Wireless Data Communications

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Invited Paper

Wireless data services and systems represent a rapidly growing and increasingly important segment of the communications industry. In this paper we present an overview of this field, emphasizing three major elements: 1) technologies utilized in existing and currently planned wireless data services, 2) issues related to the performance of these sytems, and 3) discernible trends in the continuing development of wireless data systems. While the wireless data industry is becoming increasingly diverse and fragmented, one can identify a few mainstreams which relate directly to users' requirement for data services. On one hand, there are requirements for relatively low-speed data services supporting mobile users over wide geographical areas, as provided by mobile data networks. On the other hand, there are requirements for high-speed data services in local areas, as provided by wireless LAN's. The system-level issues are somewhat different for these two categories of services, and this has led to different technology choices in the two domains, which we discuss in the paper.

I. INTRODUCTION

We are all being exposed to a revolution in communications, a revolution that is taking us from a world where telephone subscribers were constrained to communicate over fixed telephone lines, to one where a tetherless and mobile communications environment has become a reality. Wireless communications systems, of which cordless phones, pagers, and cellular telephones are some of the most familiar examples, have experienced enormous growth over the last decade. Recent market data indicate that there are currently about 13 million cellular subscribers in the United States, which compares with approximately 4.4 million in June 1990 and 90 000 subscribers in 1984. It is clear that the convenience and efficiency afforded by wireless access to communications networks is fueling enormous growth in this segment of the communications industry, a growth which is likely to continue for many years. This growth has to date primarily served the ever-growing demands for voice service and message paging services. However, the increasing reliance on data communications in the business world provides the basis for a similar growth in demand for various forms of wireless data service. Just as the pager and the cellular telephone have become standard items in the business traveler's attache case, lap-top and notebook computers are becoming increasingly familiar elements of the "mobile office." The rapid proliferation of these small portable computers, spurred by miniaturization and improvements in wireless transmission methods, is certain to create an enormous demand for wireless data services. In the marketplace one already finds portable computers which can be connected directly to a cellular telephone. Some manufacturers have introduced modems with error-correction capability implemented on a Personal Computer Memory Card International Association (PCMCIA) card, a small disk which is inserted into a PCMCIA slot on a notebook computer and also connected to the cellular telephone. These are examples of ways of providing data transmission over a network designed for wireless analog voice service, in effect the wireless equivalent of connecting a standard V-series data modem to the wired public switched telephone network (PSTN). However, just as terrestrial digital data networks have evolved to provide more efficient data communication than is provided by the use of modems, dedicated wireless data services and networks, including wireless LAN's, are being developed as well. It is the development of these wireless data networks which is the subject of this paper.

In a digital network voice and data services have different and sometimes contradictory requirements. In order to understand the differences among service requirements, one must first examine the services from the user's point of view. At the outset, it is important to understand that users' expectations are based upon their experience with services provided in the public switched telephone network. Although digitized voice, imagery, and data are all "binary digits," there are different requirements for transmission of each service in a digital network. For example, because of the user's expectation of telephone-quality voice in the public wired network, voice service in a wireless network environment must be designed with careful attention to minimizing time delays. Delays in excess of 100 ms will be noticeable and annoying to the listener. In contrast, delay in

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a data network, while not desirable, is generally acceptable to the data user. Packetized voice can tolerate packet loss rates of the order of 10^{-2}, or bit-error rates of the same order, without a noticeable degradation in service quality. An error rate of 10^{-5} is ordinarily acceptable for uncoded data, but any loss of data packets is totally unacceptable. The lengths of telephone conversations are relatively uniform (approximately 3-20 min) and a few seconds of setup time is therefore acceptable. Each telephone conversation session generates megabytes of digitized information. On the other hand, a communication session for a data service can vary over a wide range from a short electronic mail message carrying only a few bytes of information up to a long file transfer such as the text of a book, which may be as large as several megabytes. On the average, the volume of information involved in a data communication session is much smaller than that of a digitized-voice communication session. The uncertainty in the amount of the information and the low average length of data communication sessions make long setup times undesirable.

The difference between the requirements for voice and data packets have resulted in several major differences in the architecture of voice and data networks. The backbone of the voice networks is a circuit switch hierarchy while the data networks are implemented with packet swiches. The data packets access the network with a random wireless access technique while the access for the voice packets is assigned to users. The packet data networks generally use a retransmission strategy to ensure the accuracy of the transmission while voice packets are transmitted only one time. Packet data networks strive for higher data rates and as the data rate increases new applications evolve. The only application for the voice networks is transmission of the real-time voice and as the technology evolves the encoding rate is actually decreased. With all these different requirements the trend in wireline networks is to integrate because with one set of wiring and switching there are savings in the cost of the network. In the wireless arena this constraint does not hold and separation of frequency bands would be a reasonable alternative. The only time that we may intend to mix voice and data is to use the idle time among the voice spurts for data applications.

While it is true that the major thrust of telecommunications is toward multimedia services, the existing infrastructure of communications networks is still very fragmented. Today we have wired PBX's for local voice communications within office complexes, the public switched telephone network for wide-area voice communications, wired local-area networks for high-speed local data communications, packet-switched networks, voice-band modems for low-speed wide-area data communications, and a separate cable network for wide-area video distribution. The process of setting standards for various areas of communications has been similarly fragmented. The standards for voice transmission technology have evolved within the operating companies, while the standards for voice-band data modems have been developed by the CCITT, and the standards for local-area networks by IEEE 802 and ISO. This separation has come about because each individual network was designed to meet the requirements of a particular type of service, be it voice, data, or imagery/video.

The same pattern of separation exists in the wireless information industry as well. The new-generation wireless information networks are evolving around either voice-oriented applications such as digital cellular, cordless telephone, and wireless PBX; or around data-oriented networks such as wireless LAN's and mobile data networks. While it is true that all the major standards initiatives are focused on integration of services, one still sees a separation of the industrial communities that participate in the various standards bodies. That is, we see GSM, North American Digital Cellular, DECT, and other initiatives supported primarily by representatives of the voice-communications industry, while IEEE 802.11, WINForum, and HIPERLAN are supported primarily by those with interest in data communications.

Although future personal communications devices may be designed as integrated units for personal computing as well as personal voice and data communications, the wireless access supporting different applications may use different frequency bands or even different transmission technologies. A personal communications service (PCS) may use wideband Code-Division Multiple Access (CDMA) in a shared spread-spectrum band. A digital cellular service may use Time-Division Multiple Access (TDMA) or CDMA in another band. Low-speed data may be transmitted in the gaps between bursts of voice activity. High-speed local-area data may be transmitted in another shared wideband channel. At the same time, the various services may all be integrated in a metropolitan-area or wide-area network structured with Asynchrnous Transfer Mode (ATM) switches.

The future direction of this industry depends upon technological developments and a maturity in the spectrum-administration organizations, who must understand the growing massive demand for bandwidth and must, in turn, develop strategies allowing a fair sharing of increasingly scarce bandwidth. Just as governmental agencies restrict abusive consumption of other limited natural resources such as water, appropriate agencies will have to protect the spectral resources needed for wireless information networks. After all, the electromagnetic spectrum is a modern natural resource supporting the ever-widening array of telecommunications services which are becoming an increasingly important part of the fabric of our personal and professional lives.

This paper provides a summary of the rapidly expanding field of wireless data services, systems, and technologies. Section II provides an overview of the wireless data market, the user perspective of wireless data services, and the frequency admistration issues that have an important influence on the evolution of new systems. Section III provides a brief description of mobile data networks and wireless local-area networks. Section IV reviews the major technical issues that bear upon the design of wireless data networks. Section V provides concluding remarks.

II. OVERVIEW OF WIRELESS NETWORKS

A. Evolving Wireless Information Networks

The mid-1980's saw major initiatives in all sectors of the wireless information industry. To increase the capacity of cellular telephone systems, which have reached their technical limits in some large market areas, the transition to digital cellular technology was begun. The Pan-European GSM standard [1] was followed by the EIA–TIA North American Digital Cellular Standards initiatives, and the Japanese Digital Cellular standard. The extraordinary success of the cordless-telephone market spurred new standardization efforts for digital cordless and CT-2 TelePoint in the UK [2], wireless PBX, DECT, in Sweden [3], [4], the advanced cordless phone in Japan [5], and the concept of a Universal Digital Portable Communicator in the US [6]–[9]. The success of the paging industry led to development of private wireless packet data networks for commercial applications requiring longer messages [10]–[12]. Motivated by the desire to provide portability and to avoid the high costs of installation and relocation of wired office information networks, wireless office information networks were suggested as an alternative [13], [14]. Another major event in this period was the May 1985 FCC announcement on unlicensed ISM bands [15]–[17]. This announcement cleared the way for development of a wide array of commercial devices from wireless PBX's [18] and wireless LAN's [19], [20] to wireless fire safety devices using spread-spectrum technology.

Figure 1 distinguishes the various categories of wireless networks that we discuss in this paper. We first define two broad categories of networks as 1) voice-oriented or isochronous networks and 2) data-oriented or asynchronous networks. Under each main category of networks, we distinguish further between local-area networks and wide-area networks. As will be seen subsequently in this paper, each of the resulting four subcategories of networks has a set of characteristics that leads to certain design choices specific to the subcategory.

Figure 2, which is structured according to the categories and subcategories defined in Fig. 1, depicts various dimensions of today's voice and data communications industries. The figure compares local cordless personal communication with wide-area cellular, and compares wireless LAN's with wide-area low-speed data services. Figure 2(a) [21] compares various dimensions related to the wireless voice industry and Fig. 2(b) provides an analogous comparison between wireless data systems. Although from the user's standpoint the service characteristics and the appearance of the handset will be very similar for digital cellular and PCS systems, there will in fact be a major difference in the operation of the networks supporting the two types of systems. The digital cellular system is designed to support mobile users roaming over wide geographic areas, and thus coverage is provided by an arrangement of cells with cell size typically more than 2 mi in diameter. The radio cell sites for this system are large and expensive, particularly in urban areas where the cost of property is very high. The handset requires an average power of around 1 W, which is reflected in limited battery life and the need for frequent recharging. The number of users per cell is large and to provide as many user channels as possible in the allocated bandwidth, complex speech coding techniques are used. The speech coding techniques minimize the digitized speech transmission rate, but consume a significant amount of electronic power, which in turn places a high demand on battery power. The PCS systems will be designed for small, low-power devices to be carried and used in and around office buildings, industrial complexes, and city streets. The size of each cell will be less than 0.25 mi and the relatively small base stations will be installed on utility poles or attached to city and suburban business buildings. The average radiated power will be 10–20 mW, leading to relatively long battery life. The PCS services are to replace cordless phones, and the quality of voice service is intended to be comparable to wireline phone service. As a result, simple but high-quality speech coding algorithms are to be used, and at this writing, the leading candidate for adoption is 32-kbit/s Adaptive Differential Pulse Code Moduation (ADPCM) [22]. While a high-quality voice coding algorithm of this type does not provide the spectral efficiency of the lower rate (4- to 8-kbit/s) vocoders used in the digital cellular standards, it is far less demanding of digital signal processing complexity, and thus permits the use of very low prime power in the portable units. It is expected that PCS service will distinguish itself from digital cellular service by higher voice quality, and smaller user terminal. Table 1 provides a summary of the wireless technologies employed in several worldwide standards for the wireless voice industry [23]. For more details on the digital cellular and PCS initiatives, the reader can refer to [24]–[29] and other references cited there.

Mobile data networks operate at relatively low data rates over well-understood urban radio channels using familiar multiple-access methods. The technical challenge here is the development of a system which makes efficient use of the available bandwidth to serve large numbers of users distributed over wide geographical areas. The transmission technology used in mobile data networks is generally rather simple and similar from one network to another. We discuss the major existing and planned mobile data networks and services in Section III.

Wireless local area networks (WLAN's) and mobile data networks serve somewhat different categories of user applications, and give rise to different system design and performance considerations. A WLAN typically supports a limited number of users in a well-defined indoor area, and system aspects such as overall bandwidth efficiency and product standardization are not crucial. The achievable data rate is generally an important consideration in the selection of a WLAN, and therefore the transmission channel characteristics and the application of signal processing techniques are important topics [30]–[32]. Access methods and network topologies used in WLAN's are much the same from one system to another, but the transmission technologies can be quite different. Efficient deign of these systems

Table 1 Summary of the Wireless Technologies Employed in Several Worldwide Standards for the Wireless Voice Industry

	Digital Cellular				Low-Power Systems				
System:	IS-54	GSM	JDC	IS-95	DECT	PHP	CT-2	CT-3	Bellcore UDPC
Multiple Access:	TDMA/ FDMA	TDMA/ FDMA	TDMA/ FDMA	FDMA/ CDMA-SS	TDMA/ FDMA	TDMA/ FDMA	FDMA	TDMA/ FDMA	TDM/TDMA/ FDMA
Frequency Band Base TX (MHz): Mobile TX (MHz):	869-894 824-849 (U. S.)	935-960 890-915	810-826 940-956 1447-1489 1429-1441 1501-1513 1453-1465	869-894 824-849 (U. S.)	1800-1900 (Europe)	1895-1907 (Japan)	864-868 (Europe & Asia)	862-866 (Sweden)	Emerging Technology (U. S.)
Duplexing:	FDD	FDD	FDD	FDD	TDD	TDD	TDD	TDD	FDD
Ch. Spacing (kHz):	30	200	25	1250	1728	300	100	1000	350
Modulation:	$\pi/4$-QDPSK	GMSK	$\pi/4$-QDPSK	BPSK/ QPSK	GFSK	$\pi/4$-QDPSK	GFSK	GFSK	$\pi/4$-QDPSK
Portable Transmit Power, Max/Avg:	600 mW/ 200 mW	1W/ 125 mW		200 mW	250 mW/ 10 mW	80 mW/ 10 mW	10 mW/ 5 mW	80 mW/ 5 mW	200 mW/ 20 mW
Frequency Assignment:	Fixed	Dynamic	Fixed		Dynamic	Dynamic	Dynamic	Dynamic	Autonomous
Power Control									
Handset:	Yes	Yes	Yes	Yes	No		No	No	Yes
Base:	Yes	Yes	Yes	Yes	No		No	No	No
Speech Coding and Rate (kbits/s):	VSELP 8	RPE-LTP 13	VSELP 8	QCELP 1-8 (var.)	ADPCM 32	ADPCM 32	ADPCM 32	ADPC 32	ADPCM 32
Speech Channels per RF Channel:	3	8	3	-	12	4	1	8	10
Channel Rate (kbits/s)	48.6	270.833	42	1,228.8 (Chip Rate)	1152	96	72	640	500
Channel Coding:	Rate-1/2 Conv.	Rate-1/2 Conv.		R-1/2 fwd. R-1/3 rev. CRC	CRC	CRC	None	CRC	CRC
Frame Duration (ms):	40	4.615	20	20	10	5	2	16	2

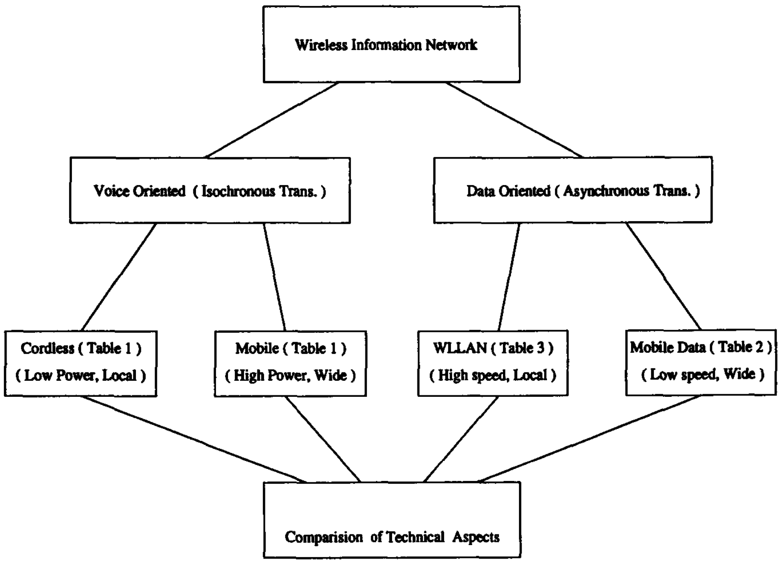


Fig. 1. Categories of wireless information networks.

requires evaluation of various transmission techniques, an understanding of the complexities of indoor radio propagation, and the analysis of the effects of interference. WLAN manufacturers currently offer a number of nonstandardized products based on conventional radio modem technology, spread-spectrum technology in the ISM bands, and infrared technology. We discuss the various WLAN technologies in Section III.

