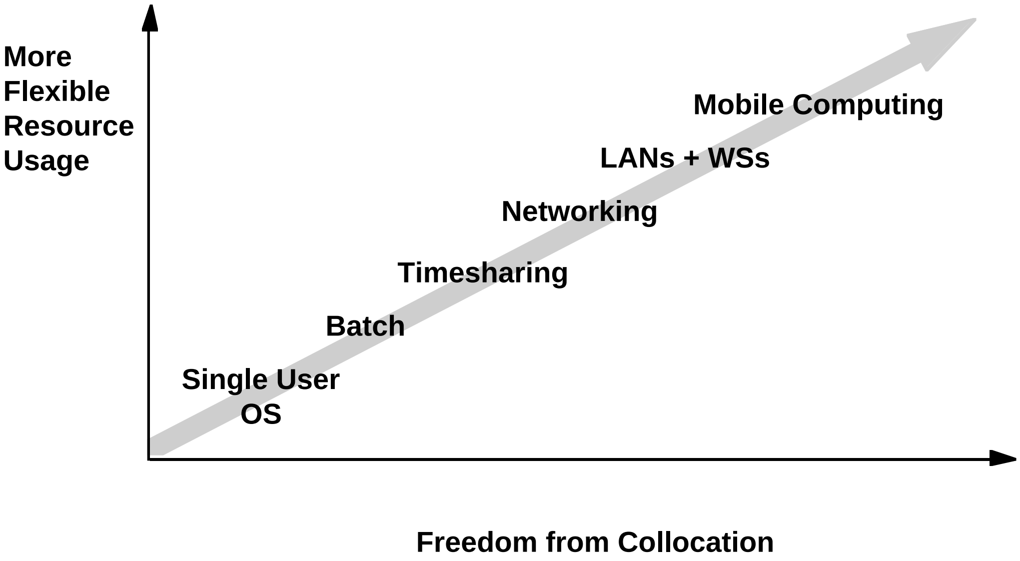

Figure 2: Evolution of Computing Systems
Over time, the general evolution of computing systems, from early single user operating systems to the more recent local area network-based workstation environment, has increased the freedom from colocation and yielded more flexible use of the computing resource. Computing on the move is the next logical development in this forty year evolution. This figure is adapted from [Hewitt 93].

Viewed as a part of this progression, mobile computing represents the next logical step in untethering the user from his/her environment. The user can access the system's resources, including diverse services and servers, anytime he or she is located within range of the wireless communications infrastructure.

3. Research Challenges

3.1. Overview

One of the most challenging aspects of wireless information systems is the need to develop engineering solutions that span a large range of considerations, from integrated circuits, to radio engineering, to system software. To make progress in wireless systems, a more interdisciplinary approach, cutting across the traditional disciplines of circuit design, signal processing, radio engineering, network design, and computer system design (including new applications) will be needed.

As we mentioned in Section 1, the key cross-cutting consideration in wireless design is the way mobility implies adaptability in the system's architecture and algorithms. Common usage of adaptability in existing wireless systems include adaptive power control, enabling a terminal close to a base station to transmit at lower power (see Section 3.3 for how this is exploited in spread spectrum communications systems), and adaptive channel allocation, where the mobile terminal and the base station select a channel based on local interference and channel conditions (this is commonly implemented in cordless phones although once a channel is selected, the selection is not changed for the duration of the call).

Another example of adaptability includes adaptable network topology, as the mobile host can serve as a transponder to some terminals that are out-of-range of the base station. In addition, cellular hand-off hints can exploit information about terminal location and the history of changes in location to predict when handoffs will need to take place (this includes soft handoffs in spread spectrum systems; see Section 3.3). And finally, communications systems must be able to adapt between the higher bandwidth environment indoors and the lower bandwidth outdoor environment.

In this section, we review the design issues at each of the levels of wireless information system. These include the handheld terminal, the wireless link, base station, the network backbone, the servers, information services, and the applications made possible by mobility.

3.2. Terminal

Increasing, mobile terminals must be seen as complex microelectronics assemblies that are attached to sophisticated network-based system. The issues that need to be addressed in building these light weight handheld wireless devices include: the display technology, advanced packaging for high circuit density in a small volume, ergonomic design, application specific integrated circuits (ASICs) for signal processing, special computations like error correction, and analog/digital radio frequency chip sets, embedded software (including support for handwriting and speech recognition), battery technology, and low power design methods.

In the display arena, active matrix liquid crystal displays (LCDs) are now widely used in laptop computers, yielding sharp displays with wide viewing angles. However, a wider diversity of sizes and formfactors are needed to support more general wireless devices, especially as terminal sizes scale down. While color displays are preferable, they require substantially greater transistor densities than gray scale displays, and are thus more costly, although prices are dropping rapidly. Power consumption remains a problem, as the display backlight is usually the most power consuming part of the system. This may be circumvented as higher contrast displays become available. New display technologies based on data spectacles (basically head mounted displays light enough to wear) are now becoming available, making possible “hands-free” devices with lower power demands.

Packaging remains an important underlying technology as terminal sizes decrease while the embedded processing capabilities increase, especially in support of greater intelligence in the terminal to sense its environment and to assist in adaptive processing like mobile-assisted handoffs. Multichip modules (MCMs) are a critical enabling technology, by increasing circuit densities, reducing interchip capacitances, and thus reducing system power requirements.

Ergonomic design is another important aspect of the terminal. It must be small and lightweight. Input may be from pen or speech, since a full keyboard would result in devices not much smaller than today’s notebook computers. Because of the need for hands-free operation in some applications, even wireless devices that could be worn have been proposed.

At the heart of the terminal is a high degree of processing made possible by application specific integrated circuits (ASICs), providing a mixed analog/digital capability. For low power, CMOS circuitry is preferred [Min 93]. Millimeter microwave integrated circuit (MMIC) technology may make possible small formfactor radio devices for higher frequency ranges. It is more likely that MMICs will be used in the transmitter infrastructure than in the mobile devices.

Embedded software implements the various control functions of the mobile terminal. These include display control, data input and output, and the various control functions layered on top of the wireless link.

