Trends in Local Wireless Networks

The authors' vision of the future, in which a ubiquitous local wireless computing environment leads to a fusion of communications and computation, must overcome significant technical obstacles before becoming a reality.

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In June 1985 the lead author of this article published an article entitled "Wireless Office Information Networks" in this magazine [1]. The article examined spread spectrum, standard radio and infrared (IR) technologies for intra-office wireless networking. This article was published in a timely manner. In May of that same year the FCC released the ISM (industrial, scientific, and medical) bands for spread spectrum local communications. Although ISM bands are not restricted to any specific application, wireless local area networks (LANs) were one of the most prominent applications that were envisioned by the rule makers in the FCC [2, 3]. Since 1985, many small startup companies, as well as small groups in larger companies, have started to develop wireless LANs.

In this article we provide a sequel to the previously mentioned article by providing an overview of the past and present of the wireless LAN industry, as well as a perspective of the future directions that encompass a vision for a ubiquitous local wireless computing environment that leads to a fusion of communications and computation.

Historical Trends

In the late 1970s IBM Laboratories in Ruschlikon, Switzerland published the results of their experimental work on the design of a wireless indoor network using diffused IR technology that was envisioned to be used on manufacturing floors [4]. Around the same time, another experiment at Hewlett-Packard (HP) laboratories [5] examined the use of direct sequence spread spectrum technology for wireless inter-terminal communications. The data rates experimented by both methods were around 100 Kb/s [1] and none of the projects were turned into a commercial product. The diffused IR design could not provide a reliable link to meet the project goal of 1 Mb/s, and the spread spectrum project had to wait for the approval of a commercial band. However, these works initiated further research in high-speed wireless indoor communications. HP laboratories and others developed directed-beam IR networks [6, 7]; Motorola's Codex worked on a wireless LAN using ordinary radio modems at 1.7 GHz and petitioned the FCC for that band [2]; and GTE Laboratories worked on a fiber optic high-speed LAN with wireless drops [8], none of which turned into a commercial product.

Motivated by HP's petition, in 1981 the FCC began exploring the feasibility of regulating a band for the commercial application of spread spectrum technology that led to the adoption of the ISM bands released in May 1985 [2, 3]. Development of commercial wireless LAN products entered a more serious phase after the announcement of the ISM bands. Motorola's petition for a 1.7 GHz band was not granted. However, it revealed very encouraging market evaluations for wireless LAN products. Later on, Motorola was able to secure licensed bands at 18 to 19 GHz for wireless LAN applications that pointed at the availability of bands at higher frequencies for wireless local communications. The release of the ISM bands, results of the market evaluations, and timely publication of some papers [1, 5, 9, 10] prompted a significant interest in the industry for the design of numerous wireless LAN products, mostly operating in the ISM bands. By 1990, wireless LAN products using direct sequence spread spectrum (DSSS) in the ISM bands [11], licensed radio at 18-19 GHz [12], and IR technology appeared in the market. These products were the first that could be called wireless LANs because they were operating at high speeds[1] and they could communicate with at least one standard LAN software product, such as Novell. In that year, the IEEE 802.11 committee was formed as an independent standards group within IEEE 802 to follow up the work of IEEE 802.4L, which had started earlier as a branch of 802.4. In May 1991 the first IEEE wireless LAN workshop dealt with this evolving technology [13]. In 1992, WINFORUM, an alliance among the major computer and communication companies to obtain bands from the FCC for the so called data-PCS, was initiated by Apple Computer in the United States, and the HIPERLAN standards activities in the European Community (EC) were initiated under ETSI direction. In 1993 the EC announced bands at 5.2 and 17.1 GHz for HIPERLAN, and the FCC announced plans for the release of unlicensed PCS bands that can be used for wireless local data communications. Both IEEE 802.11 and HIPERLAN are expecting to complete their standards in 1995. WINFORUM is working with the FCC to develop a "Spectrum Etiquette" for the PCS bands [14].

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[1] 1 Mb/s is considered by IEEE 802 LAN standards as the lowest data rate for a LAN.