The future of the wireless data communciation industry is toward multimedia, multirate, and multipower applications.

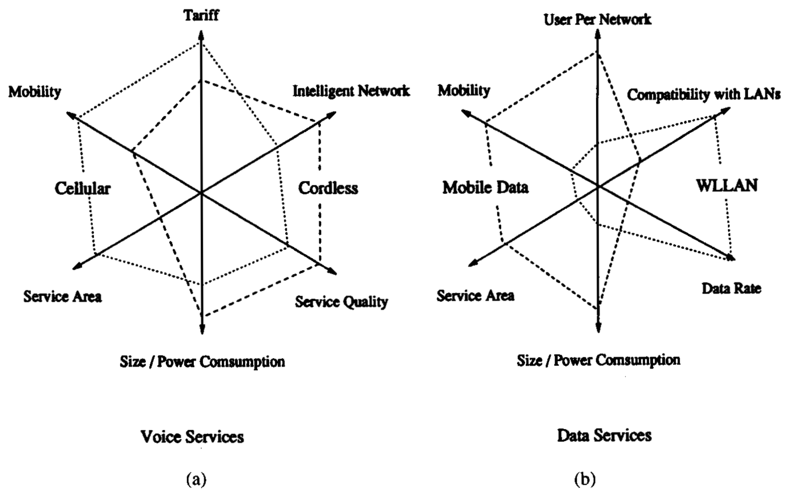


Fig. 2. Various dimensions of the voice and data services offered by the wireless information network industry. Mobile cellular is compared with cordless PCS, and WLAN's with mobile data.

Multimedia developments will support the ever-growing demand for mixed data, voice, and imagery applications and will be used to connect the pen pad and lap-top devices to backbone information resources and computational facilities. Multirate modems will support high-speed wide-area as well as low-speed local applications with a single device. Multipower terminals will allow the selection of the power resources such as ac power lines, car battery, or small batteries, based on availability; and will adapt the quality of the service to the consumption of the power resource.

B. Wireless Data: Market and User Perspectives

From the data user's perspective, the minimum satisfactory service requirement is low-speed access in wide areas and high-speed access in local areas. The low-speed wide-area access will serve a variety of short-message applications such as notice of electronic or voice mail, while the local-area access will support high-speed local applications such as long file transfers or printing tasks. In the current literature, low-speed wide-area wireless data communication is referred to as *mobile data*, while local high-speed data communication systems are called *wireless LAN's*. As we discussed in the last section, the relationship between WLAN and mobile data services is analogous to the relationship between PCS and digital cellular services. While PCS is intended to provide high-quality local voice communication, the digital cellular services are aimed at wider area coverage with less emphasis on the quality of the service.

1) Low-Speed Wide-Area Systems (Mobile Data): Mobile radio data systems have grown out of the success of the paging-service industry and increasing customer demand for more advanced services. Today 100 000 customers are using mobile data services and the industry expects 13 million users by the year 2000. This could be equivalent to 10% to 30% of the revenue of the cellular radio industry. Today, mobile data services provide length-limited wireless connections with in-building penetration to portable users terminals in metropolitan areas. The future direction is toward wider coverage, higher data rates, and capability for transmitting longer data files.

The transmission rates of existing mobile data systems are comparable to voice-band modem rates (up to 19.2 kbits/s). However, the service typically has a limitation on the size of the file that can be transmitted in each communication session. The coverage of the service is similar to standard land-mobile radio services with the difference that the mobile data service must provide in-building penetration. Land-mobile radio users typically use a telephone unit inside a vehicle and usually while driving. Mobile data users typically use the portable unit inside a building and in a stationary location. Therefore, in-building penetration is an essential feature of mobile data services.

Mobile data services are used for transaction processing and interactive, broadcast, and multicast services. Transaction processing has applications such as credit card verification, taxi calls, vehicle theft reporting, paging, and notice of voice or electronic mail. Interactive services include enterprise applications such as database access and remote LAN access. Broadcast services include general information services, weather and traffic advisory services, and advertising. Multicast services are similar to subscribed information services, law enforcement communications, and private bulletin boards.

There are other low-speed data products using voice-band modems over radio systems originally designed for voice communications. Some of these products are used in the land-mobile radio bands around 100-200 MHz, for low-speed local data communications in or around buildings. Other products, portable facsimile devices, and voice-band modems, are used over the analog cellular telephone network to provide wide-area data communications for mobile users without any restrictions on the connection time. The term *mobile office* is sometimes used to describe these applications.

2) High-Speed Local-Area Systems (Wireless LAN's): Today, most large offices are already equipped with wiring for conventional LAN's, and the inclusion of LAN wiring in the planning of a new office building is done as a standard procedure, along with planning for telephone and electric-power wiring. The WLAN market will very likely develop on the basis of the appropriateness of the wireless solution to specific applications. The target markets for the wireless LAN industry include applications in manufacturing facilities, in offices with wiring difficulties, and in branch offices and temporary offices. In manufacturing facilities, ceilings are typically not designed to provide a space for distribution of wiring. Also, manufacturing floors are not usually configured with walls through which wiring might otherwise be run from the ceiling to outlets. Underground wiring is a solution that suffers from expensive installation, relocation, and maintenance. As a result, the natural solution for networking on most manufacturing floors is wireless communications. Other wide indoor areas without partitioning, such as libraries or open-architecture offices, are also suitable for application of WLAN's. In addition, buildings of historical value, concrete buildings, and buildings with marble interiors all pose serious problems for wiring installation, leaving WLAN's as the logical solution. WLAN's are also well suited to unwired small offices such as real-estate agencies, where only a few terminals are needed and where there may be frequent relocations of equipment to accommodate reconfiguration or redecoration of the office space. Temporary offices such as political campaign offices, consultants' offices, and conference registration centers, define another set of logical applications for WLAN's. The WLAN industry expects to capture 5–15% of the LAN market in the near future.

Although the market for personal computers (PC's) is not growing as it has in past years, the market for portable devices such as lap-top and pen-pad computers and personal digital assistants (PDA's) is growing rapidly. Of greater importance to the wireless data communication industry, the market for networked portables is growing much faster than the overall market for portable computing. Obviously, wireless is the communication method of choice for portable terminals. Mobile data communication services discussed earlier provide a low-speed solution for wide area coverage. For high-speed and local communications, a portable terminal with wireless access can bring the processing and database capabilities of a large computer directly to specific locations for short periods of time, thus opening a wide horizon for new applications. For example, one can take portable terminals into classrooms for instructional purposes, or to hospital beds or accident sites for medical diagnosis.

C. Frequency Administration Issues

The major long-standing problem facing the radio communications industry is the fundamental limitation on availability of frequency spectrum. The history of the industry has been characterized by a steady migration toward higher frequency bands as new systems and services have come into the market. When cellular telephone service was launched in the late 1970's, the FCC allocated 40 MHz of bandwidth in the 800-MHz band by moving prior occupants (educational TV channels) out of the bands. An additional allocation of 10 MHz was made in 1986 as the cellular industry grew. The current state of the cellular industry in many major market areas is that the analog cellular systems have reached capacity, and this is the primary motivation for the digital cellular initiatives, which will increase capacity by factors of about 3 to 10 over the analog systems. In the land-mobile radio (LMR) bands (150, 350, and 850 MHz), capacity limits are also being reached, though the market growth there is not as strong as in the cellular market. In the LMR industry, plans are being made to migrate from 25-kHz channels to 12.5 kHz, with plans for further migration in the future . All of this means that in these bands efficient spectrum utilization is of the utmost importance, and these systems must be designed to use the available bandwidth to serve the greatest number of users over wide service areas. Thus the emphasis here is on bandwidth-efficient modulation, efficient frequency management schemes, and in the case of data services, efficient multiuser access protocols.

The principal technological problems for implementation of WLAN's are: 1) data-rate limitations caused by the multipath characteristics of radio propagation, 2) the difficulties associated with signal coverage within buildings, and 3) the need for low-power electronic implementations suitable for portable terminals. These technical difficulties can be resolved and effective solutions are being developed for all of them. The greatest obstacle to achieving wireless multimegabit data communication rates is the lack of a suitable frequency band for reliable high-speed communication. The existing ISM bands [15]–[17] assigned for multiple-user applications are suitable for WLAN's, but they are restricted to spread-spectrum technology and can suffer from unnecessary interference caused by careless users. More widespread use of high-speed wireless data communication technology will depend upon cooperation from frequency administration organizations in providing wider bandwidth allocations without restriction on the adopted technology, and in administering rules and etiquette for cooperative use of these bands.

At frequencies around several gigahertz the technology is available for wireless implementations having reasonable size, power consumption, and cost. Moving to higher frequencies is the solution for the future. As frequency increases, the prospect for obtaining a wider bandwidth from spectrum regulatory agencies will improve. However, with today's technology, implementation at a few tens of gigahertz with reasonable product size and power consumption is challenging, particularly when wideband portable communication is considered. At higher frequencies, signal transmission through walls is more difficult. This feature is advantageous in WLAN applications where confinement of the signal within a room or building is a desirable privacy feature. Also, at higher frequencies the relationship between cell boundaries and the physical layout of the building is more easily determined, facilitating the planning of WLAN cell assignments within the building. The technology at higher frequencies is highly specialized and not commonly available within the computer industry. This has encouraged joint ventures among semiconductor, radio, and computer companies to develop new WLAN products at these frequencies.

A mobile data service is shared by a number of users distributed over a large geographical area. Development of a mobile data network requires a large investment affordable only by a major industrial organization. When the need for the network is justified, the band allocation can then be obtained from the appropriate administrative agency. The transmission techniques and access methods used in these systems are very similar from one network to another, and the decisions on these elements are overshadowed by the system-level decisions that provide a compromise between the cost of implementation and the coverage provided by the network. For example, the concept of overlay onto existing cellular for the CDPD networks is the single most important technical decision for the development of the system. Motivation for this decision is to provide a system that uses the infrastructure of the existing AMPS systems in the same band, therefore it can be deployed with a low cost and a wide area coverage without any demand for additional band from the frequency allocation agencies. The second most important issue is the development of a standard. Development of the elements of the network are rather routine engineering tasks not involving major decisions.

Wireless LAN's are designed for a small number of users usually operating in indoor areas. The range of the coverage is small which leaves many options open for the transmission technology. As a result, the major decision here is on the choice of the transmission method. The development of a wireless LAN does not involve a large infrastructure entailing extensive investments. As a result, small groups in large companies or small start-up companies usually initiate development of these products. Convincing the frequency administration agencies to provide a band for such applications has been more difficult. That has encouraged companies to align the transmission technology with the existing bands rather than asking for new bands. An overview of wireless data networks, with emphasis on wireless LAN's, is given in [31] and [32].

III. DESCRIPTION OF WIRELESS NETWORKS

In this section we describe mobile data networks and WLAN's, including existing systems and new systems under development or being defined by standards organizations. We describe the main characteristics of these systems as well as the applications they are intended to serve. Finally, we comment on the future directions of technological development in each category of system.

A. Mobile Data Networks

Packet data services currently available for mobile applications include ARDIS, formed by IBM and Motorola, and the RAM Mobile Data Network, which uses Ericsson MOBITEX data technology. Soon to be introduced into the market is Cellular Digital Packet Data (CDPD), being designed to transport data as a supplementary service overlaid onto existing analog cellular telephone networks. The new digital cellular standards, IS-54 and IS-95, will eventually include an array of data services, including both circuit-mode and packet-mode services, for the next-generation North American digital cellular systems. In Europe, the European Technical Standards Institute (ETSI) has begun developing a public standard for trunked radio and mobile data systems, designated as TETRA.

1) ARDIS: ARDIS is a two-way radio service developed as a joint venture between IBM and Motorola, and first implemented in 1983. The ARDIS network consists of four network control centers with 32 network controllers distributed through 1250 base station in 400 cities in the U.S. The service is suitable for two-way transfers of data files of size less than 10 kbytes, and much of its use is in support of computer-aided dispatching, such as is used by field service personnel, often while they are on customers' premise. Remote users access the system from lap-top radio terminals, which communicate with the base stations. Each of the ARDIS base stations is tied to one of the 32 radio network controllers, as shown in Fig. 3. The backbone of the network is implemented with leased telephone lines. The four ARDIS hosts, located in Chicago, New York, Los Angeles, and Lexington, KY, serve as access points for a customer's mainframe computer, which can be linked to an ARDIS host using async, bisync, SNA or X.25 dedicated circuits.

The operating frequency band is 800 MHz, and the RF links use separate transmit and receive frequencies 45 MHz apart. The system was initially implemented with an RF channel data rate of 4800 bits/s per 25-kHz channel, but this has been upgraded to 9.6 kbits/s, with a user data rate of about 8000 bits/s. The system architecture is cellular, with cells coverage areas overlapped to increase the probability that the signal transmission from a portable transmitter will reach at least one base station. The base station power is 40 W, which provides line-of-sight (LOS) coverage up to a radius of 10-15 mi. The portable units operate with 4 W of radiated power. The overlapping coverage, combined with designed power levels and error-correction coding in the transmission format, insure that the ARDIS can support portable communications from inside buildings, as well as on the street. This capability for in-building coverage is an important characteristic of the ARDIS service. The modulation technique used is frequency-shift keying (FSK), the access method is frequency-division multiple access (FDMA), and the transmission packet length is 256 bytes.

The lap-top portable terminals access the network using a random access method called data sense multiple access (DSMA). A remote terminal listens to the base station transmitter to determine if a "busy bit" is on or off. When the busy bit is off, the remote terminal is allowed to transmit. However, if two remote terminals begin to transmit at the same time, the signal packets may collide,

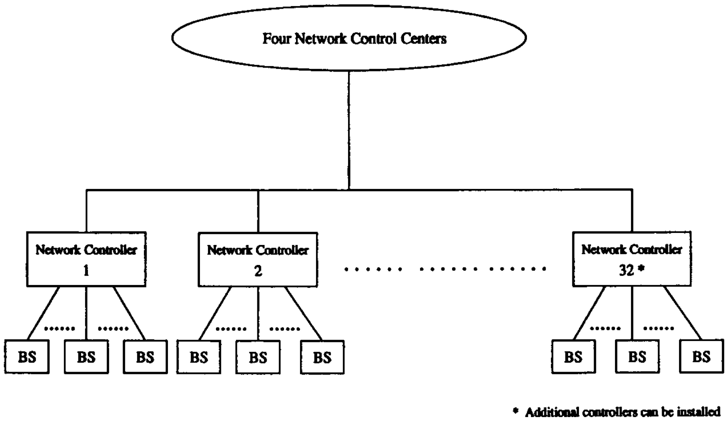


Fig. 3. ARDIS network architecture.

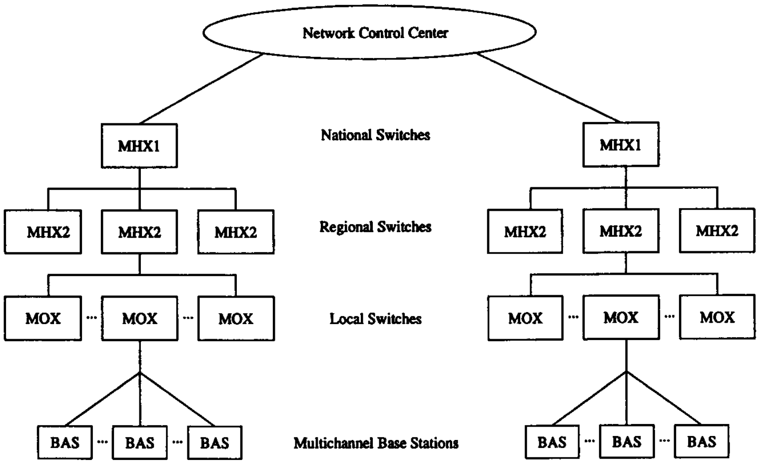


Fig. 4. MOBITEX network architecture.

and retransmission will be attempted, as in other contention-based multiple-access protocols. The busy bit lets a remote user know when other terminals are transmitting, and thus reduces the probability of packet collision.