Wireless frees the terminal from only the communications tether. The other tether is power. A variety of improvements to battery technologies (nickel cadmium, lithium, nickel hydride) are being pursued, but improvements of only about 20% in battery lifetime are expected over the next ten years. The best opportunity for extending battery life is not a new battery technology but rather reducing the power requirements of the mobile terminal. This can best be accomplished through a consistent strategy for low power circuit and system design [Sheng 92]. For example, algorithms for image compression/decompression can be used which reduce the computational demands at the expense of more storage in the terminal. The development of lower power circuit technologies and chip architectures, as well as low power design tools are an area of intensive research and development within the microsystems community.

The major radio engineering problem faced by the mobile terminal is that of multipath fading.This falls into two classes: *short-term* and *long-term* [Lee 93]. The short-term fading is caused by multipath reflections of a transmitted waves by local scatterers such as houses, buildings, and other man-made structures. Long-term fading, sometimes called “radio shadows,” is caused by terrain contours like mountains that can lead to signal drop outs. For example, at 850 Mhz the distance between signal peaks and valleys is approximately six inches. To combat the problems of short-term fading, one approach is to exploit antenna diversity. The idea is to provide two or more inputs at the mobile terminal so that the fading phenomena are uncorrelated. Examples include antenna space, frequency, polarization, field component, angle, or time diversity combined with combining techniques [Lee 93]. Recent terminal designs are investigating embedding multiple antennas into the packaging of the mobile host. Long-term fading can sometimes be dealt with by multiple antenna sites within the cell or sharing of frequencies amongst cells, especially as is possible in spread spectrum techniques (see Section 3.3).

3.3. Wireless Link

The critical issues in the engineering of the wireless link are how to efficiently encode the signal so as to minimize the bit error rate in the face of interference and fading. The data encoding is particularly stringent because signal fading will cause burst errors. Design considerations include efficient radio frequency link design, efficient system design, improved frequency reuse, and better traffic management. Signal processing techniques focus on how to encode the waveforms to maximize the signal-to-noise ratio.

A wide diversity of choices exist for encoding the wireless link. Most activity has focused on radio transmission, but infrared techniques for high bandwidth in-building systems have also been investigated. While existing radio transmission systems use frequency division multiple access (FDMA) or time division multiple access (TDMA), the general trend appears to be in the direction of code division multiple access (CDMA), also known as *spread spectrum*. Spread spectrum techniques spread the communications waveform across a wide range of frequencies, selected in such a fashion that allows multiple waveforms to be superimposed or “coded” to limit cochannel interference. Spread spectrum has many advantages that accrue to the wideband transmission technique, including significant tolerance to interference (thus permitting higher user capacity), less susceptibility to fading, and the able to reuse frequencies in adjacent cells simply by assigned different spreading codes. The latter makes possible “soft handoffs” (see below).

Spatial division multiple access (SDMA) depends on exploiting advanced array processing techniques to locate and track mobile terminals, and to adaptively form narrow beams by steering the transmitter’s antennas. This makes possible more efficient reuse of frequencies than the standard fixed hexagonal reuse patterns. In essence, the scheme can adapt the frequency allocations to where the most users are located.

The IS-54 North American digital cellular standard was designed to improve voice capacity within existing frequency allocations. Three 16 Kb/s digitally encoded TDMA channels are embedded in each 30 Khz cellular channel. Unfortunately, the system is only suited for low data rate communications. A conventional analog cellular modem user ties up a whole channel while achieving approximately 2400 bps. An IS-54 modem will still allocate a full voice channel but should be able to exceed 4800 bps.

The IS-95 CDMA standard is an alternative based on spread spectrum techniques. A sophisticated power control algorithm is used to regulate the transmission power of the mobile terminals. A terminal close to the base station will transmit at lower power than one that is far away. This has the advantage of reducing power as well as avoiding the so-called *near-far terminal problem*. This is a problem in spread spectrum methods where all channels share same frequencies. A strong signal received from near-in mobile terminal may mask a weak signal from one that is far away. The adaptive power control scheme can insure that all transmitted signals are at the same level within the cell [Lee 93]. In addition, the scheme supports *soft handoff*, so called because a given terminal can communicate with more than one base station at a time, choosing to communicate with the one with the highest perceived power.

Cellular Digital Packet Data (CDPD) provides a capability for 19.2Kbps connectionless data packets layered on top of the 30 KHz cellular phone channels. The system enables many data users to share one or more packetized data channels. This is efficient because many forms of data communications are inherently bursty, and do not require a full channel to be allocated on a per user basis.

The Federal Communications Commission has recently reallocated spectrum in response to WARC ’92 to make possible experimentation with digital techniques. These allocations include: 1850-1990 MHz, reallocated from private service to emerging technologies (Wideband CDMA); 1910-1930 MHz, proposed for unlicensed PCS devices for cordless phones and data communications (this represents only half of the 40 MHz requested by Apple Computer); 2110-2150 MHz, reallocated for emerging technologies; and 2160-2200 MHz, reallocated for emerging technologies. In addition, the unlicensed industrial/scientific/

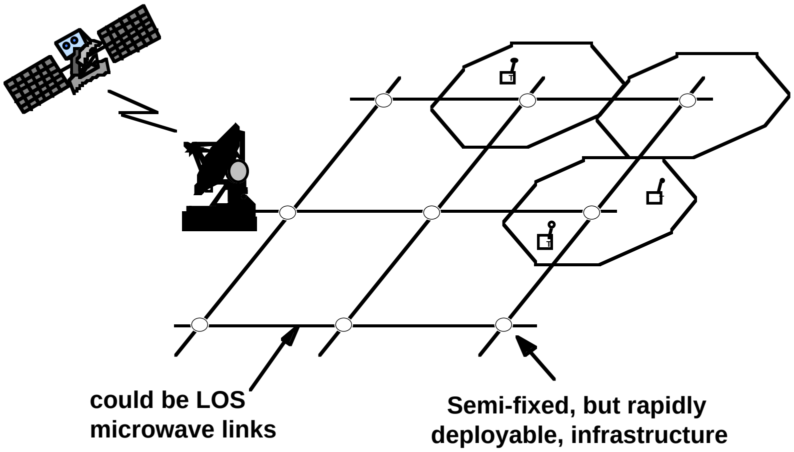

Figure 3: *Instant Infrastructure*
It is highly desirable to be able to establish the underlying infrastructure for cellular communications as rapidly as possible. Intelligent base stations with high bandwidth line-of-sight (LOS) narrow beam radios can establish point-to-point connections rapidly.

medical (ISM) bands in the 902-928 MHz, 2400-2483.5 MHz, and 5725-5875 MHz frequencies are being used for a variety of digital communication services [Kobb 93].