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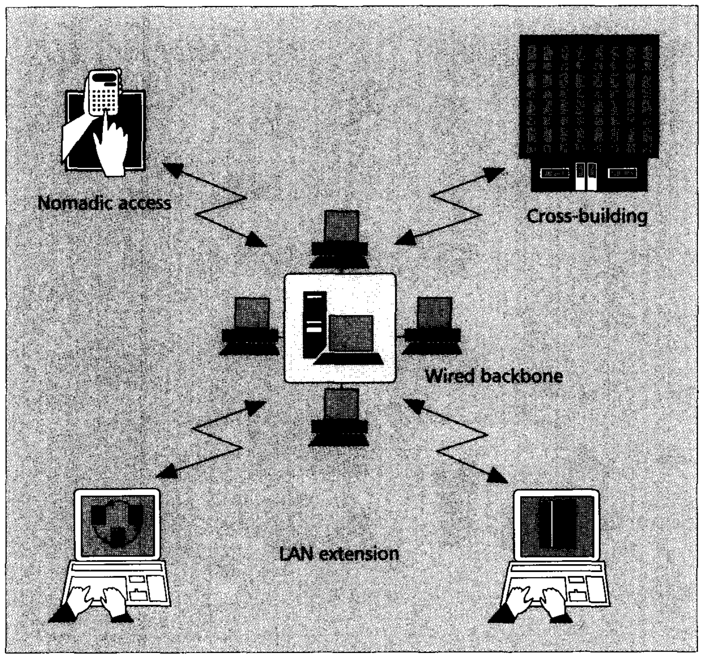
Trends in Applications

During the development of the first-generation wireless LANs at the end of the last decade, it was thought that the savings from the installation and relocation costs of wired LANs justified the additional cost of wireless equipment. It was expected that a market close to a billion dollars would evolve around workstations adopting wireless LANs. In reality, old buildings were already wired and the cost of wiring in new construction was so low that it would be done during construction. Meanwhile, the twisted pair LAN technology dominated the more expensive coaxial cable LANs, which reduced the installation costs significantly. As a result, the first-generation wireless LANs did not closely meet the predicted market.

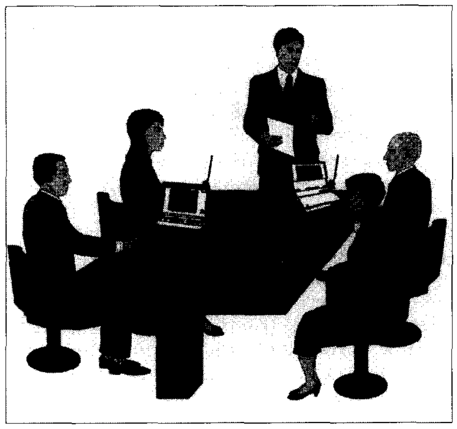
The first generation of wireless LANs were designed to operate with workstations and had an electronic power consumption of approximately 20 Watts. These devices are not suitable for battery operated portable computers. The next-generation wireless LANs are developing around the lap-top, palm-top, and pen-pad computers in a PCMCIA card operating with small batteries. Wireless connection is the natural medium for the personal portable computing devices that are growing in popularity. In this environment researchers are thinking of new concepts such as ad hoc networking, nomadic access and mobile computing that leads to the fusion of the computer and communications in a ubiquitous computing environment.

Today, first-generation wireless LANs are marketed mostly as LAN extension. LAN extension refers to applications in which the coverage of a wireline LAN is extended to areas with wiring difficulties. Examples of buildings with wiring difficulties are buildings with large open areas such as manufacturing floors, stock exchange halls, or warehouses; historical buildings where drilling holes for wiring is prohibited; and small offices such as a branch of a real estate agency where maintenance of wireline LANs is not economically attractive. Recently, wireless LAN manufacturers were also marketing their products aggressively for connecting LANs located in two different buildings. Here, the wireless LAN is a LAN interconnect device that is easy and inexpensive to install.

Figure 1 shows wireless LANs used for LAN extension, cross-building interconnect, and nomadic access. A nomadic access provides a wireless connection between a hub and a personal portable computer. This access is particularly useful for a person returning to the office from traveling who needs to transfer large data files between his personal portable computer and the backbone information network. Another situation related to the same users is ad hoc networking in which a group of portable users, for example in a classroom or a meeting, intend to set up a network among themselves in an unpredicted situation. Figure 2 shows an ad-hoc network among several lap-tops. Figure 3 depicts a ubiquitous computing environment in which a large distributed information and computing base is available to the pen-pad users in a local area through a high-speed wireless link. Typical applications include a wireless campus or a wireless battlefield in which a user (a student or a soldier) can move within a local area with continuous access to the backbone distributed computational facilities.