2) MOBITEX: The MOBITEX system is a nationwide, interconnected, trunked radio network developed by Ericsson and Swedish Telecom. The first MOBITEX network went into operation in Sweden in 1986, and other networks have been implemented in Norway, Finland, Canada, the U. K., and the U.S. In the U.S., MOBITEX service was introduced by RAM Mobile Data in 1991 and now covers almost 100 major metropolitan areas. While the MOBITEX system was designed to carry both voice and data services, the U.S. and Canadian networks are used to provide data service only. MOBITEX is an intelligent network with an open architecture which allows establishing virtual networks. This feature facilitates the mobility and expandability of the network [11], [12]. The system supports a number of standardized network interfaces, including TCP/IP and X.25, and interfaces are added in response to market demands.

The MOBITEX network architecture is hierarchical, as shown in Fig. 4. At the top of the hierarchy is the Network Control Center (NCC), from which the entire network is managed. The top level of switching is a national switch (MHX1) that routes traffic between service regions. The next level comprises regional switches (MHX2's), and below that are local switches (MOX's), each of which handles traffic within a given service area. At the lowest level in the network, multichannel trunked-radio base stations communicate with the mobile and portable data sets. MOBITEX uses packet-switching techniques, as does ARDIS, to allow multiple users to access the same channel at the same time. Message packets are switched at the lowest possible network level. If two mobile users in the same service area need to communicate with each other, their messages are relayed through the local base station, and only billing information is sent up to the NCC.

The base stations are laid out in a grid pattern using the same system engineering rules as are used for cellular telephone systems. In fact, the MOBITEX system operates in much the same way as a cellular telephone system, except that handoffs are not managed by the network. That is, when a radio connection is to be changed from one base station to another, the decision is made by the mobile terminal, not by the network computer as in cellular telephone systems.

To access the network, a mobile terminal finds the base station with the strongest signal and then registers with that base station. When the mobile terminal enters an adjacent service area, it automatically re-registers with a new base station, and the user's whereabouts are relayed to the higher level network nodes. This provides automatic routing of messages bound for the mobile user, a capability known as *roaming*. The MOBITEX network also has a store-and-forward capability.

The mobile units transmit at 896-901 MHz and the base stations at 935-940 MHz. About 10 to 30 frequency pairs are used in each service area. The system uses dynamic power setting, in the range of 100 mW–10 W for mobile units and 100 mW–4 W for portable units. The Gaussian Minimum Shift-Keying (GMSK) modulation technique is used, with noncoherent demodulation. The transmission rate is 8000 bits/s half duplex in 12.5-kHz channels, and the service is suitable for file transfers up to 20 kbytes. The packet size is 512 bytes with 1–3-s delay. Forward-error-correction, as well as retransmissions, are used to ensure the bit-error-rate quality of delivered data packets. The system uses the dynamic Slotted-ALOHA random-access method, which we discuss further in Section IV.

RAM Mobile Data has installed approximately 800 base stations in 100 metropolitan areas throughout the U.S., providing coverage to about 90% of the urban business population. By locating its base stations close to major business centers, the RAM Mobile system provides a significant degree of in-building signal coverage.

3) CDPD: The Cellular Digital Packet Data (CDPD) system is being designed to provide packet data services in an overlay to the existing analog cellular telephone network. CDPD is being developed by IBM in collaboration with nine cellular carriers: McCaw, GTE, Contel Cellular, Ameritech, Bell Atlantic, NYNEX, Pacific Telesis, Southwestern Bell, and US West. These carriers will cover 95% of the U.S., including all major urban areas. A basic goal of the CDPD system is to provide data services on a noninterfering basis using the same 30-kHz channels used by the existing cellular telephone services. To do this, CDPD is designed to make use of cellular channels that are not being used for voice traffic, and to move to another channel when the current channel is allocated to voice service. As an alternative, some carriers may choose to simply dedicate some number of channels in each cell to CDPD service. The compatibility of CDPD with the existing cellular telephone system allows it to be installed in any analog cellular system in North America, thus providing data services that are not dependent upon support of a digital cellular standard in the service area. A preliminary field demonstration system was operated during the second half of 1992, and subsequently the participating companies issued a specification for the CDPD system [33]. Intended applications for CDPD service include: electronic mail, package delivery tracking, inventory control, credit card verification, security reporting, vehicle theft recovery, traffic and weather advisory services, and a potentially wide range of information retrieval services.

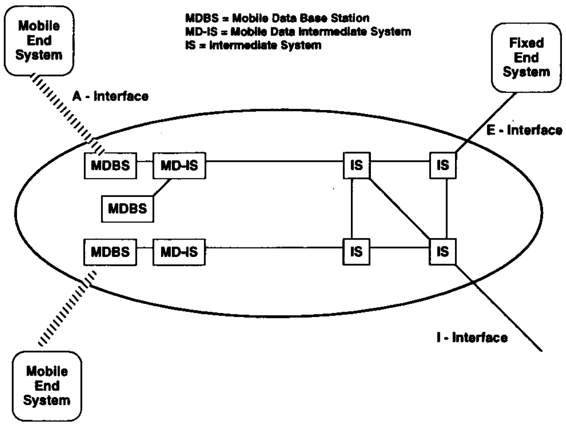


Fig. 5. CDPD data service network.

Although CDPD cannot increase the number of channels usable in a cell, it can provide an overall increase in user capacity if data users use CDPD instead of voice channels. This capacity increase would result from the inherently greater efficiency of a conectionless packet data service relative to a connection-oriented service, given bursty data traffic. That is, a packet data service does not require the overhead associated with setup of a voice traffic channel in order to send one or a few data packets. In the following paragraphs we briefly describe the CDPD network architecture and the principles of operation of the system. Our discussion follows [34] closely.

The basic structure of a CDPD network (Fig. 5) is similar to that of the cellular network with which it shares transmission channels. Each mobile end system (M-ES) communicates with a mobile database station (MDBS) using the protocols defined by the air-interface specification, to be described below. The MDBS's are expected to be collocated with the cell equipment providing cellular telephone service, to facilitate the channel-sharing procedures. All the MDBS's in a service area will be linked to a mobile data intermediate system (MD-IS) by microwave or wireline links. The MD-IS provides a function analogous to that of the Mobile Switching Center (MSC) in a cellular telephone system. The MD-IS may be linked to other MD-IS's and to various services provided by end-systems outside the CDPD network. The MD-IS also provides a connection to a network management system, and supports protocols for network management access to the MDBSs and M-ESs in the network.

Service endpoints can be local to the MD-IS or remote, connected through external networks. An MD-IS can be connected to any external network supporting standard routing and data exchange protocols. An MD-IS can also provide connections to standard modems in the PSTN by way of appropriate modem interworking functions.

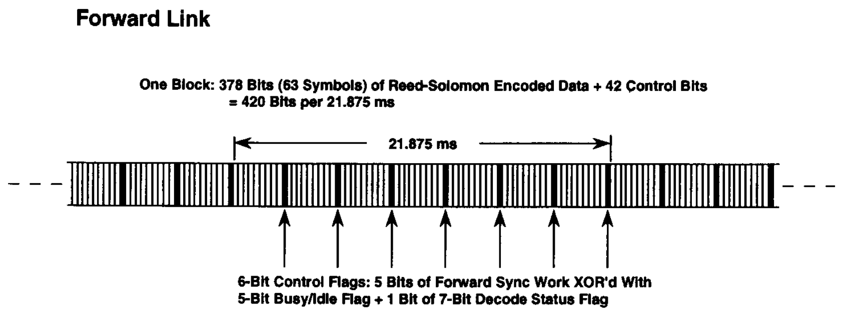


Fig. 6. CDPD data service: Forward-channel block structure.

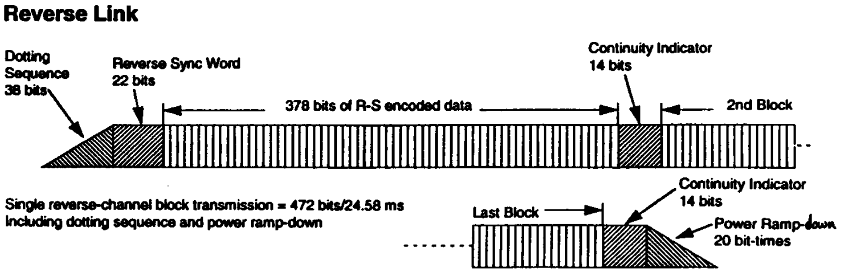


Fig. 7. CDPD data service: Reverse channel block structure.

Connections between MD-IS's allow routing of data to and from M-ES's that are roaming, that is, operating in areas outside their home service areas. These connections also allow MD-IS's to exchange information required for mobile terminal authentication, service authorization, and billing.

CDPD employs the same 30-kHz channelization as is used in existing analog cellular systems throughout North America. Each 30-kHz CDPD channel will support channel transmission rates up to 19.2 kbits/s. However, degraded radio channel conditions will limit the actual information payload throughput rate to lower levels and will introduce additional time delay due to the error-detection and retransmission protocols.

The CDPD radio link physical layer uses GMSK modulation at the standard cellular carrier frequencies, on both forward (base-to-mobile) and reverse (mobile-to-base) links. The Gaussian pulse-shaping filter is specified to have bandwidth–time product $B_bT = 0.5$. The specified B_T product assures a transmitted waveform with bandwidth narrow enough to meet adjacent-channel interference requirements, while keeping the intersymbol interference small enough to allow simple demodulation techniques. The choice of 19.2 kbits/s as the channel bit rate yields an average power spectrum that satisfies the emission requirements for analog cellular systems and for dual-mode digital cellular systems. It should be noted that CDPD will be able to coexist with the IS-54 TDMA digital cellular system, but not with the IS-95 CDMA system operating on the same channels.

The forward channel carries data packets transmitted by the MDBS, while the reverse channel carries packets transmitted by the M-ES's. In the forward channel, the MDBS forms data frames by adding standard HDLC terminating flags and inserted zero bits, and then segments each frame into blocks of 274 bits. These 274 bits, together with an 8-bit *color code* for MDBS and MD-IS identification, are encoded into a 378-bit coded block using a (63, 47) Reed–Solomon code over a 64-ary alphabet (6-bit symbols). A 6-bit synchronization and flag word is inserted after every 9 code symbols. The flag words are used for reverse link access control. The forward-channel block structure is shown in Fig. 6.

In the reverse channel, when an M-ES has data frames to send, it formats the data with flags and inserted zeros in the same manner as in the forward link. That is, the reverse link frames are segmented and encoded into 378-bit blocks using the same Reed–Solomon code as in the forward channel. The M-ES may form up to 64 encoded blocks for transmission in a single reverse channel transmission burst. During the transmission, a 7-bit transmit continuity indicator is interleaved into each coded block, and is set to all ones to indicate that more blocks follow, or all zeros to indicate that this is the last block of the burst. The reverse channel block structure is shown in Fig. 7.

The media access control (MAC) layer in the forward channel is relatively simple. The receiving M-ES removes the inserted zeros and HDLC flags and reassembles data frames that were segmented into multiple blocks. Frames are discarded if any of their constituent blocks are received with uncorrectable errors.

On the reverse channel, access control is more complex, since several M-ES's must share the channel. CDPD uses a multiple-access technique called digital sense multiple access (DSMA), which is closely related to Carrier Sense Multiple Access with Collision Detection (CSMA/CD) (see Section IV).

The network layer and higher layers of the CDPD protocol stack are based on standard ISO and Internet protocols. It is expected that the earliest CDPD products will use the Internet protocols.

The selection of a channel for CDPD service is accomplished by the radio resource management entity in the MDBS. Through the network management system, the MDBS is informed of the channels in its cell or sector that are available as potential CDPD channel when they are not being used for analog cellular service. There are two ways in which the MDBS can determine whether the channels are in use. If a communication link is provided between the analog system and the CDPD system, the analog system can inform he CDPD system directly about channel usage. If such a link is not available, the CDPD system can use a forward power monitor ("sniffer" antenna) to detect channel usage on the analog system. Circuitry to implement this function can be built into the cell sector interface.

4) Digital Cellular Data Service: In response to the rapid growth in demand for cellular telephone service throughout the U.S. and Canada, the Cellular Telecommunications Industry Association (CTIA) and The Telecommunications Industry Association (TIA) have been developing standards for new digital cellular systems to replace the existing North American analog cellular system (called the Advanced Mobile Phone System, or AMPS). Two air-interface standards have now been published. The IS-54 standard specifies a 3-slot TDMA system, and the I-95 standard specifies a CDMA spread-spectrum system. A variety of data services are being planned for both systems.

The general approach taken in the definition of IS-95 data services has been to take the previously specified physical layer of the IS-95 protocol stack as the physical layer of the data services, with an appropriate link-layer Radio Link Protocol (RLP) to be overlaid [35]. The current standardization effort is directed to defining three primary services: 1) asynchronous data, 2) Group-3 facsimile, and 3) Short-Message service. Later, attention will be given to other services, including packet data,synchronous data, and other primary services .

IS-95 Asynchronous data will be structured as a circuit-switched service. For circuit-switched connections, a dedicated path is established between the data devices for the duration of the call. It is used for connectivity through the PSTN requiring point-to-point communications to the common PC or Fax user. There are several applications which fall into this category. For file transfer involving PC-to-PC communications the Asynchronous Data Service is the desired cellular service mode. The service will employ a radio link protocol (RLP) to protect data from transmission errors caused by radio channel degradations at the air interface. The RLP employs Automatic Repeat Request (ARQ), Forward Error Correction (FEC), and flow control. Flow control and retransmission of data blocks with errors are used to provide an improved error performance in the mobile segment of the data connection at the expense of variations in throughput and delay. Typical raw channel rates for digital cellular transmission are measured at approximately a 10^{-2} bit-error rate. However, acceptable data transmission usually requires a bit-error rate of approximately 10^{-6} and achieving this will require the design of efficient ARQ and error-correction codes to deal with error characteristics in the mobile environment.

In parallel with the CDMA data services effort, anther TIA task group has been defining standards for digital data services for the TDMA digital cellular standard IS-54 [36], [37]. As with the IS-95 data services effort, initial priority is being given to standardizing circuit-mode asynchronous data and Group-3 facsimile services. As of this writing, a standard for asynchronous data service is being drafted and will be ready for balloting in mid-1994 [38].

5) TETRA: As is the case in the U.S. and Canada, there is interest in Europe in establishing fixed wide-area standards for mobile data communications. While the Pan-European standard for digital cellular, termed Global Systems for Mobile (GSM), will provide an array of data services, data will be handled as a circuit-switched service, consistent with the primary purpose of GSM as a voice service system [39]. Therefore, the European Telecommunications Standards Institute (ETSI) has begun developing a public standard for trunked radio and mobile data systems. The standards, which are known generically as Trans-European Trunked Radio (TETRA), are the responsibility of the ETSI RES 6 Sub Technical Committee [40].

TETRA is being developed as a family of standards. One branch of the family is a set of radio and network interface standards for trunked voice (and data) services. The other branch is an air-interface standard optimized for wide-area packet data services for both fixed and mobile subscribers, and supporting standard network access protocols. Both versions of the standard will use a common physical layer, based on $\pi/4$-Shift Differential Quaternary Phase-Shift Keying ($\pi/4$-DQPSK) modulation operating at a channel rate of 36 kbits/s in each 25-kHz channel.

Figure 8 is a simplified model of the TETRA network, showing the three interfaces at which services will be defined. The U_m interface is the radio link between the Base Station (BS) and the Mobile Station (MS). At the other side of the network is the Fixed Network Access Point (FNAP) through which mobile users gain access to fixed users. Fixed host computers and fixed data networks typically use standardized interfaces and protocols, and it is intended that the mobile segments of the TETRA network will utilize these same standards. Finally, there is the interface to the mobile data user, the Mobile Network Access Point (MNAP). This is shown in the figure as a physical interface between a Mobile Terminating Unit (MTU) and a data terminal. However, the MNAP may

Table 2 Chief Characteristics and Parameters of Five Mobile Data Services

System:	ARDIS	Mobitex	CDPD	IS-95[b]	TETRA[b]
Frequency Band Base to Mobile (MHz): Mobile to Base (MHz):	(800 Band, 45 kHz sep.)	935-940[a] 896-901	869-894 824-849	869-894 824-849	(400 and 900 Bands)
RF Channel Spacing:	25 kHz (U. S.)	12.5 kHz	30 kHz	1.25 MHz	25kHz
Channel Access/ Multiuser Access:	FDMA/ DSMA	FDMA/ Dynamic-S-ALOHA	FDMA/ DSMA	FDMA/ CDMA-SS	FDMA/ DSMA & SAPR
Modulation Method:	FSK, 4-FSK	GMSK	GMSK	4-PSK/DSSS	$\pi/4$-QDPSK
Channel Bit Rate (kbits/s):	19.2	8.0	19.2	9.6	36
Packet Length:	Up to 256 Bytes (HDLC)	Up to 512 Bytes	24 to 928 Bits	(Packet Service-TBD)	192 Bits (Short) 384 Bits (Long)
Open Architecture:	No	Yes	Yes	Yes	Yes
Private or Public Carrier:	Private	Private	Public	Public	Public
Service Coverage:	Major Metro. Areas in U. S.	Major Metro. Areas in U. S.	All AMPS Areas	All CDMA Cellular Areas	European Trunked Radio
Type of Coverage:	In-Building & Mobile	In-Building & Mobile	Mobile	Mobile	Mobile

Notes:

a) Frequency allocations in the U. S. (In the U. K., 380-450 MHz band is used.)
b) IS-95 and TETRA data services standardization in progress.
DSMA = Data-Sense Multiple Access
DSSS = Direct Sequency Spread Spectrum
S-ALOHA = Slotted ALOHA
SAPR = Slotted-ALOHA Packet Reservation

be only a logical interface and not a physical interface, if the MS is an integrated device with no external data port. It is envisioned that all three interfaces, FNAP, MNAP, and the air-interface U_m, will support data services with packet-mode protocols.