3.4. Base Station

The base station design issues include wireline/wireless protocol conversion, ruggedized packaging (at least for base stations to be located out-of-doors), real-time software, network-capable high performance components, and decentralized intelligence and control.

Cellular telephone systems critically depend on the supporting infrastructure of base stations and mobile telephone switching offices (MTSOs). In those situations where the existing wired infrastructure does not exist or has been damaged, such as in the wake of a natural disaster, it is important that communications be (re)established rapidly. Today, the set-up time for base stations is time consuming, requiring significant efforts to set up a cell and to prepare the site. This is due in part to the careful tuning and positioning of the high frequency, high bandwidth microwave radios that are used to link the base stations. In the future, even higher bandwidth fiber optics will be used for these links (see Figure 3).

This suggests a possible strategy for constructing “instant infrastructures” in support of wireless communications. Base stations use low bandwidth wide area radios to transmit GPS information to neighboring base stations. A distributed, decentralized algorithm is used for the base stations to use adaptive beam forming and antenna steering techniques to establish high bandwidth point-to-point radio links among the base stations. MMIC technology can be used to obtain high frequency, high bandwidth digital radios for these links, reducing the size and expense of the base station. More conventional radios are used to implement the cellular system for the mobile terminals.

3.5. Networking

The network design issues include protocols and algorithms for mobile hosts and multimedia communications. These include network addressing schemes for network nodes that move, support for real-time packet delivery for continuous media, and network scalability in terms of number of users, bandwidth and distance. The radio engineering of the wireless link and the design of network protocols are intimately linked, though a detailed study of these design tradeoffs remains to be done. For example, one strategy to increase the probability of delivery across the wireless link is to place more sophisticated checksums in the network headers. An alternative strategy simply retransmits the packet should their transmission not be acknowledged after a time out. A good wireless protocol will need to balance both approaches.

The first issue in wireless networking is how to access the wireless media. A standard collision detection scheme can be used, as in the Ethernet and Aloha protocols. But this requires the sending terminal to be able to hear all other terminals which may attempt to communicate with the base station at the same time. This is the so called *hidden terminal problem*: a terminal on one side of a cell may not be able to detect that it is colliding with a terminal at the opposite end of the cell.

A proposed solution is the MACA media access protocol proposed by Karn and modified by Xerox [Weiser 93]. The protocol contains two special messages, *Request to Send N Byte*s and *Clear to Send N Bytes*. This indicates to the listening terminals how long they should remain silent. Collisions are detected by timeouts, and these should only occur during the actual Request to Send commands. Xerox's modification includes a third message, *Not Clear to Send N Bytes*, which can be used by the base station to manage the allocation of bandwidth to mobile terminals that require bandwidth guarantees for real time, multimedia data.

Besides media access, the protocols must be concerned with routing data between the wireline network and the wireless devices. The network protocol set in widest use is the Internet's Transmission Control Protocol/Internet Protocol (TCP/IP). Addresses of hosts are fixed and used to route traffic through the network. Designed at the time that hosts did not move, the existing protocols are ill suited for highly mobile nodes. As a host moves from one network domain to another, its address would need to change. Rebuilding and redistributing the necessary routing information is prohibitively expensive.

Mobile IP is the general term for several proposed solutions to this problem. [Ioannidis 91, Ioannidis 93] uses a level of indirection to forward packets to correct temporary addresses. Each mobile host has a unique home address. As the mobile moves through the network, the control protocol notifies the gateway managing its home address of the terminal's current temporary address. Packets sent to the home address are automatically forwarded by the gateway to this address. The scheme is similar to how roaming is handled in cellular phone systems. More recent proposals are based on techniques that cache forwarding information in the network gateways, establishing the forwarding path only once per sender. This makes it possible for the packets to take an almost direct route to the mobile node [Perkins 92, Perkins 93].

However this approach leads to increased network latency, which is intolerable for those communication streams like video and audio that require real time delivery guarantees. The only feasible way to provide such guarantees appears to be through connection-oriented services combined with stream buffering in the base stations. But these are expensive to tear down and reestablish when a mobile host moves from the range of one base station into another. [Keeton 93] describes several schemes for partially reestablishing connections while forwarding buffered data from the old base station to the new one. An idea exploited there is to use multicast techniques to distribute the media stream to several adjacent base stations, thereby eliminating the need to forward buffered data among the base stations. Hints about the movement of terminals can be used to reduce the handoff latency.

3.6. New Information Servers and Services

A critical underlying assumption that we make is that wireless terminals are part of a networked environment, although they may be temporarily disconnected from that environment from time to time. The wireline network backbones are continuously being upgraded in terms of transmission bandwidth (gigabits per second), storage capabilities through attached servers (terabytes of near-line storage), and new network services for multimedia and information on demand. These capabilities should also be provided to wireless users of the network, to the degree that is possible given the inherent limits in wireless network bandwidth. In a sense, users should have the same kinds of services they see through wireline connections, albeit at potentially lower resolutions and perhaps with longer latencies. A critical challenge is to make applications aware of their limited and dynamically changing connection bandwidths, so that they can adapt to what is available as appropriate.

It is difficult to identify in advance all of the applications that are enabled by wireless connectivity to information sources. Some key applications are those that provide critical information to active individuals on the move, or in remote or dangerous places. These include (1) the delivery of time sensitive information, like stock quotations to a broker or the latest inventory information to a traveling salesman, or instantaneous computer mail, or the delivery of critical news items, (2) training applications in remote locations, like shipboard repair or on airfields, or (3) wireless classrooms, where students bring their computers to class for notetaking or for in-class computations, or to participate in lectures at a distance from wherever they are.