It is planned that TETRA will provide both connection-oriented and connectionless data services [40]. While work is still in progress on defining protocols for the three interfaces in the TETRA network model, some broad decisions have been made. It has been decided that the physical data port at the mobile station will be a true X.25 interface, which means that any attached data terminal must implement the X.25 protocol. This will provide true peer-to-peer communication between the mobile and fixed ends of the call connection. For connectionless data services, the protocol definition is still incomplete, but it is envisioned that the protocols will be based on ISO standards for connectionless-mode network service [41].

The protocol for the radio link has not yet been defined, but it will certainly employ a combination of forward-error correction (FEC) coding, Cyclic Redundancy Check (CRC) error-detection coding, and an ARQ scheme. It has been reported that the TETRA standard is being designed to accommodate two popular forms of multi-user access, Slotted ALOHA (with and without packet reservation), and Data-Sense Multiple Access.

Table 2 compares the chief characteristics and parameters of the five wireless data services described above.

B. Wireless LAN's

The existing technologies for wireless LAN's are licensed cellular systems operating at 18-19 GHz [42], unlicensed spread-spectrum systems operating in ISM bands [20], and diffused and directed-beam infrared (IR) systems [43]. Table 3 summarize the features of the systems currently available in the market. Diffused IR LAN's provide moderate data rates and coverage, and are suitable for moderate-size offices, short-distance battery-oriented applications (portable to printer), and environments with significant amounts of radio interference. Directed-beam IR offers higher data rates with reasonable coverage for applications employing fixed terminals. Directed-beam IR is suitable for large-file transfers between main frames and servers as well as large open offices with many fixed terminals. WLAN's at tens of gigahertz are suitable for high-speed communications in large partitioned areas such as larger offices or similar open areas such as some libraries. The spread-spectrum systems provide the largest coverage and are suitable for applications where penetration through building floors is desired. Spread-spectrum technology is suitable for small-business applications where a few terminals are distributed over several floors of a building. An important factor in selection is the ease of installation and flexibility of the software to accommodate various protocols for interconnecting with backbone-wired LAN's. The evolving next generation of WLAN's is designed to be incorporated into lap-top, notebook, and pen-pad computers, where significant reductions in size and power

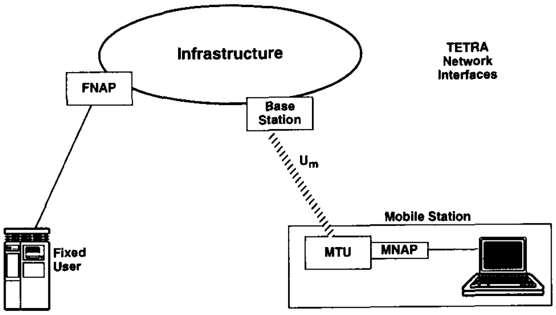


Fig. 8. TETRA network interfaces.

Table 3 A Comparison of Available Wireless LAN's

Technique:	DF/IR	DB/IR	RF	RF/SS
Data Rate:	1 Mbit/s	10 Mbits/s	15 Mbits/s	2-6 Mbits/s
Mobility:	Good	None	Better	Best
Detectability:	Negligible	Negligible	Some	Little
Range:	70-200 ft	80 ft	40-130 ft	100-800 ft
Frequency/Wavelength:	λ = 800-900 nm	λ = 800-900 nm	f = 18 GHz	f = 0.9, 2.4, 5.7 GHz
Radiated Power:	–	–	25 mW	< 1 W

consumption are needed. It will be ideal if these devices also provide low-speed wireless access with wide area coverage.

IV. TECHNICAL ISSUES

This section provides a discussion of the major technical issues arising in the design of wireless data networks. This discussion starts with radio propagation measurement and modeling for indoor and outdoor areas. Decription of the modem design technologies used in wireless data communications will follow the radio propagation discussion. The standard radio, spread-spectrum, and wireless optical modems are described here. The description of the technical issues will end with a discussion of the topologies and wireless access method employed in wireless data networks.

A. Radio Propagation

The dependence of a wireless network on efficient use of the transmission medium leads to a requirement for measurement and modeling of the channel characteristics. The results of measurements and modeling are used for assessing feasibility of a communication technique at a given operating frequency and determining the optimum location for installation of the base-station antennas.

Radio propagation in indoor and outdoor environments is very complicated. The signal arrives at the receiver through mechanisms of free-space transmision, transmission through objects, reflections, and diffractions. Therefore, the radio waves travel from transmitter to receiver via many paths with various received signal strengths. The transit time of the signal along any of the various paths is proportional to the length of the path which is in turn determined by the size and the architecture of the indoor or outdoor area and location of the objects around the transmitter and receiver. The strength of each such path depends upon the attenuation caused by passage, reflection, or diffraction of the signal from various objects along the path. Figure 9 shows a sample of the measured channel time response and the associated frequency response in a typical indoor radio environment. The time response shows the arrival of multiple paths. The frequency response shows the received power dropping, or *fading*, on the order of 30-40 dB at selected frequencies. If the location of the transmitter or the receiver is changed, or some object moves close to the transmitter or the receiver, the multipath condition and the frequencies selected for fading will change.

The most commonly used mathematical model for the impulse response of the channel in indoor and outdoor portable and mobile applications is the one originally suggested by Turin [44] for urban radio propagation. In this model the overall impulse response of the channel is given by

$$h(t,\tau) = \sum_{k=1}^{L} \beta_k \delta(t - \tau_k) e^{\theta_k} \tag{1}$$

where β_k, τ_k, and θ_k represent the magnitude, excess delay, and phase of the arriving paths, respectively.

1) Characteristic Parameters for Radio Propagation: Radio propagation is characterized by three parameters: the rms multipath delay spread, the gradient of the distance–power relation, and the Doppler spread.

The normalized averaged received power as a function of delay is referred to as the *delay-power spectrum* [45]. The square root of the second central moment of the delay-power spectrum function is the *rms multipath spread*, which is used as a measure of the multipath delay spread of a channel. Using the above mathematical model, the rms multipath spread is given by

$$\tau_{\text{rms}}^2 = \frac{\sum_{k=1}^{L} (\tau_k - \overline{\tau})^2 \beta_k^2}{\sum_{k=1}^{L} \beta_k^2}$$

where

$$\overline{\tau} = \frac{\sum_{k=1}^{L} \tau_k \beta_k^2}{\sum_{k=1}^{L} \beta_k^2}$$

with $\overline{\tau}$ the mean excess delay. Figure 10 shows the cumulative distribution function of the rms multipath delay spread of five areas in three manufacturing floors and three partitioned office areas [46]. In most indoor radio environments the rms multipath delay spread measured at maximum distances of 100 m is below 100 ns. The multipath spread in residential buildings is less than the offices and manufacturing floors. In most outdoor areas the rms multipath spread measured at distances up to a few kilometers is less than 10 μs. The multipath spreads in urban canyons and hilly terrains are more that in flat residential or farm areas. Measured statistics of the rms delay spread in various environments are available in the

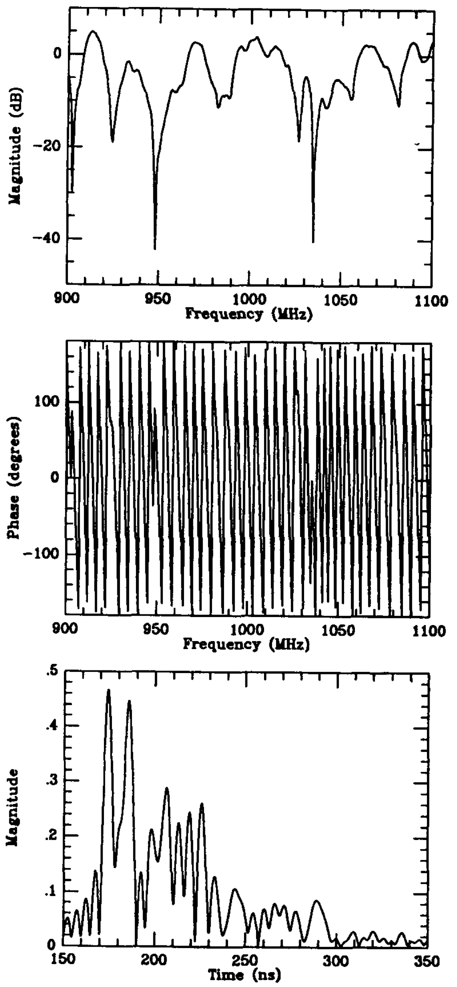


Fig. 9. A measured sample of the time and frequency response of an indoor radio channel.

literature. Most of the recent literature is concentrated on the indoor radio propagations [44] [47]–[60].

Multipath affects the expected average received signal power and causes the received power to fluctuate statistically as a terminal is moved from one location to another or as people move around close to the transmitter or the receiver. The average received signal power as a function of the path amplitudes is given by

$$P_r = \sum_{k=1}^{L} |\beta_k|^2$$

and it is proportional to the inverse of the distance between transmitter and receiver, raised to a certain power. This power factor is referred to as the *distance-power gradient.* The distance-power gradient multiplied by ten gives the power loss in decibells per decade of increase in the distance. In free-space radio propagation, the distance-power gradient is 2, which means the received power decays with inverse of the square of the distance between transmitter and receiver, or the power decays at the rate of 20 dB per decade of distance. For indoor and urban radio channels the distance-power relationship will change with the building and street layouts as well as construction material, and density and height of the buildings in the area. Generally, variations in the value of the distance-power gradient in different outdoor areas is less than variations in the indoor areas. Examination of the results of indoor radio propagation studies shows values smaller than 2 for corridors or large open indoor areas and values as high as 6 for metal buildings. In residential areas, offices, and manufacturing floors gradients of 2–3 are usually recommended for general simulations. The distance-power gradient of 4 is often used in urban radio communications. The distance-power gradient varies in differnt environments and depends on the architecture of the areas and the materials used in constructing the building.

Table 4 [59] shows the distance-power gradient and other parameters for eight different indoor areas discussed earlier. The first five represent five manufacturing areas and the last three represent three partitions in an indoor area. Partitioning is a common practice for modeling the path loss. The area is divided into sections according to ranges of distances between the transmitter and the receiver and each section is identified with a separate gradient. Partitioning is very popular in path loss modeling of the microcellular areas. In addition to the distance-power gradient, three other factors are included in the prediction of the received average power. The initial power loss at 1 m from the transmitter includes the physical characteristics of the antenna, the extra path loss to include the number of floors or in-building penetration loss, and a log-normal distributed random factor that reflects the effects of shadowing. A power loss of 30–40 dB at 1-m distance, power loss of 10-20 dB per floor or for in-biulding penetration, and a log-normal random variable with variance around 10 dB are usually considered in path-loss calculations for different areas.

The path loss models represent the average received power over a small area as a functon of the distance between the transmtter and the receiver. As we saw in the last paragraph, in addition to a deterministic relation between the path loss and the distance we usually add a log-normal distributed component that represents the fluctuations of the average received power. The fluctuation of the average received power is caused by shadowing and for this reason it is referred to as *shadow fading.* In addition to shadow fading the amplitude of the signal has a fast changing component that is caused by the phase differences in the arriving paths. This fluctuation is usually called *multipath fading.* In most statistical models for the amplitude fluctuations of different paths two seprate models are developed for line-of-sight (LOS) and Obstructed LOS (OLOS) communications. In LOS communications the path amplitudes variations are modeled with Rician or log-normal distributions and in OLOS communications with a Rayleigh distribution. Results of measurements in different buildings at different frequencies are available in [53]–[56], and [60]–[68].

Table 4 Examples of Distance–Power Gradients and Related Propagation Parameters Measured in Residential Spaces, Office Areas, and Manufacturing Floors

Measurement Area	Number of Measurement Locations	Distance-Power Gradient α	Max RMS Delay Spread in nsec	Median RMS Delay Spread in nsec	Mean RMS Delay Spread in nsec	Range of Power Fluctuations in dB
A	54	2.348	40	15.29	16.64	30.34
B	48	3.329	60	31.62	29.03	39.85
C	75	2.185	152	48.90	52.38	35.50
D	45	2.196	150	52.57	73.13	28.02
E	66	1.398	146	19.37	33.13	24.97
F	54	1.76	48	12.40	15.75	18.0
G	96	2.05	55	44.19	39.53	24.50
H	88	4.21	146	50.3	55.19	28.53

Whenever a transmitter and a receiver are in relative motion with velocity v_m, the received carrier frequency f_c differs from the transmitted carrier frequency. This shifting of frequency is referred to as the *Doppler shift* and is given by the following equation:

$$f_d = \frac{v_m}{C} f_c$$

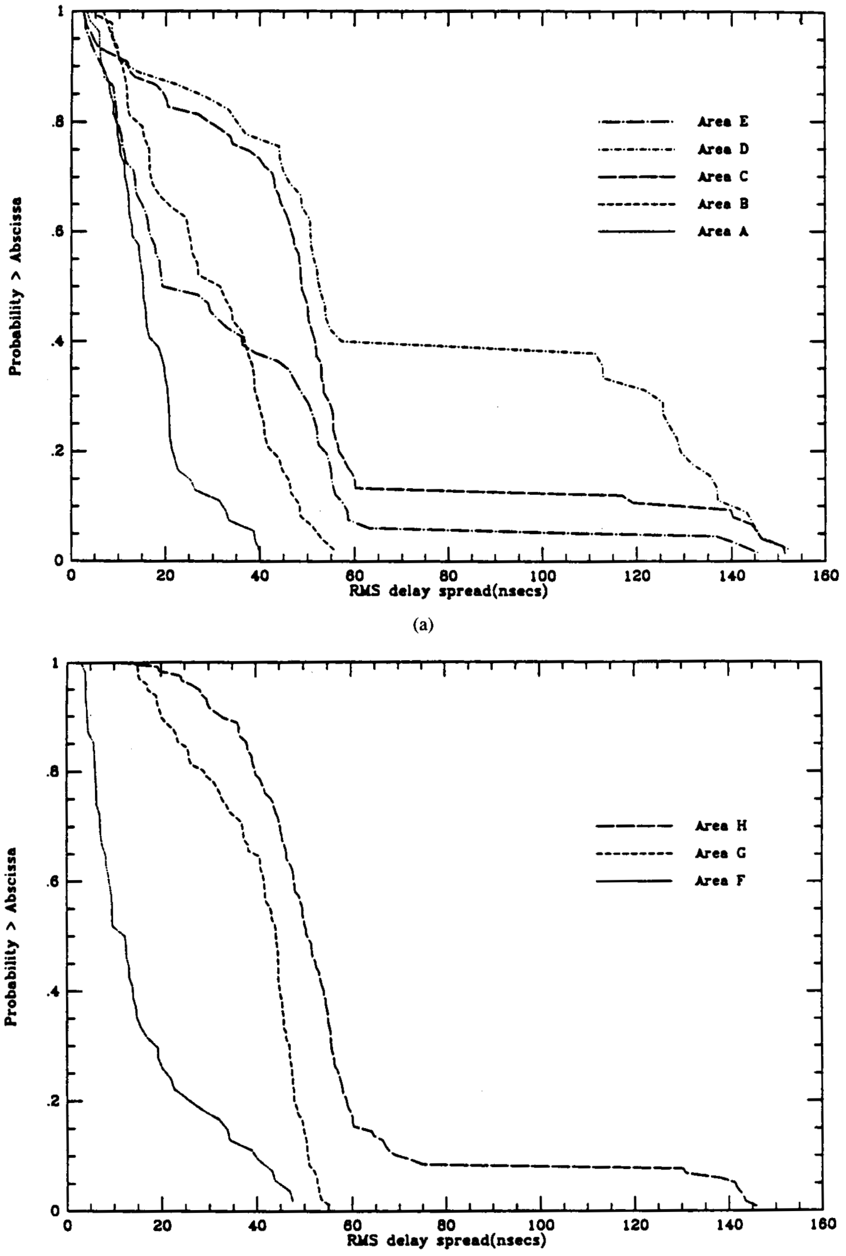
where C is the velocity of radio wave propagation. The Doppler frequency shift can be either positive or negative in accordance with whether the transmitter is moving toward or away from the receiver. If this equation is applied to a typical indoor environment, a person walking at 3 mi/h (1.33 m/s) will cause a maximum Doppler shift of ± 4 Hz for a carrier frequency of 910 MHz. In a mobile radio environment with a car moving at a speed of 60 mi/h the Doppler shift will increase to 120 Hz.