Collaborative applications enabled by wireless communications include law enforcement, public safety (recall the firefighter scenario of Section 2.1), or remote medical diagnosis and telemedicine, perhaps involving an emergency medical team at the site of an accident. These may require very high resolution images to be transmitted over wireless links, which may not be possible to accomplish in real time.

Design and manufacturing provides another environment for wireless communication. Besides the traditional uses of networks to allow collaborative design at a distance, made even more flexible by the incorporation of wireless links, the communication systems makes possible item location tracking as well as unique tagging for work-in-progress and warehousing applications. Such capabilities are already used extensively in the mail package handling industry.

Multimedia applications, especially those that incorporate continuous time-sensitive data like video, will be a challenge for wireless systems. The quality of the transmitted image will need to adapt to the available bandwidth. It is critical that the application and the underlying network system be able to determine the amount of bandwidth available on the wireless link, and for them to negotiate a level of quality in transmission that is achievable over the link, all the way from the video server to the mobile terminal. For example, progressive image techniques will make it possible to receive a low resolution image first, with progressively better image quality should more bandwidth be available.

New concepts for energy-efficient querying and data transmission are also under development. For example, Imielinski [Imielinski 92] describes an innovative energy-efficient scheme for wireless data transmission based on broadcast and asymmetric communications. If a mobile’s request for a particular piece of information need not be satisfied immediately, it can transmit its request at low power and low bandwidth. The response is combined with those to other mobiles, and is periodically broadcast to all of them at high power and bandwidth from the base stations. This saves power in two ways. First, many requests may be for the same information, such as the current weather or traffic information. These can be combined into a single one-to-many broadcast rather then several one-to-one transmissions. If a particular piece of information is requested by many users, it can be rebroadcast frequently to reduce latency. And second, for some kinds of information, the mobile may simply use information filters that it applies continuously to certain kinds of information being continuously broadcast, such as the baseball scores of a selected team. The mobile saves power by reducing the number of times it needs to transmit its requests.

Finally, the situation-aware and location-aware nature of mobile systems makes possible new kinds of location-dependent information services. Primary among these are geographical queries, of the form “find the nearest doctor to my current location,” “find the nearest movie theatre playing ‘Jurassic Park’,” “how many taxis are within a 5 minute drive?,” etc. The user must be able to tolerate somewhat inaccurate answers because these requests are inherently imprecise. This is because the user’s location and the current situation (e.g., the number of nearby taxis) are constantly changing, and even terms like “near” are fuzzy concepts. New query processing techniques in database management systems must be developed to handled such forms of imprecision.

3.7. Challenges for Wireless Technology

The following list describes a number of advanced engineering challenges for wireless systems. Although each is fairly straightforward to state, they demand a level of technical sophistication not available in today’s systems.

- Design low power, high bandwidth, small size, frequency agile, computer capable digital radio devices.

  For adaptive communications systems, it should be possible for a single radio device to work across a wide range of frequencies, to determine the best frequency to use given the detection of its external environment. For example, the same basic radio should be able to be used in-building at the 2 GHz PCS band and outside using a cellular CDPD system. The ability for the same radio device to be used as a pager, phone, modem, or GPS receiver is highly desirable. While there already exist some military radios that can operate over a wide range, they are currently too large in formfactor. Antenna design remains a challenge.

- Simultaneously boot tens of wireless terminals in a lecture room-sized space.

  This is a realistic challenge that must be met for wireless computers to be used in a classroom situation. This scenario places considerable stress is on the network and server system, to establish and maintain sessions with the mobile terminals. This represents a fairly large number of terminals in a relatively small area, sharing common command channels. Thus, an effective solution to back off and retry, that does not thrash the server, must be developed.

- Continuously transmit high bandwidth video to walking-speed mobiles across cell handoffs, with hundreds of users in an in-building local area.

  There is some controversy as to whether users will really move and demand high bandwidth at the same time. Nevertheless, as computing systems begin to integrate more forms of continuous media, which demand realtime playback, this is likely to become important. The challenge is to provide real time, latency sensitive communication to a relatively large user community in the presence of cell handoffs. By limiting the challenge to in-building, we assume that higher bandwidth communications can be maintained by using microcellular techniques. An open question is the processing overhead associated with microcellular handoffs.

- Repeat the previous challenge, except outside and across a larger geographical area.

  To satisfy this engineering challenge, the system must able to adapt between the high bandwidth in-building environment and the lower bandwidth outside environment, while maintaining delay sensitive communications. Applications will also need to be adaptive, since the quality of the transmitted media stream must match the available bandwidth of the outside environment.

- Allow a user to seamless move from his/her in-building infrastructure to the outside infrastructure to the in-building infrastructure of a client (or competitor) he or she is calling on.

  This challenge focuses on the terminal’s ability to cross infrastructures with different levels of trust. A user trusts his or her own infrastructure to a high degree, but the same may not be said about a remote infrastructure controlled by another organization. Furthermore, can “guest” users of your infrastructure be trusted not to intrude upon it?

- Locate an addressee among millions of globally distributed terminals within a couple of seconds.

  A significant problem faced by this challenge is scaling up the network addressing scheme as very large numbers of nodes are allowed to roam within the system. While the current network addressing schemes use the address as a method of routing to the node, an alternative hierarchical scheme similar to telephone numbers may be more appropriate. In such a scheme, terminals are hierarchically clustered by common characteristics, perhaps by region or organization. The issue still remains of how to rapidly find objects which have moved to new parts of the hierarchy.

4. Alternative Architectures

4.1. Analog Cellular Phone System

A general future trend will embed more processing in the wireless infrastructure with greater participation of the mobile terminals in distributed control of the system. This is critical to make truly adaptive communications systems a reality. To understand how this is different from the cellular phone system infrastructure, it is important to understand what currently exists.