In a realistic environment, the received signal arrives along several reflected paths with different path distances, and the velocity of movement in the direction of each arriving path is in general different from that of another path. Thus a transmitted sinusoid, instead of being subjected to a simple Doppler shift, is received as a spectrum, which is referred to as the *Doppler spectrum.* This effect, which can be viewed as a spreading of the transmitted signal frequency, is referred to in a general way as the *Doppler spread* of the channel. Doppler spread also occurs with a fixed transmitter and receiver when a person or an object moves within the propagation path, producing time-variant multipath characteristics. In radio communication applications, as the terminals move about or objects move around the terminals, the received signal level fluctuates. The width of the Doppler spread in the frequency domain is closely related to the rate of fluctuations in the observed signal. The adaptation time of algorithms used in receivers (e.g., for automatic gain control or adaptive equalization) must be faster than the Doppler spread of the channel in order to accommodate the fluctuations in the received signal. For narrow-band measurements of the Doppler spread see [57], [64], [69], and for short time variations for wideband indoor radio propagation see [70], [71].

2) Computer Simulation of the Channel: The performance analysis for wideband data communication systems requires a statistical model and a computer simulation to regenerate the profiles of the channel at different locations in a building. The computer simulation of the radio propagation is done either by the use of statistical models developed from measurements of radio propagation or by an approximate solution to the Maxwell's equations, using the layout of the building as the boundaries for the solution.

In wideband measurements, the channel is represented by either the time-domain or frequency-domain response. In either case, the measured channel consists of samples of the channel response, which are typically on the order of several hundreds of points. To provide reasonable coverage of an area, measurements should be taken in hundreds or thousands of locations. To observe the effects of local movements we need several measurements in the near vicinity of each location. As a result, the database created by measurements in a single building will require thousands of files occupying several megabytes of disk space on the computer. A simple way of describing the statistical modeling approach is to say that these models compress all the observed data into a few statistical parameters which can then be used in a software program to regenerate a similar set of profiles on the computer. The statistics of the model are determined so that certain parameters such as power or the rms multipath delay spread of the profiles fit those of the large measurement database.

Time-domain statistical models for wideband radio propagations are the most popular methods for computer simulation of indoor and outdoor radio propagation for personal and mobile users. Standards bodies usually recommend a generalized and simple time-domain wideband statistical model for simulation of the radio propagation. The mathematical model used to describe the time-domain characteristics of the channel relates the impulse response, $h(t,\tau)$, to the delay, τ_k, amplitude, β_k, and phase, θ_k, of the signal arriving from different paths represented by (1). This mathematical formulation was first suggested for statistical modeling of the urban radio channel by Turin [44] and later used for statistical modeling of the indoor radio channel [26], [46], [72]–[75]. The simple and generalized models recommended by GSM for mobile radio channel modeling and by NTIA for PCS channels are using the same



(a)

(b)

Fig. 10. Cumulative distribution function of the rms multipath delay spread measured in five areas of three manufacturing floors, and in three partitioned office areas. (Source: [46].)

mathematical formulation. To develop a statistical model for computer simulation using this formulation we need the statistics of the arrival delay, amplitude, and phase of the receive signals from different paths [44], [56], [72]–[74], [76], [77].

Another approach to reproducing the measured channel responses is to use the frequency response of the channel for statistical modeling. The frequency response of the channel shown in Fig. 9 (top) is assumed to be an autoregressive process. The poles of the process at different locations are calculated from the sample measurement of the channel impulse response in different locations, Fig. 11 represents the plots of the poles in four different sets of measurements. The statistics of the locations of the poles over a set of measurement represent the model. To reproduce the channel frequency response a set of poles are reproduced from the given statistics. The poles are used in a filter driven by complex Gaussian noise. The output of the filter is

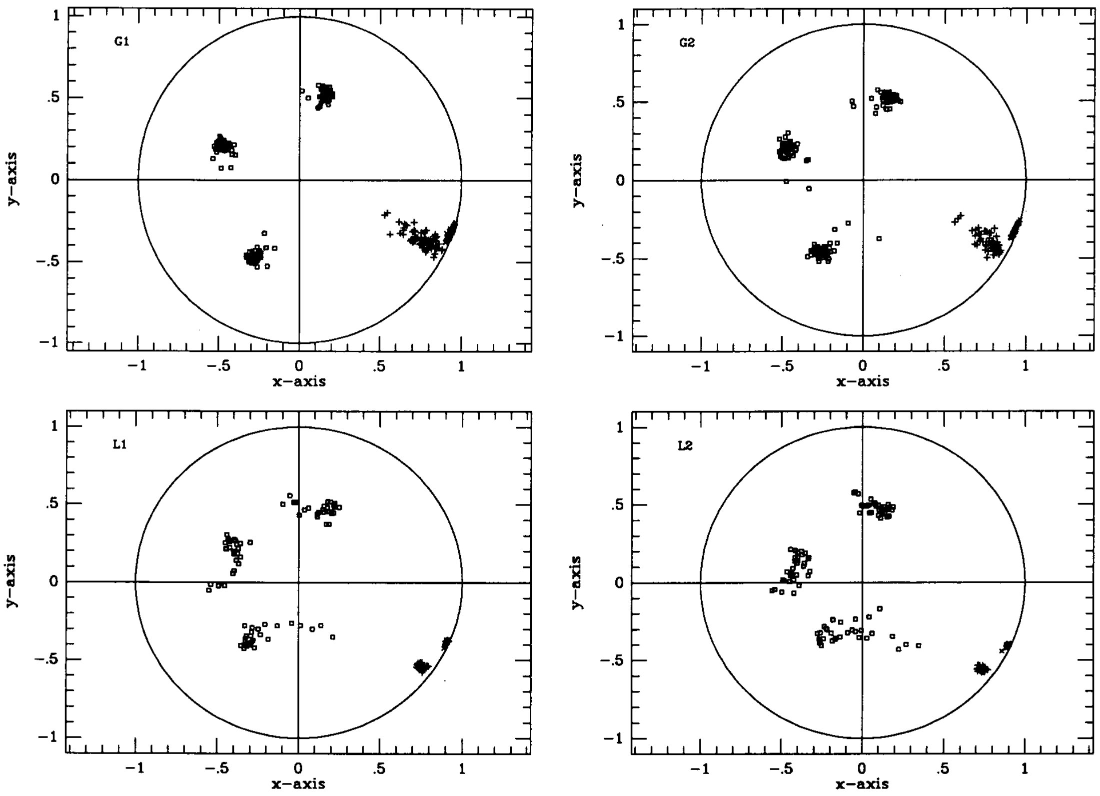


Fig. 11. Scatter plots of the location of the poles of the autoregressive model in four different measurement sites.

used as the frequency response and its inverse Fourier transform as the impulse response of the channel [57], [78], [80], [81]. The relationship between the arriving paths and location of the poles is more complex than in the time-domain approach. However, evaluation of the parameters for the autoregressive model is simpler and it requires fewer statistical parameters to represent the channel.

Statistical models cannot relate the radio propagation to exact location of the transmitter and the receiver; rather, they only provide a collection of possible channel profiles. Deterministic or building-specific radio propagation modeling relates the radio propagation to the physical layout of the building by solving the radio propagation equations. A relatively simple approximate solution to indoor radio propagation is obtained by the ray-tracing algorithm [82], [83]. In this method walls, ceilings, and floors are assumed to be dark mirrors. The paths between the transmitter and the receiver are determined through transmission, reflection, and diffraction mechanism. Figure 12 [84] shows a typical indoor radio channel, the pattern of the rays traced for a specific location of the transmitter and the receiver, and the simulated channel impulse response. Computational time with the ray-tracing algorithm grows exponentially with the complexity of the area. For applications in which directions of the arriving paths are important, such as analysis of modems using sectored antenna, ray-racing provides a more reasonable model for the channel. Several groups of investigators are developing ray tracing for radio propagation for indoor and outdoor applications as reported in [68], [84]–[92].

Using numerical analysis methods, direct solution of Maxwell's equations is possible. In particular. the Finite Difference Time-Domain (FDTD) method can be used to solve the equations. The advantage of the FDTD method is that it provides a complete solution for all points in the map at one time. This is very important when the coverage of the signal is considered. The FDTD method solves the equations over the area with a grid on the order of magnitude of the wavelength. As a result, memory requirements increase with the increase in the frequency of operation and the size of the area. Some results for indoor radio propagation using the FDTD method are available in [93].

B. Transmission Techniques

The application of modem technology to radio systems has evolved along a path similar to that followed in PSTN data transmission, but has lagged several years behind wireline developments. This has of course been due to the special characteristics of radio propagation, which create a much harsher environment for data transmission than we encounter in the telephone network. Location-dependent power variations, fading, and multipath act to limit the data rates and performance achievable over radio circuits. Consequently, the earliest of modem applications in radio systems used only the simplest of wireline modem techniques, though much more advanced techniques were already in use in the PSTN [94]. For example, while wireline modems incorporating adaptive equalization were coming into general use in the early 1970's, adaptive equalization was not successfully applied to radio systems until the late 1970's. Similarly, while the technique of *trellis coded modulation* (TCM) has been used in standard commercial modems for several years now, the application of TCM to mobile radio systems is just beginning. Thus the transfer of evolving wireline modem technology from the wired network to wireless systems is a continual process, with the radio applications employing certain design features and enhancements which are needed to deal with the special characteristics of that environment.

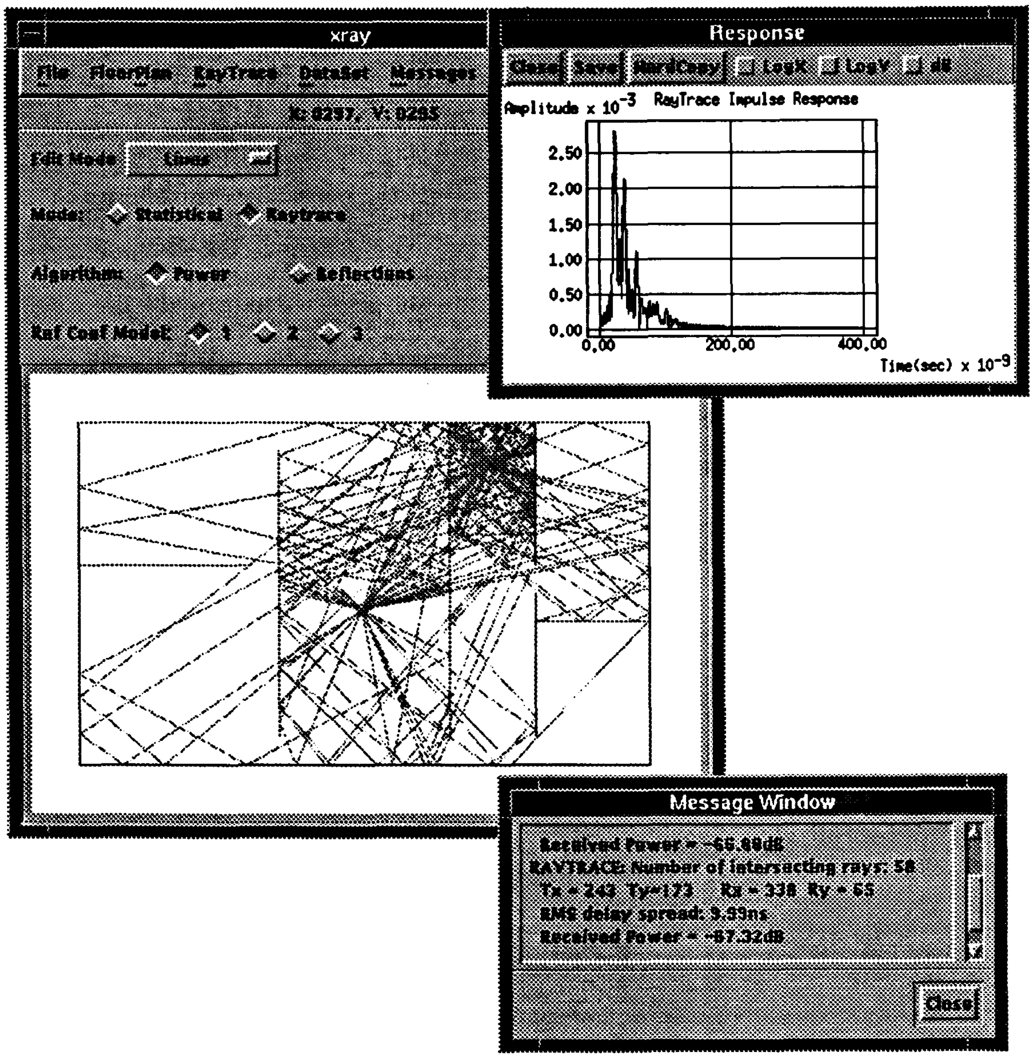
For wide-area data networks, including the digital cellular systems and mobile data networks, modem techniques have been adopted which are closely related to bandwidth-efficient wireline modem techniques. In the wireless LAN market, only the simplest of modem techniques are being employed thus far. However, as the market for portable data terminals, notebook computers, and portable facsimile devices grows, the demand for steadily higher data rates over WLAN's will also grow, and there will undoubtedly be a migration of the more sophisticated wireline modem technologies into WLAN products.

Wireless digital networks that support mobile users have a need for bandwidth-efficient modulation. They must serve large numbers of users over wide geographical areas using relatively limited frequency bands. The channel allocations in these systems have generally been carried over from the analog voice systems which preceded the digital systems, e.g., 30-kHz cellular telephone channels and 25-kHz land-mobile radio channels. As these systems have transitioned from analog to digital transmission, the growing market demand for services carried over these systems has created requirements for achieving the highest possible data rates relative to available bandwidth. This has led to the adoption of two bandwidth-efficient modulation schemes for the new digital systems and standards. In Europe, the ETSI selected Gaussian Minimum Shift Keying (GMSK) for the Pan-European digital cellular system, GSM [1], [95]. A few years later, in 1988, the Telecommunications Industry Association selected $\pi/4$-Shift QPSK for the North American Digital Cellular TDMA Standard IS-54 [96]. The Japanese Digital Cellular Standard also employs $\pi/4$-Shift QPSK modulation. The MOBITEX mobile data system and the planned CDPD cellular packet data system use GMSK, while the ARDIS system uses Frequency Shift Keying (FSK) modulation.

The GMSK modulation scheme is based on MSK, which can be described succinctly as continuous-phase FSK with modulation index m =0.5. MSK is commonly implemented as offset quadrature phase modulation with cosine pulse shaping on the quadrature branches [97]. MSK is itself a spectrally compact waveform, but it was observed by Murota and Hirade [98] that the spectrum could be made even more compact, and the spectral skirts further lowered, by implementing the modulation in its direct FM form with a low-pass filter applied to the data stream before modulation. The specific filter characteristic proposed in [98] is the Gaussian low-pass filter, which has frequency response of the form $H(f) = e^{-\alpha f^2}$, where α is a filter rolloff parameter. The choice of rolloff parameter for the Gaussian filter involves a tradeoff between spectral confinement and performance loss. GMSK can be demodulated by several different methods, which makes it attractive to implementers, who can have the freedom to manufacture devices with different levels of complexity and cost. Because GMSK can be treated as a form of digital frequedncy modulation, it can be demodulated with a simple limiter-discriminator detector [99], [100]. However, because of its close relationship to ordinary MSK, best performance is obtained by demodulating the received GMSK signal with a two-branch coherent demodulator very much the same as used with MSK [101]. In GMSK reception, extra care must be taken in the design of the demodulator to assure reliable carrier and timing recovery given the use of pre-modulation filtering. These issues are discussed in some detail in [98].