The North American AMPS cellular phone system is without a doubt the triumph of an extensive engineering effort that spanned decades. Yet if the system were to be redesigned from scratch using today’s technology, especially high performance microprocessors, it would take on a very different form. The cellular system can be characterized as consisting of a “dumb infrastructure” of base stations and terminals,

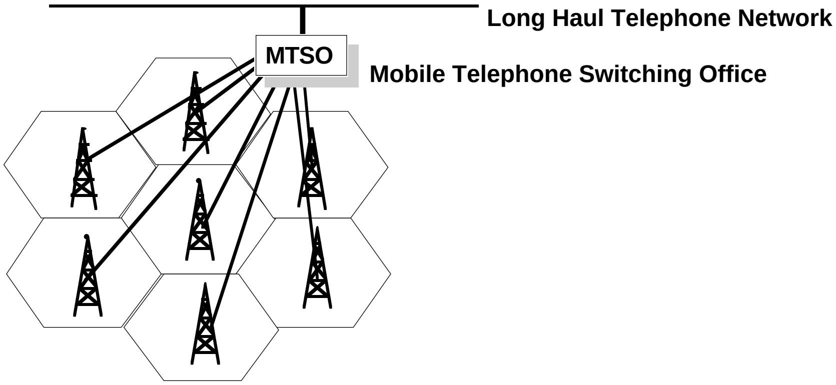

Figure 4: *Traditional Cellular Communications System*
Base stations have little local processing capabilities. All global decisions like frequency assignments and cell handoffs are made in the MTSO, the *Mobile Telephone Switching Office*.

combined with highly centralized and very intelligent processing in the switching system.

The basic cellular system architecture is shown in Figure 4. The antennas represent the base stations within cells. The MTSO, or Mobile Telephone Switching Office, integrates the cellular environment into the wireline telephone switching fabric. Base stations and MTSO are typically connected by high bandwidth telephone lines or directional radios.

There are a number of problems with this architecture that make it ill-suited for basis of wide-scale wireless information systems. These are outlined below:

- *Expensive Switches*: The MTSO coordinates all switch functions, performs all switching of calls, and provides the service features implemented by software. The MTSO also makes the power control decisions, to avoid saturating the receiver amplifier and to reduce the chance of interference [Lee 89]. These offices cost several million dollars apiece.
- *Dumb Base Stations*: These do little processing on their own except to locate mobiles and provide the signal conversion between the wireless cellular environment and the wireline switched telephone system.
- *Large Antennas*: Antenna height is approximately 40 meters. This is determined in part by the desired radius of the cell and the chosen frequencies for communications. The large size implies expensive sites and relatively few of them.
- *32 Km Cell Radius*: Cell size is chosen by a variety of considerations including expected density of users, frequency of cell handoff, and assumptions about radiated transmission power. Smaller cell sizes are possible, but the cost of cell sites place a limit on how small these can be made.
- *Limited Handoff Capability*: Since the MTSO makes all handoff decisions, it represents the critical processing bottleneck. Large cells imply relatively few cell crossing, thus limiting the handoff processing demands to some extent.
- *Optimized for Voice Channels*: The existing cellular system is optimized for good quality human voice transmission within the allocated frequency channels. Assumptions about the frequency range of the human voice are inherently built into these systems.
- *Low Bandwidth (< 32Kbps)*: Since each channel is limited to 30 kHz, it is unlikely that more than 30 Kbps data transmission can be encoded into the channel. Other factors significantly reduce the practical bandwidth to below 9600 bps.
- *Analog Design*: The analog design of the system has implications for the encoding and error correcting schemes that can be exploited to improved data transmission throughput.

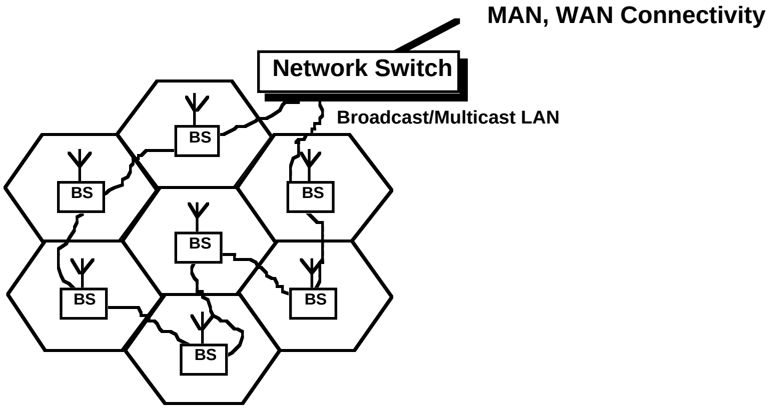

Figure 5: *Alternative Distributed Infrastructure*
The more modern view of the cellular infrastructure has the base stations connected together on a high speed local/metropolitan area network. Intelligence is distributed in such a fashion that terminals and base stations decide when to hand-off. Data buffering in the base stations makes possible support for latency sensitive applications, like real time video transmission.

- *Blank and Burst Signaling*: Control signaling between the base station and the mobile device is performed "in band" through special tone sequences inaudible to the human ear. However these control sequences often span tens to hundreds of milliseconds, thus reducing the data transmission efficiency of the channel.

Nevertheless, with techniques such as CDPD, it is possible to exploit the very substantial existing cellular infrastructure for a low data rate, reasonably ubiquitous communications capability.

4.2. Digital Microcellular

Digital microcellular technology holds forth the promise for an alternative wireless infrastructure with more distributed intelligence and lower cost elements. This "smart infrastructure" is shown in Figure 5. The base stations are now computers which are interconnected via fiber optic or high bandwidth microwave radio networks. The network provides both high bandwidth and a low cost method for broadcast or multicast. The network switch connects the local cells into a wide area/metropolitan area computer network. With the arrival of Asynchronous Transmission Mode (ATM) networking, this figure is not too far removed from the general direction in which both computer networking and digital telephony are evolving. It will be used first for in-building wireless systems, and may eventually find application as wireless extensions to "fiber to the curb" telephony deployments.