A search for a bandwidth-efficient modulation scheme amenable to nonlinear amplification in mobile radio systems led to the work of Akaiwa and Nagata [102] and others [103]–[105] on $\pi/4$-Shift Quartenary Phase Shift Keying (QPSK) modulation, a modulation method first introduced in 1962 [106]. Simply described, $\pi/4$-Shift QPSK is a form of QPSK modulation in which the QPSK signal constellation is shifted by 45° in each symbol interval. This means that the phase transitions from one symbol to the next are restricted to $\pm\pi/4$ and $\pm 3\pi/4$ radians. By eliminating the $\pm\pi$ transitions of ordinary QPSK, the $\pi/4$-Shift QPSK modulation provides the bandwidth efficiency of QPSK with a diminished level of amplitude fluctuations. The reduced amplitude variations allow the use of nonlinear power amplification at the transmitter without a drastic elevation of out-of-band spectral components. As with GMSK, $\pi/4$-Shift QPSK modulation has the advantage that it can be implemented with coherent, differentially coherent, or discriminator detection [96], [107], [108]. A detailed treatment of $\pi/4$-Shift QPSK is given in [109]. The multiple advantages for $\pi/4$-Shift QPSK led to its adoption for the North American Digital Cellular TDMA standard (IS-54) as well as the Japanese Digital Cellular standard [110]. In the case of the IS-54 standard, the modulation is specified in a differentially encoded form.

In the WLAN industry, developers are striving to achieve steadily higher data rates, due to users' expectations that have been set by advances in wired LAN's. The 1-Mbit/s first-generation wired LAN's are now being replaced by high-speed 10-Mbits/s Ethernet LAN's, and 100-Mbits/s FDDI products are beginning to enter the market. The IEEE-802 standards committee is considering the next generation of FDDI at 650 Mbits/s. If WLAN's are to