This alternative architecture has several advantages over the existing cellular system outlined in the previous subsection. These include:

- *Inexpensive Switches*: The switches are based on microprocessor technology and are designed to route short packets with low latency through the network.
- *Smart Base Stations*: The base stations also contain microprocessors and work with near by base stations in a distributed fashion to decide how to control power and when to trigger handoffs.
- *Small Antennas*: The usual description of a microcellular system places the base stations on top of existing utility poles. Along with reduced size comes reduced site preparation costs.
- *100 m radius*: Use of lower transmission power will reduce the effective radius of the cells. This also makes possible greater frequency reuse to meet increasing demand for spectrum.
- *Extensive Handoff Capability*: With a more distributed control algorithm, the bottleneck in effecting handoff is no longer the central switch, but rather the capacity of the network to transmit the protocol messages.

- *Optimized for Data Channels*: The system is designed from the ground up for data transmission. Voice data is only one of the many possible forms of encoded data streams that require realtime delivery guarantees.
- *High Bandwidth (>1Mbps)*: Because of the smaller cell radii and greater frequency reuse, it should be possible to support higher data transmission rates. With spread spectrum techniques, the available bandwidth can be allocated based on the needs of a particular terminal: low bandwidth for text data and high bandwidth for audio/video data.
- *Digital Design*: A complete digital design makes it possible to embed error detection and correction capabilities throughout the system.
- *Dedicated Control Signaling*: With greater terminal intelligence, the control signaling will either be performed “out of band,” in dedicated control signals, or as embedded control packets within the allocated data channels.

5. Technology Roadmap

5.1. Telephony

In the previous sections, we have described a number of approaches for cellular telephony. These as well additional proposals for cordless telephones are summarized in Table 1 [Reed 92]. AMPS is the current North American analog system. IS-54 is the digital system providing service within the currently allocated AMPS channels. GSM is the European digital cellular telephony standard. QCDMA is the Qualcomm CDMA proposal that forms the basis for IS-95. RCDMA is an alternative scheme proposed by Rockwell. CT is the first generation cordless phone standard using narrowband FM with 10 channels. CT2Plus is a

Table 1: Comparison of Cellular and Cordless Radio System Parameters

Parameter	AMPS	IS-54	GSM	Q-CDMA	R-CDMA	CT	CT2	UD-PCS	DECT
Radio Access Method	FDMA	TDMA/ FDMA	TDMA/ FDMA	CDMA/ FDMA	CDMA	NFM	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA
RF Channel Size	30Khz	30KHz	200 KHz	1.25MHz	40MHz	20Khz	100KHz	700KHz	1.7MHz
Channel Rate	—	48Kbps	270.8Kbps	10 or 32Kbps	20 or 40Kbps	—	72Kbps	514Kbps	1.1Mbps
Voice Chan per RF Chan	1	3	8	20-60 per sector	126	1	1	10	12
Duplex Voice Channel Size	60Khz	20Khz	50Khz	—	—	40Khz	100Khz	70Khz	144Khz
Voice Bit Rate	—	8 Kbps	13 Kbps	8-32Kbps	16Kbps	—	32Kbps	32Kbps	32Kbps
Handset xmit Pwr Max/Avg (mW)	600/600	3000/ 200	1000/ 125	200/6	100/1	≤10	10/5	100/10	250/10
Max Cell Radius	>32 Km	>32 Km	32 Km	2.5 Km	450 m	100 m	100m	500 m	500m

second generation digital cordless system that support telepoint service (i.e., a handset can initiate but not receive calls). UD-PCS (Universal Digital PCS) is an alternative system that has been proposed by Bellcore for in-building cordless phone service. DECT is the European digital cordless telephone standard. Each system is characterized by the radio access method it employs, the channel frequency band, the channel rate in bits per second for digital systems, the number of voice channels superimposed onto one RF channel, the duplex voice channel size, the voice coder bit rate for digital systems, the transmitter power both max and average, and the maximum cell radius. The CDMA systems are particularly attractive because of their low power and support for large numbers of voice channels.

5.2. Satellite Communications

A number of globe spanning satellite telephone systems have been proposed and constructed [Lodge 91, Reinhart 92]. These provide communications coverage over very wide areas, including over the ocean as well as in remote land areas. Satellite systems fall into three broad classes: geosynchronous (GEO), “big” low earth orbit (LEO), and “little” LEOs.

Geosynchronous systems include Inmarsat and OmniTRACS. The former is geared mainly for analog voice transmission (it was used by reporters to transmit from Bagdad during the Gulf War), and the first generation Inmarsat-A system was designed for large (1m parabolic dish antenna) expensive terminals, Newer generations of Inmarsats are incorporating digital techniques for use with smaller, less expensive terminals. The Inmarsat system uses allocations in the 6 Ghz band for the ground station to the satellite,1.5 Ghz for the satellite to terminal downlink, 1.6 Ghz for the terminal to satellite uplink, and 4 Ghz for the satellite to ground station.

Qualcomm’s OmniTRACS provides two-way communications as well as location positioning. The system operates in the 12/14 Ghz bands. The downlink data rate is between 5 Kbps and 15 Kbps while the uplink is between 55 bps and 165 bps. The system is used extensively for alphanumeric messaging and on-board sensor reading for trucking fleets.

Little LEOs are relatively small and inexpensive satellites that provide low cost, low data rate, two-way digital communications and location positioning to small, handheld terminals. The frequency allocations are in the VHF band below 400 MHz. The advantage of little LEOs are their small size and relatively low costs. Systems include Leosat, Orbcomm, Starnet, and Vitasat. For example, the Orbcomm system requires 34 satellites for reliable, full world coverage, and provides 2400 bps on the uplink and 4800 bps on the downlink.

Big LEOs are larger, more expensive satellites that provide voice communications as well as moderate to high speed data communications (56 Kbps). Proposals include Aries, Ellipso, Globalstar, Iridium, and Odyssey. Frequency allocations are above 1 GHz. For example, Motorola’s Iridium system will offer worldwide cellular phone service from 77 satellites placed in 7 polar orbits.

Some experimental satellite systems are aiming for higher data rates. For example, the NASA ACTS satellite will transmit to terminals in the 20 Ghz band and will receive signals in the 30 Ghz band. T1 data rates, at 1.5 Mbps, will be available on an experimental basis. No doubt future direct broadcast high definition television satellites will play an important role in providing high bandwidth wireless data communications.

5.3. In-building Wireless LANs

In building technologies fall into two classes: those that use radio frequency and those that use infrared. In general, the existing products are not really designed to support true mobility, but rather to replace wired connections with (relatively) easy to reconfigure wireless connections. Also the cost of these systems is sufficiently high that they are configured to concentrate multiple desktop computers onto a single wireless link. In essence, these provide a wireless bridge between conventional wired networks. These products demonstrate that the industry has a considerable way to go before small, low cost, high bandwidth wireless devices will be widely available.

Motorola’s Altair system operates at 18 Ghz (a special pioneer frequency allocation made solely to Motorola), uses time division multiplexing, and implements the Ethernet protocols including TCP/IP. It has been benchmarked at 3.3 Mbps [Berline 92], despite a claimed maximum performance of 15 Mbps [Freeburg 91]. Motorola attributes several advantages to using this microwave frequency band, including good signal diffusion properties coupled with containment within building structures and avoidance of interference with commonly encountered office equipment. A second generation Altair-II system is said to approach 10 Mbps. The link can operate over a diameter of 130 feet in an open area, 65-70 feet in a semi-closed space, and only 40-50 feet in an enclosed space.

NCR's WaveLAN system uses spread spectrum techniques, operates in the ISM band at 900 Mhz, and implements Ethernet media access and the popular personal computer Netware protocols. It has been benchmarked at 2 Mbps [Berline 92]. However to achieve these throughputs, the system must use the entire ISM band, making it more susceptible to interference, and short spreading codes, decreasing its immunity to co-channel interference. It has a greater range than the Motorola system, and is able to operate at 800 feet in the open, 200 feet in semiclosed spaces, and 110 feet in closed spaces. It suffers from the usual problem of using the ISM bands, namely the need to tolerant interference from many devices including government radars, medical and industrial equipment, and consumer products like microwave ovens.

InfraLAN is an example of an IR-based system. Operating on a line of sight basis, it has been benchmarked at 4 Mbps. Its primary use is to interconnect computers to their peripherals such as printers, without using wires. It can operate within a diameter of 80 feet for either semiclosed or completely enclosed spaces. However, line of sight systems have limitations, in that the propagated signal can easily be blocked by some objects or reflected by others. This has lead some vendors to investigate diffused infrared systems, in which the IR radiation fills an enclosed space, like an office or a meeting room.

6. Summary, Conclusions, and Future Directions

In this paper, we have described wireless information systems in terms of these needs to be both mobile and adaptive. Wireless systems are sparking so much interest of late because of the cross cutting set of skills to construct such systems. While traditional engineering scales are focused in one particular engineering domain, such as circuit design, radio engineering, networks, or computer systems, the real breakthroughs will come from new techniques that span areas.

Figure 6 illustrates the role of system design in driving the development of wireless systems. Technologists develop new technologies that solve parts of the problem, such as a new network protocol or circuit design methodology. Applications drive the need for new systems by creating demands for systems

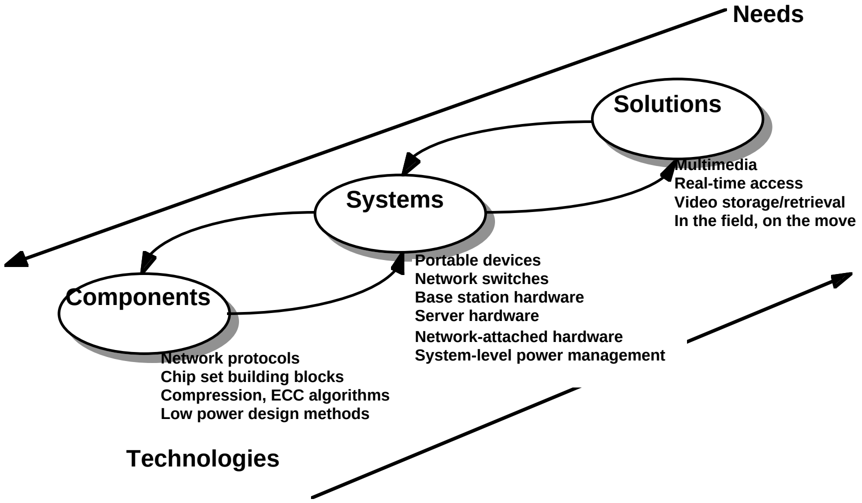

Figure 6: *Research Issues in Wireless, Adaptive, Mobile Information Systems*
Needs pull the development of systems while technologies push them. The components must be coupled to systems to demonstrate their value, while systems must be fielded and proven in applications.

capabilities, such as access to multimedia in the field or on the move. The system designer must integrate these applications needs with the capabilities of new technologies.

While the ultimate goal of the systems described in this paper is to make wireless systems ubiquitously available, there are rational steps along the way which must be developed first. For example, small scale wireless systems, based on local area networks with a focus on providing basic services, should be constructed first. These would be able to support tens of terminals on a floor and perhaps hundreds within a building. This could be accomplished within the next 1-2 years.

The next step is to scale up to medium scale systems. Such systems would be usable within a metropolitan area, and would focus on the issues of latency and real-time constraints over multimedia data. Perhaps thousands of such devices would be in use in a cluster of buildings, like a college campus. This could be accomplished within the next 2-3 years.

The final step would be large scale wireless systems, spanning wide area networks, with a focus on addressing and scaling up to potentially millions of users in a global spanning network. This could be achieved within 3 to 5 years.

Along the way, the kinds of prototypes that need to be built include terminals, base stations, network switches, servers, protocols, continuous media toolkits, and new file and network services. To test out the ideas, testbeds at the small, medium, and large-scale should be undertaken, scaling up in terms of both the number of users and the geographical span of the network. New applications enabled by wireless communications should be prototyped as well. These include collaborative design, engineering/manufacturing co-design, multimedia engineering design notebooks, and crisis management/planning support environments. Some of the challenges and attractive technology opportunities for wireless information systems are summarized in Table 2.