X: 0237, Y: 0285

Edit Mode: Lines

Mode: ○ Statistical ● Raytrace

Algorithm: ● Power ○ Reflections

Ref Coef Model: ● 1 ○ 2 ○ 3

```
Received Power = -66.88dB
RAYTRACE: Number of intersecting rays: 58
 Tx = 243 Ty=173   Rx = 338 Ry = 65
 RMS delay spread: 9.99ns
 Received Power = -87.32dB
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Fig. 12. Traced-ray pattern for a typical indoor radio channel, and the simulated channel impulse response.

establish a strong position in the LAN market, data rates will have to be pushed to near their ultimate limits.

The maximum symbol transmission rate for a communication system is bounded by the multipath delay spread of the channel. As the symbol transmission rate increases, the duration of a transmitted symbol becomes comparable to or even smaller than the delay spread. As a result, the pulses arriving along multiple paths associated with one symbol interval will interfere with the multiple pulses associated with the neighboring symbol intervals. This *intersymbol interference* is manifested as an *irreducible error rate* observed at high levels of signal-to-noise ratio. As the symbol transmission rate increases, the worsening intersymbol interference created by the multipath increases the irreducible error rate of the modem. Thus if one establishes a maximum tolerable value of the irreducible error rate, this in turn determines the maximum transmission rate attainable with a chosen modulation technique.

For a simple binary modulation technique, such as Binary Phase Shift Keying (BPSK) with omnidirectional antennas, the maximum achievable data rate can be estimated as around 10% of the inverse of the maximum rms multipath delay spread of the channel [111]. In most indoor areas having path lengths in the range of 50–100 m, the rms multipath spread is less than 100 ns, resulting in data rate limitations of around 1 Mbit/s. Results of extensive computer simulations based on prior multipath measurements confirms the validity of the aforementioned approximation [112].

The estimated data rate of 1 Mbit/s should be regarded as the low end of the range of data rates achievable with wireless LAN's. Data rates can be increased significantly by using diversity reception techniques and sectored antennas, as well as employing modulation and coding techniques yielding greater bandwidth efficiency, using multirate modems, implementing adaptive equalization techniques at the receiver, or using multitone modems.

Since the mid-1950's, many investigators have developed a variety of adaptive receivers as means of increasing the data rates on fading multipath channels. The most significant of these developments is the *RAKE correlator* or *RAKE matched filter* developed by Robert Price and Paul Green [113]. We will return to the RAKE system in the next section, where we discuss spread-spectrum techniques.

In the past two decades other adaptive techniques have emerged in the development of a new generation of radios for fading multipath channels. In one development of a family of modems for military troposcatter radio links, the approach included time-gating of the transmitted pulse to avoid intersymbol interference (ISI), and adaptive digital matched filtering on each received pulse [114]–[116]. The adaptive decision feedback equalizer is another approach taken for troposcatter [117], [118], microwave line-of-sight [119], [120], high frequency (HF) [121], and more recently indoor radio [112], [122], [123] applications. Finally, an adaptive version of the maximum-likelihood sequence estimation (MLSE) [124], [125] was considered for troposcatter in [126] and for HF in [121].

A common method for increasing the data rate on a fading channel is the use of antenna diversity [127]. Diversity is usually provided by using multiple transmitter and/or receiver antennas; diversity can also be provided by using sectored antennas [128], [129]. A sectored receiving antenna selects the received signal arriving from specific directions. Ideally, the strongest path at the receiver is selected and all the paths arriving from other directions are eliminated. Elimination of unwanted paths reduces the delay spread and consequently provides an opportunity for signaling at higher rates. An adaptive equalizer is an adaptive filter at the receiver whose frequency response adapts (approximately) to the inverse of the frequency response of the channel. Linear equalizers, commonly used in voiceband modems, are not effective on frequency-selective fading multipath channels and therefore the *decision feedback equalizer (DFE)* technique is typically used on these channels [130]–[132]. As we mentioned earlier, the multipath causes ISI which in turn causes degradation in modem performance. A DFE can isolate the arriving paths and take advantage of them as a source of in-band time diversity or *implicit diversity* to actually improve the performance of the modem [118]. Use of the DFE technique has been shown to increase the achievable data rate by an order of magnitude relative to operation without equalization [112], [122], [133]–[136]. Adaptive equalization techniques are being utilized in the new equipment being developed for use in the new digital cellular systems [137], [138].

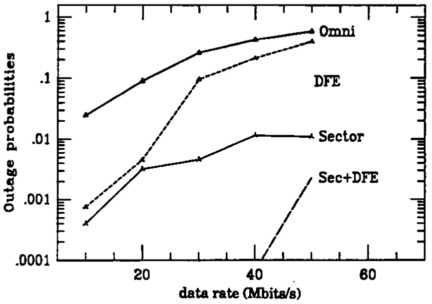

Fig. 13. Probability of outage versus data rate for BPSK and BPSK/DFE modems with omni-directional and sectored antennas in a 30-m by 30-m room.

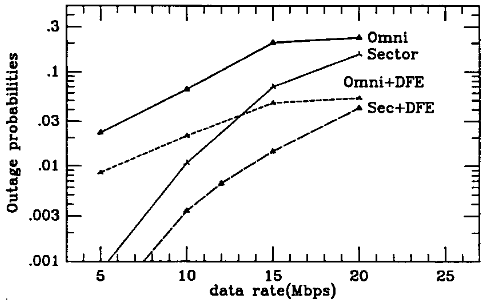

Fig. 14. Probability-of-outage results obtained from simulations performed for a multi-room indoor area previously shown in Fig. 12.

Now we turn our attention to the issue of achieving increased data rates. Figure 13 shows the probability of outage versus data rate in a 30-m by 30-m room for a BPSK modem with and without a DFE, and compares the results with those for the same modem operating with a sectored antenna [128], [139], [140]. The outage probability represents the percentage of locations in an area for which probability of error for the terminal is a chosen threshold. Radio propagation is modeled by using a two-dimensional ray-tracing algorithm. The results indicate that either a sectored antenna or a DFE can increase the data rate limitation of the LOS indoor radio channel by an order of magnitude if the probability of outage is kept at around 1%. In a single room, where an LOS path always exists between the transmitter and the receiver, the sectored antenna is more effective than the DFE. Figure 14 shows results similar to those of Figure 13, obtained from simulations in a multi-room indoor area previously shown in Fig. 12. In a multi-room indoor area, where in most locations LOS transmission is obstructed by walls or other objects, the DFE is more effective than the sectored antenna. For the DFE, similar results are obtained from performance analysis over measured indoor radio channels [134], [123]. Sectored antennas are incorporated into modems operating at 18–19 GHz, achieving an uncoded data rate of 15 Mbits/s with 4-ary FSK modulation [42], [139]. While adaptive linear equalizers are commonly used in voiceband data modems on wireline channels, and adaptive DFE's have been applied to a number of troposcatter and HF radio modems, adaptive equalization techniques have not yet been incorporated into wireless LAN products for high-speed local packet communication. A major issue here is the need to transmit a training sequence with each packet, enabling the adaptive equalizer to properly initialize itself to the current channel multipath structure. If the data packets are short, the training sequence can add a significant amount of transmission overhead, which reduces the useful data capacity of the system. This remains a challenging obstacle to the achievement of high packet data rates on wireless LAN's.

A *multi-rate modem* operates at the high data rate in most of the locations in the area where the multipath fading allows the high rates. In locations where the signal quality is degraded by multipath fading, the data rate is decreased to bring the BER to an acceptable level. The work in [141] suggests that an order of magnitude improvement in the data rate is achievable if an optimum dual-rate modem is used.

Another approach to achieving high-speed indoor communications is the use of *multicarrier modems*. In multicarrier systems the incoming data stream is divided into several channels each using a different carrier frequency. At the receiver, the errors appearing in the channels affected by frequency-selective fading are treated by error-correction coding applied to the complete data set. Data rates on the order of several megabits per second have been reported for multicarrier systems in indoor areas [142]

Further increases in data rate can be achieved by using more complex modulation and coding techniques to increase the number of bits transmitted per symbol. This concept has been used in some of the wireless LAN's operating in the ISM bands. Using Trellis-Coded Modulation (TCM), today's voice-band modems have achieved 8 bits per symbol to provide a data rate of 19.2 kbits/s with a channel signaling rate of 2.4 ksymbols/s [94]. This modulation efficiency is four times greater than is achieved with the $\pi/4$-QPSK or GMSK adopted for the major digital cellular standards. By reducing the distance between the transmitter and the receiver, the multipath delay spread in LOS channels is reduced significantly. For short LOS distances, with the combined use of anti-multipath techniques and multi-amplitude phase modulation and coding technique, data rates of the order of 100 Mbits/s are feasible. It should be noted that such rates approach those provided by SONET and FDDI.

C. Spread Spectrum

A more complex and effective method of counteracting radio multipath is the use of spread-spectrum transmission with a RAKE receiver. The RAKE receiver uses the correlation properties of a spread-spectrum signal to resolve the multipath signals and then combines them as inband diversity components. The effectiveness of the RAKE lies in the fact that the pseudonoise (PN) chip duration is smaller than the multipath spread, which allows resolution of the multipath signals, and a large reduction in effects of ISI. In the presence of multipath fading and additive white Gaussian noise (AWGN) the analysis of the RAKE receiver is similar to that of the time-gating system used with a Discrete Matched Filter receiver [114]. The RAKE system uses a much wider bandwidth but has the advantage of much greater resistance to interference [79], [115]. In the last several years, other versions of RAKE receivers have been examined for urban radio [143], HF radio [144], and indoor radio [145] channels.

Beginning in the mid-1970's, the CDMA spread-spectrum technique was proposed for cellular mobile radio as a replacement for the existing analog cellular system [146]–[148]. Spread spectrum was also considered for a wide-area packet radio data network designed for military application [149]. Spread spectrum has been used for packet radio to improve the performance in multipath, and to provide resistance to intentional interference.

Since the May 1985 FCC announcement of the ISM bands [15]–[17] for commercial application of spread-spectrum technology, various spread-spectrum commercial products, from low-speed fire safety devices to high-speed wireless LAN's, have come rapidly into the market. Today, both the voice-oriented and data-oriented wireless information network industries are involved in the application of spread-spectrum technology. However, as explained in the following paragraphs, their points of view toward spread spectrum are quite different.

The voice-oriented digital cellular and personal communication industries are considering CDMA spread spectrum [13], [18], [150]–[152] as an alternative to time-division multiple access (TDMA). Much attention in this industry has been directed toward the issues of system capacity and design complexity of the CDMA approach as compared with the TDMA approach [151], [153]-[156]. So-called *Broadband CDMA* is also being proposed as a means of sharing spectrum with other system on a noninterfering basis [157], [158]. Analysis of broadband direct-sequence CDMA over measured indoor radio channels is available in [145], [159], [160].

The mobile data industry is expecting new data services as a part of the evolving CDMA digital cellular and PCS networks. As we described in Section III, circuit-mode and packet-mode data services are being developed for incorporation into the evolving CDMA standards. However, the manufacturers of these mobile data devices must wait for the finalization of standards before they can commit to manufacturing and marketing. In contrast, to develop and market a wireless LAN, a manufacturer needs only a suitable frequency band for high-speed data communications, and the existence of a standard is not very important. Many WLAN's are using spread-spectrum technology simply because the first bands available for high-speed data communication were ISM bands, which are specifically designated for spread-spectrum technology. An important feature of spread-spectrum technology for the WLAN industry is the anti-multipath and anti-interference nature of the technique, which increases the coverage and reliability of the modem. However, the availability of the ISM bands is the main reason for development of the spread-spectrum wireless LAN products.

In the 902–928-MHz ISM band, 26 MHz of bandwidth is available with a minimum bandwidth expansion factor of

10. The designers of WLAN products for this band usually sacrifice bandwidth expansion to achieve higher data rates. In this way one can achieve a data rate of around 2 Mbits/s with a simple QPSK modem. The spread-spectrum devices operating in the 910-MHz ISM band can cover several floors of a building, a feature which is not matched by other technologies. The ISM bands at higher frequencies offer wider bandwidths and consequently higher data rates. Products operating in the 2.4- and 5.7-GHz ISM bands operate at data rates above 5 Mbits/s, which provides a unique feature for high-speed applications. However, at these frequencies signal coverage is more restricted.

Today, an important issue for the wireless LAN industry is to provide services for portable devices that must operate with low electronic power consumption in order to give the user satisfactory battery-powered service. In the ISM bands, slow frequency hopping is being considered for this purpose. Since the September 1993 release of the 1.8-GHz bands for data-PCS, many companies have been at work defining air-interface signal designs for consideration by the pertinent standards committees. While direct-sequence and frequency-hopped spread-spectrum transmission will continue to have application in WLAN's developed under IEEE 802.11 standards (for ISM bands), it is unlikely that spread spectrum will find wide support for WLAN applications in the new PCS bands. The use of spread spectrum in a multivendor non-power-controlled environment carries a significant penalty in usable data rate, due to the large processing gains that must be employed to deal with interference. Alternative approaches can be taken based on nonspread transmission, in which the errors caused by interference are dealt with by error-control procedures operating at higher network protocol layers.

D. Wireless Optical Networks

Infrared (IR) transmission technology is dominating the low-speed remote-control market [161], and has been used for wireless multichannel indoor audio systems [162], cordless phones [163], and short distance wireless connection between keyboards and terminals [164]. The operational bandwidth in all these applications is far below the bandwidth necessary for WLAN's. Since the late 1970's [165]–[167], significant research has been done on applications of optical wireless technology to high-speed indoor data communications and this is still an active area of investigation [168]–[176]. Several companies have introduced data communication products using IR technology and many other computer communication products are entering the market.

Several features of IR communications are well suited to application in wireless office networks. Transmitters and receivers for IR systems use light-emitting diodes (LED's) and photo-sensitive diodes. These diodes are inexpensive in comparison with RF equipment and are cost-compatible with wires regardless of the installation cost. IR transmissions do not interfere with existing RF systems and do not come under FCC regulations. The IR signal does not penetrate walls, thus providing a degree of communications privacy within the office area. The only way for IR signals to be detected outside the office is through the windows, which can be covered with curtains or shades. In addition to privacy, this feature of IR systems allows concurrent usage of similar systems in neighboring offices without mutual interference. Therefore, in a cellular architecture all units can be identical, as opposed to RF configurations in which the operating frequencies of neighboring cells have to be different. The major problems for IR in wireless networks are its limitation on coverage (specially at high data rates), extensive power fluctuation, and interference from ambient light. In particular, the effects of ambient light and of moving objects near a transmitter or receiver are ever-present problems, and a reliable multiple-access technique to counteract these problems is not readily available.

Broadly speaking, IR LAN's use either directed-beam or diffused radiation. In the past decade, most of the development efforts in wireless optical LAN's have been concentrated on diffused infrared (DFIR) radiation [165]–[167] [173], [174]. The advantage of this mode of radiation is that it does not require a direct line of sight between the transmitter and the receiver; since the receiver can collect a transmitted signal through reflections from the walls, ceiling, or other objects in the room. Therefore, the installation of the network does not require alignment to establish the communication link, and this provides portability for the terminal. The disadvantages relative to directed-beam radiation are: 1) DFIR requires higher power to cover a given area, 2) the data rates are limited by multipath, 3) there is a higher risk for eye exposure, and 4) in simultaneous two-way communications, each receiver collects its own transmitted reflections which are sometimes stronger than the transmitted signal from the other end of the connection. As a result, DFIR networks tend to be used primarily for applications demanding portability, such as cordless phones or communication with lap-top or pen-pad computers.

In recent years, the application of directed beam infrared (DBIR) communications to wireless information networking has been investigated [169], [171] and some products using this technology have appeared in the market. With this mode of radiation, the transmitted radiation pattern must be adjusted in the direction of the receiver. The advantages of this method relative to DFIR are: 1) it requires less optical power for reliable communication, 2) it does not suffer from extensive multipath, and 3) it can handle bidirectional communications better than diffused radiation. As a result, higher data rates and better area coverage can be achieved with this method. The disadvantages are the need for terminal alignments and the severe interruption caused by shadowing. Consequently, the DBIR method is typically used for applications in which the terminals are relatively fixed, such as desktop computers in an office. The LED's are usually positioned high on posts to avoid shadowing [169]. Personnel in the area are cautioned to avoid direct eye exposure in this kind of installation.

A third method of transmission for optical networks is Quasi-Diffused IR (QDIR) [175]. With this method the terminals communicate using an active or passive reflector. Each terminal communicates with the reflector using a directed beam. Passive reflectors are mirror-like devices with high scattering and reflecting properties. The active reflectors are the same as the satellites used in DFIR systems. The active reflector amplifies and rebroadcasts the received signal. Passive reflectors require more transmission power from the terminals but they avoid the installation and maintenance problems associated with the active reflectors. Similar to the DFIR networks, the QDIR networks are broadcast networks in which all terminals receive the transmitted message. The required radiated light from the terminals in a QDIR network is less than for DFIR and the flexibility and coverage are better than for DBIR. The QDIR architecture provides a compromise between the DFIR and DBIR options.

There are three limitations for IR communications, which are related to: 1) interference from ambient light sources, 2) multipath characteristics of the channel for diffused radiation, and 3) the transient characteristics of the IR devices. The rise time and fall time of the inexpensive LED's limit the data rate to around 1 Mbit/s. Explanation of the other two limitations requires a more detail discussion, which follows.

The infrared content of ambient light can interfere with IR radiation and, if extensive, can overload the receiver photodiode and drive it beyond its operating point. Three sources of ambient light are daylight, incandescent illumination, and fluorescent lamps, all of which potentially interfere with IR communications. Fluorescent light is the common method of lighting in office environments and poses the most serious problem for IR communications. Fluorescent light normally has a small amount of IR radiation and during turn-on time emits a 120-Hz interfering baseband signal rich in harmonics which may reach up to 50 kHz [165]. The effects of ambient light are reduced by modulating the transmitted IR signal. The modulation carrier frequency should be at least several hundred kilohertz to avoid being compressed by fluctuation of the ambient light. For high-speed baseband communication Miller coding is usually adopted. Since only a small portion of the power of a Miller-coded signal resides at low frequencies, the effects of low-frequency interference caused by ambient light is minimized. For diffused IR, the data rate limitation caused by the ambient light sources is secondary to the data rate limitations imposed by multipath characteristics of the channel.

Diffused IR transmission exhibits multipath similar to that found on a radio channel. The multipath causes a time dispersion of the transmitted symbols, and the resulting intersymbol interference restricts the maximum digital transmission rate. As in radio propagation, as room dimensions become larger, the multipath spread is increased, and the supportable bit rate is decreased. Results of computer simulations, using only the first reflections, suggest that the theoretical limitation for the baseband transmission rate with diffused IR is 260 Mbit · m/s [165]. Results of more elaborate simulations for reflections up to fifth order provides 60 Mbit · m/s as a realistic upper bound on achievable data rate [173], [174]. Therefore, for a room with a length of 10 m, one expects to be able to achieve a transmission rate of 6 Mbits/s, if multipath is the only limitation on data rate. During the past decade various modulation techniques have been examined for use on wireless optical LAN's. The most popular transmission methods for low-speed communications are pulse duration modulation and pulse position modulation, and for high-speed communications baseband pulse transmission.

Various modulation techniques have been considered for IR LAN's [13], [31], [174]. The most popular optical modulation is intensity modulation in which the voltage of a diode is changed according to the signal amplitude. The detector is a photodiode generating a voltage proportional to the light incident on the photodetector plate. The transmitted symbol is distorted due to the multipath and a DFE can be used to achieve data rates on the order of 100 Mbits/s [174].

E. Network Topologies and Access Methods

Thus far in Section IV, we have concentrated on the characteristics of individual point-to-point wireless links and the transmission technologies that are used for data communication over such links. In the remainder of the section we turn our attention from links to networks, and we examine both the topologies of wireless networks and the access methods which are used to enable a number of users to transmit data to one another across the network.

Just as the nodes in a wired computer network can be connected in a variety of ways, the terminals in a wireless network can be interconnected using a variety of topologies. The reader familiar with the configurations of wired communication networks, such a the public telephone network, long-haul computer networks, and wired LAN's will find a few similarities, but several important differences in wireless networks relative to wired networks. The differences are due to the fact that wireless communications is fundamentally a broadcast medium. One consequence of this characteristic is that, since terminals are not connected together by wired circuits, transmitted message can, in principle, be received by an arbitrary (and perhaps unknown) number of other users. At the same time, given the uncertainties of radio propagation, one cannot always be guaranteed a link from every transmitting terminal to every intended receiving terminal. Another consequence of the broadcast nature of wireless communications is that any user, in transmitting a message to any other user, is utilizing a limited resource (some portion of the system bandwidth, perhaps the entire system bandwidth) for the duration of the message. Thus means must be provided for the fair and efficient utilization of available bandwidth. Yet another consequence of the characteristics of wireless communications is that transmit signal power is an important parameter. Enough signal power must be used to achieve reliable communication from terminal to terminal, but care must also be taken to avoid excessive interference to other networks operating in the same

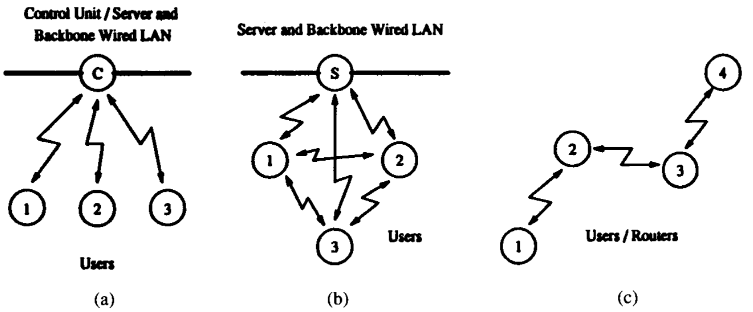

Fig. 15. Three common topologies in wireless networks: (a) centralized, (b) distributed, and (c) multihop.