Table 2: Wireless, Adaptive, Mobile Information Systems

Concept	Goal	Challenge	Technology Opportunity
Radio Frequency Link	Wireless Communications	Raw high b/w; security	Low power microwave, Microcellular techniques
Error Tolerating Data Types	Integrated ECC, Cryptography, Compression	High Effective b/w, with security	Signal processing chips in base station, terminals
Continuous Media Service	Audio, Video Synchronization	Real-time constraints, Network coordination	Real time network protocols
Nomadic Hosts	Ubiquitous Acess	Addressing: network connections on the move	Mobile IP and extensions
Multimedia Server	High capacity storage High data rate access	High capacity per ft^3 support for large #s of simultaneous sessions	File servers built around disk array concepts
Engineering Design Notebook	Collaboration, computer-based design record	Wireless device integrating multimedia with design tools and environments	Driving application for development of wireless infrastructure

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7. References

[Berline 92] Berline, G., E. Perratore, “Portable, Affordable, Secure: Wireless LANs,” PC Magazine, (February 11, 1992), pp. 291-314.

[Bhagwat 93] Bhagwat, P., C. Perkins, “A Mobile Networking System Based on Internet Protocol,” USENIX Symp. on Mobile and Location Independent Computer, Cambridge, MA, (August 1993).

[CDPD 93] CDPD Industry Coordinator, “Overview of CDPD: Cellular Digital Packet Data Specification,” Release 1.0, PO Box 97060, Kirkland, Washington 98083-9760, (TBD).

[Cox 89] Cox, D. C. “Portable Digital Radio Communications—An Approach to Tetherless Access,” *IEEE Communications Magazine*, (July 1989).

[Cox 90] Cox, D. C., “Personal Communications—A Viewpoint,” *IEEE Communications Magazine*, (November 1990), pp. 8-20.

[Duchamp 91] Duchamp, D., S. K. Feiner, G. Q. Maguire, “Software Technology for Wireless Mobile Computing,” *IEEE Network Magazine*, (November 1991), pp. 12-18.

[Freeburg 91] Freeburg, T., “Enabling Technologies for Wireless In-Building Networks—Four Technical Challenges, Four Solutions,” *IEEE Communications Magazine*, (April 1991), pp. 58-64.

[Goodman 91] Goodman, D. J., “Trends in Cellular and Cordless Communications,” *IEEE Communications Magazine*, (June 1991), pp. 31-40.

[Hewitt 93] Hewitt, C., C. Manning, “Joint Information Services Architecture for Mobile Distributed Telecomputing,” Briefing Slides, 1993.

[Imielinski 92] Imielinski, T., B. Badrinath, “Mobile Wireless Computing: Solutions and Challenges in Data Management,” Rutgers University Computer Science Department Technical Report, 1992.

[Ioannidas 91] Ioannidas, J., D. Duchamp, G. Maguire, “IP-based Protocols for Mobile Internetworking,” Proc. ACM SIGCOMM Conference, (1991), pp. 235-245.

[Ioannidas 93] Ioannidas, J., G. Maquire, “The Design and Implementation of a Mobile Internetworking Architecture,” Proc. Winter USENIX Symp., San Diego, CA, (January 1993), pp. 491-502.

[Karn 93] Karn, P., “The Qualcomm CDMA Digital Cellular System,” Proceedings of USENIX Symposium on Mobile and Location-Independent Computing, Cambridge, MA, (August 1993).

[Keeton 93] Keeton, K., B. Mah, S. Seshan, R. H. Katz, D. Ferrari, “Providing Connection-Oriented Network Services to Mobile Hosts,” Proceedings of USENIX Symposium on Mobile and Location-Independent Computing, Cambridge, MA, (August 1993).

[Kistler 92] Kistler, J. J., M. Satyanarayanan, “Disconnected Operation in the Coda File System,” *ACM Transactions on Computer Systems*, V10, N 1, (February 1992), pp. 3-25.

[Kobb 93] Kobb, B. Z., “Personal Wireless,” *IEEE Spectrum*, V 30, N 6, (June 1993), pp. 20-25.

[Kucar 91] Kucar, A. D., “Mobile Radio: An Overview,” *IEEE Communications Magazine*, (November 1991), pp. 72-85.

[Lee 89] Lee, W. C. Y., *Mobile Cellular Telecommunications Systems*, McGraw-Hill, New York, 1989.

[Lee 93] Lee, W. C. Y., *Mobile Communications Design Fundamentals*, 2nd Ed., Wiley International, New York, 1993.

[Lodge 91] Lodge, J., “Mobile Satellite Communications Systems: Toward Global Personal Communications,” *IEEE Communications Magazine*, (November 1991), pp. 24-30.

[Mello 93] Mello, J., P. Wayner, “Wireless Mobile Communications,” *Byte Magazine*, (February 1993), pp. 147-154.

[Min 93] Min, J., A. Rofongaran, V. Lin, M. Jensen, H. Samueli, A. Abidi, G. Pottie, Y. Rahmat-Samii, “A Low Power Handheld Frequency-Hopped Spread Spectrum Transceiver Hardware Architecture,” UCLA EE Department Technical Report, 1993.

[Perkins 92] Perkins, C., “Simplified Routing for Mobile Computers using TCP/IP,” First IEEE Conference on Wireless LAN Implementation, (September 1992).

[Rappaport 91] Rappaport, T., “The Wireless Revolution,” *IEEE Communications Magazine*, (November 1991), pp. 52-71.

[Reed 92] Reed, D., “Putting It All Together: The Cost Structure of Personal Communications Services,” Federal Communications Commission Office of Policy and Plans, Working Paper #28, (November 1992).

[Reinhart 92] Reinhart, E., “Mobile Communications,” *IEEE Spectrum*, V29, N2, (February 1992), pp. 27-29.

[Sheng 92] Sheng, S., A. Chandrakasan, R. W. Brodersen, “A Portable Multimedia Terminal,” *IEEE Communications Magazine*, V 30, N 12, (December 1992), pp. 64-75.

[Weiser 91] Weiser, M., “The Computer for the Twenty-First Century,” *Scientific American*, V 265, N 3, (September 1991), pp. 94-104.

[Weiser 93] Weiser, M., “Some Computer Science Issues Related to Ubiquitous Computing,” *Comm. ACM*, V 36, N 7, (July 1993), V 36, N 7, (July 1993), pp. 75-85.