frequency band. These various considerations have led to the use of different types of topologies for wireless networks. As is the case in any area of system design, there are advantages and disadvantages with each type of configuration, and these will be outlined and discussed. An ultimate goal in designing a wireless network is to enable users to communicate at rates comparable to the rates achievable in wired networks in the same category of application. This would imply rates close to high-performance data modems for mobile applications and rates close to wired-LAN rates in the case of WLAN's. These goals imply that efficient channel access methods must be provided, and different access methods are appropriate for use with different network topologies. The principal access methods and their performance characteristics are briefly described after we outline the common topologies for wireless networks.

1) Network Topologies: The basic topologies commonly used in local wireless networks are centralized, distributed, and multihop configurations, all three of which are shown in Fig. 15. The architecture of larger networks requires a cellular structure to provide frequency reuse and extend the coverage.

a) Centralized topology: In the centralized configuration in Fig. 15(a), one station (C) serves as the hub of the network and the user stations are located at the ends of the spokes. Any communication from one user station to another, that is, between peers, goes through the hub. The hub station controls the user stations and monitors what each user station is transmitting. Thus the hub station is involved in managing the access by user stations to the network's allocated bandwidth. There is no provision in the centralized topology for direct peer-to-peer communication. The centralized topology is a common one in the realm of telephone communications, where all the subscribers in a local exchange area are connected through the central office switch. The star topology for wired LAN's is another example of a centralized configuration. Cellular mobile telephone systems use a centralized network configuration to serve the mobile terminals currently operating within the coverage area of any one cell site. In the LAN industry, the Altair, ARLAN, and FreePort products use the centralized, or hub-based, network configuration. Optical WLAN's using IR radiation are typically cellular networks, in which each cell is served by a central base station, usually ceiling-mounted, providing coverage throughout the cell.

One important advantage of the centralized topology is that the network can be designed to operate with relatively efficient use of signal transmission power. For example, if contrasted with a fully connected peer-to-peer network, user stations in the centralized network can reach stations at twice the distance with the same signal power. A related advantage is that the hub station can be placed in a location that is optimized with respect to the set of user stations. For example, in a WLAN application, the central hub might be placed in an appropriate location to facilitate unobstructed propagation between user stations and the hub. For IR networks, the central unit is often installed on a ceiling, while for radio WLAN's operating at frequencies on the order of 10 GHz , it is usually recommended that the central unit be located high on a wall. In the centralized configuration, the central hub also provides a natural point at which connection is made to a backbone network, as indicated in Fig. 15(a). For this latter reason, many WLAN's have this centralized configuration. Another advantage of this topology is that the user terminals can be made functionally simple, while the more sophisticated control functionality is concentrated in the single hub station. The hub-based WLAN configuration also offers convenience in network setup, since each user node need only communicate with the hub.

Power control is an effective means of minimizing the radiated power of individual user terminals, which in turn conserves terminal power and controls interference. The issue of interference will be addressed more fully below. Where battery-operated portable units are to be used, power control serves an important function of maximizing battery life. If power control is to be employed in a radio network, a centralized configuration is necessary.

One disadvantage of the centralized topology is the existence of a single failure point. If the central control module fails, the entire network is disabled. Another disadvantage is the delay characteristic of the network. Since all user-to-user communication passes through the hub, the store-and-forward delay is twice that of a fully connected peer-to-peer network. Another measure of communication efficiency is channel occupancy measured in hertz-seconds (bandwidth × time). This parameter is gaining favor as measure channel occupancy in assessing the fair sharing of a common bandwidth among multiple users. By this measure, the occupancy for store-and-forward communication between users in the centralized network is twice that of direct user-to-user communication in the fully connected network.

Today, WLAN's are at the early stages of market penetration and one does not expect to see large numbers of wireless terminals in offices in the near future. For limited numbers of users per office, the single failure point, the delay and bandwidth–time usage characteristics are not as important as signal coverage and the ease of connection to the backbone network. As a result, the centralized topology is more popular than other topologies in today's market.

b) Distributed topology: In a distributed network as shown in Fig. 15(b), all terminals can communicate with one another directly. This topology is an ideal solution for the evolving *ad hoc* network applications where several portable terminals such as lap-tops intend to form a network in a quickly arranged setup. The peer-to-peer capability of this topology provides an instant connectivity without any need for a central controller. However, in the existing WLAN's, distributed (peer-to-peer) network configurations are not as widely used as are hub-based configurations, though at least one product, NCR's spread-spectrum WaveLAN, is a peer-to-peer network [177]. Many small very-high-frequency (VHF) and ultra-high-frequency (UHF) land-mobile radio networks, such as those used for fleet dispatch and public safety communications, are distributed networks. However, distributed configurations are generally not used in mobile data networks.

In a distributed topology, connection to a backbone network is provided by a server node that acts as a bridge or gateway. In Fig. 15(b) the server node (S) provides the connection between the terminals and the wired backbone. An important advantage of the fully connected topology is that it has no single point of failure. A advantage is that the peer-to-peer messages do not suffer the store-and-forward delay of the centralized topology, and thus time delay and channel occupancy, as measured in hertz-seconds, are both halved. Given that no routing functions need be implemented in any of the stations, the complexity of equipment in this design can be minimized. Another disadvantage of the fully connected peer-to-peer network is that we do not have a central unit to contol the power or timing. A related issue is the presence of a *near-far problem*, owing to the fact that transmitters needing to operate at high power level can interfere with unintended receivers in close proximity to the transmitting station. However, the fully connected topology offers an attractive alternative for small networks where reliable connectivity can be assured between all pairs of user stations.

c) Multihop topology: In a multihop topology, shown in Fig. 15(c), any user can reach another via transmissions traversing multiple links in the network. This topology provides the best user-to-user connectivity among the all topologies. A major advantage of the multihop topology is power efficiency, which derives from the fact that message transmission between widely separated users is accomplished with multiple shorter hops. In some applications, such as military tactical communication over a wide operational area, multihop networks provide the only practical approach to reliable connectivity among mobile users. A prominent example of a multihop network design for military application is the U.S. Army Mobile Subscriber Equipment (MSE) network [178], [179]. Multihop networks using repeater stations are also used in the land-mobile radio industry, where, for example, networks are required to serve municipal and state public safety organizations over wide geographical areas. As with a fully connected network, connection to a backbone or other networks is provided by equipping one or more nodes with the appropriate connection capability. One disadvantage of the multihop topology is the added complexity needed in user terminal to implement efficient message routing and control algorithms. A further disadvantage is the accumulated store-and-forward delay incurred by multiple hops connecting widely separated users. Associated with the store-and-forward capability is a considerable amount of transmission overhead carried with transmitted messages. While multihop topologies have found important applications in military radio and public safety communications networks, as well as other packet radio networks [180], they have not been adopted in the wireless LAN industry.

d) Cellular networks with frequency reuse: Another important network topology is that of cellular networks with frequency reuse. This is the network architecture employed in cellular mobile telephone networks. This network configuration is particularly well suited to serving large numbers of mobile users operating over large geographical areas. In a cellular system, a large service area is divided into smaller areas each of which is served by a fixed cell site. The cell sites are distributed in an approximately regular geometric pattern to cover the entire service area with the level of signal strength needed for acceptable service quality. Each cell in effect is a centralized network, with all communications to an from a mobile user in the cell area passing through and controlled by the cell site. Typically, all of the cell sites in the service are connected by landline (e.g., T1 lines) to a Mobile Telephone Switching Office (MTSO). The MTSO controls call establishment and manages the handoff of calls from cell to cell as mobile users move about the system. The MTSO also provides the connection to the public switched telephone network.

Cellular mobile networks are designed with frequency reuse, so as to maximize the overall capacity attainable with a given set of frequency channel allocations. Cellular telephone systems operate with 30-kHz channels in the 824–849- and 869–894-MHz bands. A typical cellular frequency reuse scheme is pictured in Fig. 16, where a frequency reuse factor of seven is assumed. That is, the cells are organized into seven-cell clusters, with the cells in a cluster designated as A through G. Seven sets of frequency channels are used in each cluster, one set in each cell. At a sufficient distance from any cell, the same set

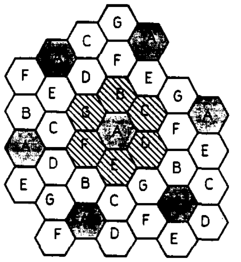

Fig. 16. Typical cellular frequency-reuse pattern. Seven-cell cluster, with letters representing channel groups.

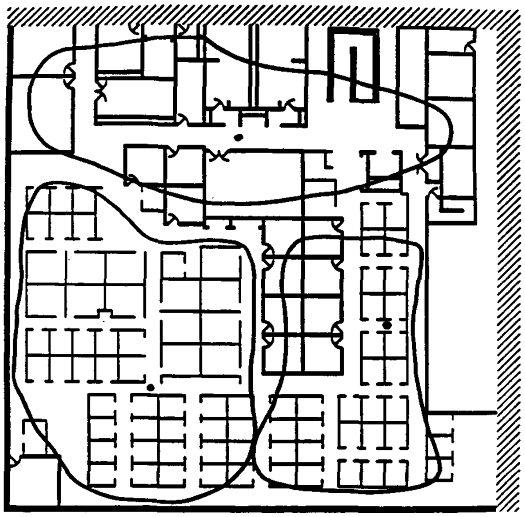

Fig. 17. Example of a WLAN microcell layout in an area of an office building.

of frequencies is used simultaneously. Using this design scheme, the overall system capacity can in principle be made as large as desired by steadily reducing the area of each cell, while controlling power levels to avoid *co-channel interference*, that is, interference to other users operating in another cell with the same set of frequency channels. System designs are now under development for use in cities, where very small cells called *microcells* will each cover an area the size of a city block and will serve users carrying low-power pocket-size phones.

Microcell configurations are also used in WLAN's [42], [128], [181]. Cellular arrangements of WLAN's are sometimes used in large office buildings or factories, and the relatively small area covered by each network justifies use of the name microcell. Figure 17 gives an example of a microcell layout in an area of an office building. There are several advantages in using small microcells. Signal coverage is better due to fewer obstructions, and higher data rates can be achieved due to reduced multipath dispersion. Typically, the boundaries between microcells will be set to provide carrier-to-interference (C/I) levels of 18–20 dB at the boundaries.

Cellular networks with frequency reuse and full mobility-management capability provide an excellent system design to support widespread mobile and portable communications services. However, they represent a level of complexity which is not needed in WLAN systems, where user terminals are relatively immobile and generally constrained to a well-defined area of use, such as a factory or office building. If a microcellular WLAN configuration is used to cover a large work area, a wired backbone will ordinarily be used to connect the microcells, as depicted in Fig. 18 [128]. Though wired interconnections are typically used, wireless bridges and routers are coming into increasing use. Furthermore, the propagation characteristics of WLAN links are such that co-channel interference between separated networks, e.g., networks installed in separate buildings or even separate floors of the same building, can be avoided. Thus cellular configurations with frequency reuse have found only minimal adoption in the WLAN industry. The backbone can be used to interconnect microcells implemented in different configurations. The figure shows the interconnection of a centralized microcell with a fully connected peer-to-peer microcell. In this case, the fully connected network must have one station implemented with a backbone connection. Where WLAN products from different manufacturers are to be interconnected, compatible software must be provided. Implementing combinations of WLAN products from different manufacturer raises the question of interference between systems. Some combinations of manufacturers' products will mutually interfere, while others will not. At this writing, the IEEE 802.11 Committee on Wireless LAN Standards is evaluating the issue of interference among WLAN products.

Cellular mobile packet radio networks are discussed in [182]. The topologies used in IR networks are discussed in [172], [183].

2) Multiple-Access Methods: Channel-access methods and methods for sharing a channel among multiple users are essential ingredients in achieving efficient operation and good performance in a wireless network. Users in a wireless network seldom have need to access a channel for a long period of time, and thus what are needed are schemes for providing *multiuser access*, usually referred to simply as *multiple access*, to the frequency-and-time resources of the network in an orderly manner and in a way that minimizes transmission overhead and maximizes overall network capacity. In this section we outline the principal channel access methods used in wireless information networks. Broadly speaking, the access methods fall into two categories—fixed-access or random-access schemes, where the schemes in either category are fundamentally the same as those commonly used in wired networks, with some variations that are important for operation in the wireless environment. Detailed descriptions of multiple-access protocols can be found in a number of references, including [184]-[186].

With the *ALOHA* protocol, users transmit whenever they have data to send. If a collision occurs and the user does not receive an acknowledgment (ACK) of a packet receipt, the packet is retransmitted. In *Slotted ALOHA*, users synchronize their transmission times to uniformly

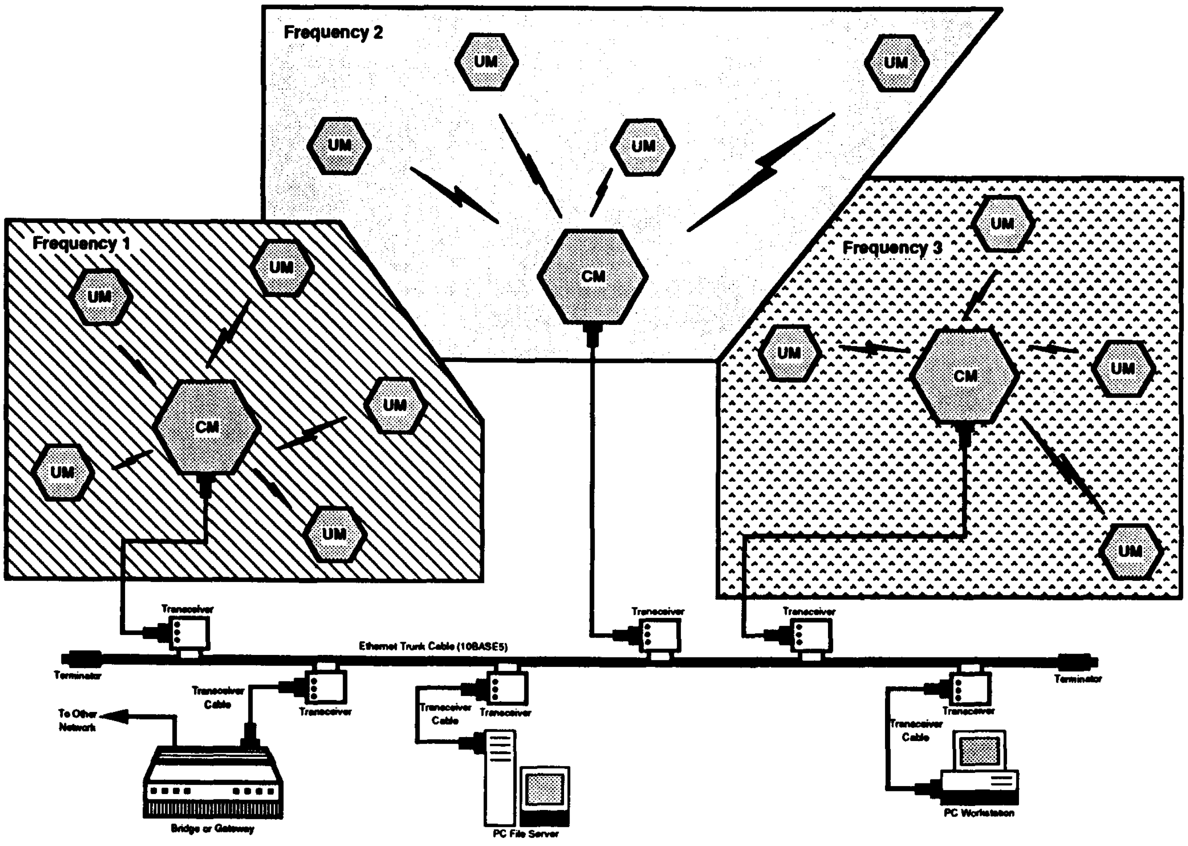

Fig. 18. Microcell WLAN configuration with microcells at different frequencies connected by a wired backbone.

spaced time slots, and this reduces the probability of packet *collision*, in turn increasing the achievable throughput. The *Carrier Sense Multiple Access* (CSMA) scheme improves upon ALOHA by having each user station with data to send first sense the channel and transmit only when the channel is free. A widely used refinement of CSMA is *CSMA* with Collision Detection *(CSMA/CD)*, sometimes referred to as the *listen while talk* protocol. With CSMA/CD, each station not only monitors the channel before transmission, but also monitors while transmitting. If a collision is detected, the transmission is aborted, a jamming signal is transmitted, and a retransmission procedure is initiated, just as in CSMA. The advantage of these contention-based access methods is that they operate with reasonable amounts of overhead while allowing the system to be expanded easily. The central problem in use of these schemes is reduction in throughput caused by packet collisions. In a nonfading wired network, the maximum throughput of the Slotted ALOHA protocol is only 36%, while the maximum throughput of CSMA is slightly more than 50%.

In radio channels, the difference in the level of received signal power in two packets involved in a collision is sometimes so large that one of the packets survives the collision, resulting in an increase in the throughput over the throughput in a wired network. This phenomenon is referred to as *capture*. Figure 19 [187] shows the throughput of ALOHA and CSMA in Rayleigh fading and nonfading channels for various packet lengths and BPSK modulation [188]. It should be noted that the differences among the signal power levels received from different terminals, if not controlled, causes a reduction of the bandwidth efficiency of the cellular TDMA, FDMA, and in particular CDMA systems [154].

Data traffic is being carried over today's analog cellular telephone network (AMPS) and over many land-mobile radio networks, using modems and facsimile devices designed for use in the mobile environment. These applications do not represent true data services, since the modems and fax machines transmit and receive standard modem line signals, which are carried in an analog traffic channel just as a voice signal would be carried. These systems are structured with frequency-division multiplex (FDM) channels, as appropriate to their primary purpose, which is voice service. A call connection is established by means of control signaling, and an FDM channel is assigned to the call throughout its duration. In the second-generation cellular

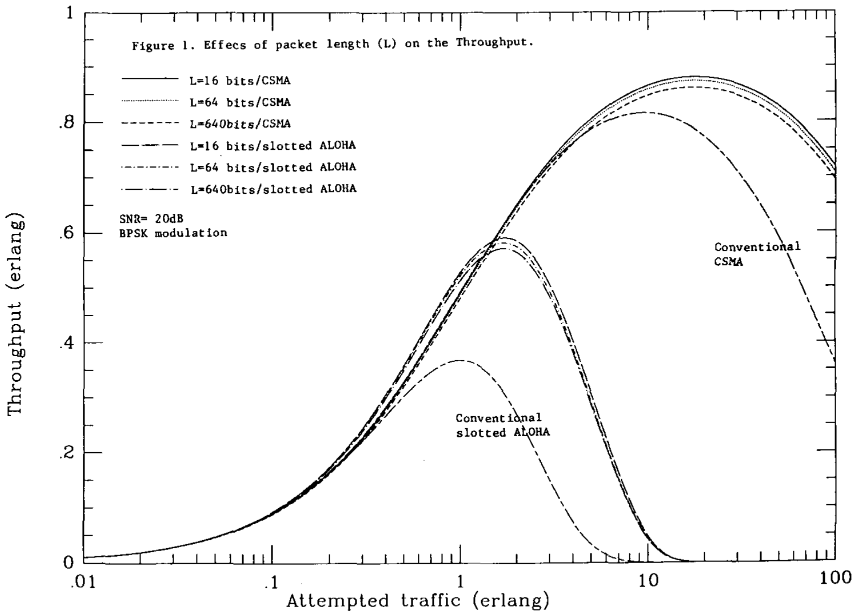

Fig. 19. Throughput versus traffic performance of CSMA and ALOHA networks, showing the effects of Rayleigh fading, modulation, and coding on throughput.

systems, analog FM service will be replaced by digitized voice service, and the channel plans will be restructured in accordance with which digital cellular standard is adopted in any given service area. In the case of the cellular telephone systems, at least four major digital standards are being developed. The Pan-European GSM system, the North American IS-54 system, and the Japanese Digital Cellular system have all been designed to operate with an FDM/TDMA channel structure. For example, in the North American IS-54 standard, an existing 30-kHz analog voice channel will be replaced by a 6-slot TDMA digital channel. In the initial phase of the IS-54 system, the system will assign two slots to each user channel, thus providing three user channels per 30-kHz FDM channel. Data services are being planned for these systems, with initial priority being given to circuit-mode services to support asynchronous data modems and Group-3 facsimile machines. In supporting these services, the cellular system will assign a TDMA time slot to a user just as it does for voice service, but the user channel will carry a data stream instead of a digital voice stream. In the case of the IS-95 CDMA digital cellular standard IS-95, work is in progress to define circuit-mode asynchronous data and facsimile services, in which a CDMA user channel will carry data instead of digitized voice traffic. Future work is planned for definition of packet and other data services for the CDMA system [35].

The major existing mobile data systems were designed specifically for data services, and therefore they employ access methods appropriate to the efficient utilization of the system for supporting large numbers of data users. The ARDIS system, a cellular data network described briefly in Section III, uses the FDMA access method, but in any service area, multiple users are typically using the same 25-kHz FDM channel with a packet transmission format [10]. The problem of interference between simultaneous transmissions is dealt with somewhat differently for outgoing and incoming transmissions. When an outbound transmission is scheduled to begin from a particular base station, the ARDIS network turns off neighboring transmitters for 0.5–1 s, thus preventing interference, at a cost of some reduction of overall network capacity. For incoming transmissions, the remote portable terminals use a random-access technique called data sense multiple access (DSMA). This is a *collision avoidance* scheme in which the remote terminal listens to the base station to determine if a "busy bit" is on or off. When the busy bit is off, the terminal takes this as an indication that the channel is free, and is allowed to transmit. However, if two remote terminals begin to transmit simultaneously, collisions can occur, and these are dealt with using a retransmission strategy, as in other contention-based multiple access protocols [186], [189].

The MOBITEX mobile data system is a cellular network which operates with 12.5-kHz FDM channels and a random-access method to share each channel among multiple users in a cell area. As in the ARDIS system, the random-access scheme in MOBITEX incorporates collision avoidance measures. The random-access method is based on principles of both Slotted ALOHA and Carrier Sense Multiple Access (CSMA) [11], [12]. When a base station transmits a FREE message, the mobile terminal will randomly select one of a group of allocated time slots to begin transmitting. If no acknowledgment is received, perhaps due to packet collision, the mobile terminal will repeat the process. The base station broadcasts a SILENCE message when it is busy receiving from a mobile terminal, preventing others from interfering. A MOBITEX terminal sends an INACTIVE message to the network before it shuts down, preventing the network from making wasted transmissions to terminals that are not active.

As described in Section III, CDPD transmits packet data in the idle channels of a co-resident analog cellular telephone system. The multiuser access protocol for outgoing transmissions is very simple. A base station formats data messages into standard HDLC frames, and then segments the frames into blocks which are protected by Forward Error Correction (FEC) coding. Each FEC-coded block includes bits identifying the base station and intended mobile receiver. On the incoming links, the access control is more complex, since several mobile users must share the reverse channel [34]. CDPD uses an access technique referred to as digital sense multiple access (DSMA), which is closely related to CSMA/CD. Mobile users are cued by the base station using Busy/Idle and Fail/Success bits. Packet collisions can still occur on the incoming channel, and these are dealt with using a backoff algorithm [33]. Thus it is seen that versions of CSMA, with various features for collision avoidance, are the most popular access methods for mobile data systems.

Exiting wireless LAN's are designed for data communication as their primary application. Therefore, essentially all of these products use random-access protocols. Radio LAN's typically use CSMA/CD, the media access control (MAC) protocol of IEEE-802.3, used in Ethernet. Infrared LAN's utilize either CSMA/CD or token ring access methods. CSMA/CD is an appropriate access scheme for diffuse IR systems, while token ring protocols, such as IEEE-802.5, are used in narrow-beam line-of-sight systems [174]. The EEE-802.11 standards committee is working on a standard for wireless LAN's, with primary attention being given to the region of spectrum from 2.4 to 2.5 GHz. Their goal is to provide a standard that supports data rates between 1 and 20 Mb/s, the range of rates provided by most wired LAN's [190]–[192]. One of the challenges facing the committee has been the definition of a physical and MAC layer interface that will deal efficiently with collisions in the multiuser radio environment. At this writing, there are two proposed MAC standards under consideration by 802.11, one a version of CSMA/CD, the other a collision-avoidance protocol similar to Packet Reservation TDMA.

Further information on multiple-access protocols for the wireless environment can be found in [193]–[198].

V. CONCLUDING REMARKS

Current trends in the evolution of wireless data services are either in the direction of high-speed wireless LAN's or low-speed wide-coverage mobile data services. The direction for the future is toward flexible multirate services for multimedia applications, adjusting the specifications of the service with the user requirement and the environment. We have provided an overview of the rapidly expanding field of wireless data services and systems. After a brief overview of the wireless data market, and the user perspective of wireless data services, we briefly described the major mobile data networks and standards; the characteristics of wireless channels and the limitations they impose on achievable data rates; and the transmission technologies and access methods most commonly used in wireless data systems. There are many technical details which could not be included in this paper, but we have attempted to provide the reader with an understanding of the main paths along which the existing and emerging wireless data systems have grown, and the principle characteristics of the major systems. An extensive list of references is included which will provide the reader with more detailed information on the topics covered in the paper.

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