■ **Figure 1.** *Applications for wireless LANs.*



■ **Figure 2.** *Ad hoc networking.*

Trends in Frequency Administration

A major difference between a wireline and a radio service is that the transmission medium for radio communications is regulated and needs frequency administration. All new services and products must go through an exploratory phase to examine various technologies against the available market. In a wireline environment, innovative ideas and new technologies can be examined against the market immediately. To examine the market for an innovative idea or a new concept using radio technology, one first needs to convince the frequency administration organization. On one hand, wireless LANs need a relatively large bandwidth for high-speed transmission, and the current market needs more time to grow to a reasonable size. On the other hand, it is a new technology that is expected

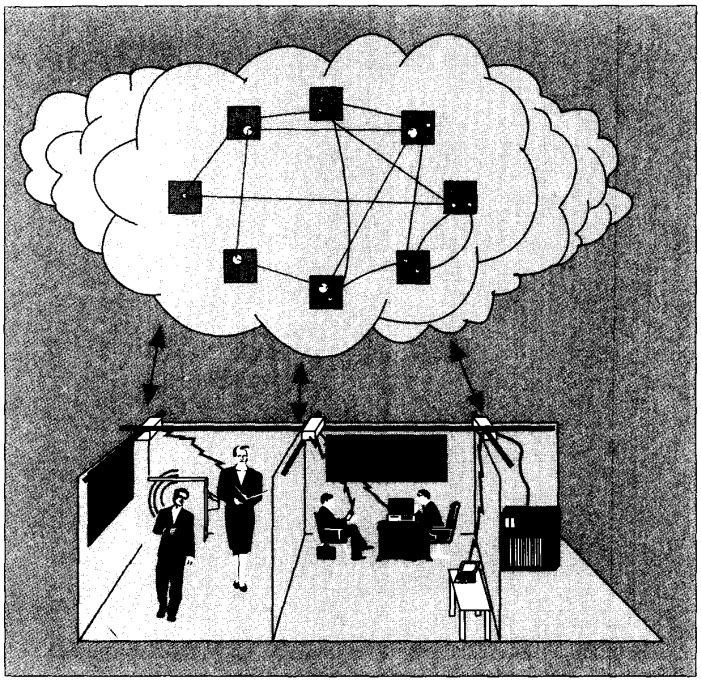


Figure 3. *Fusion of computers and communications into a computational cloud.*

to bring revolutionary applications to the market. This situation leaves the frequency administration agencies in a difficult position to justify the assignment of adequate bands to this application while other traditional voice-oriented services may use the same bands to stimulate a larger market. Two steps are taken to resolve this situation: one is to resort to higher frequencies where larger bandwidths are available; the other is to release unlicensed bands. Raising the frequency of operation increases the size and power consumption and limits the coverage of the signal in indoor areas. The size and power consumption will reduce in time as the electronic design technologies advance. Limitations on coverage is not important in many applications and can be solved easily by reducing the size of the cells. In fact, in some applications confinement of the signal to a small area is a desirable feature for wireless LANs [15].

An unlicensed band with minimum regulation provides a ground for exploration of different wireless technologies against the market in a multivendor environment. This approach particularly suits listen-before-talk random access methods commonly used in wireless LANs. Today, all activities around wireless LANs are focused on unlicensed operation. The major criticism of the unlicensed bands is that they provide a self-defeating purpose. In an unlicensed band a successful market generates high utilization by devices from different manufacturers possibly using different technologies. In the contention access methods used in data communication applications, high utilization causes instability in the system [15]. Any sort of traffic control to stabilize the system requires a hub base network which is an extremely challenging task in a multivendor environment. This situation pushes the trend toward integration with other cellular networks.

Trends in Spread Spectrum

Spread spectrum wireless LANs have been more successful in the market than any other wireless LAN technology, and most firms involved in wireless LANs are using this technology. These spread spectrum wireless LANs are developed in the ISM bands that were the first unlicensed bands in which a high-speed wireless LAN could be implemented. These bands allow unlicensed transmissions of up to 1 W of spread spectrum signal with a minimal spreading factor specified for direct sequence and frequency hopping. Operating in these bands is secondary to other users that already existed in these bands, such as microwave ovens at 2.4 GHz or amateur radios at 900 MHz. These bands can be used for any application, but wireless LANs were one of the primary applications considered in the rule making [2, 3].

At the time of rule making it was thought that spread spectrum technology had two interesting features for wireless LAN applications: It allowed different systems in a multivendor environment to operate simultaneously using CDMA, and its anti-multipath nature provided a reliable transmission at high data rates. It was thought that other access methods such as TDMA or FDMA require explicit cooperation among those sharing the channel. This is not practical in a multivendor environment. Therefore, CDMA was thought to be the only choice [2, 3].

Shortly after the announcement of the ISM bands, the efficiency of CDMA for wireless PBX operation was shown [10]. However, it was pointed out that to avoid the near-far problem, power control is essential for proper operation in a CDMA environment [10, 16]. Power control, however, requires communication among all terminals and a central unit and it cannot be implemented in a multivendor environment unless all manufacturers agree to certain principles that were not envisioned in the rule making for ISM bands. In a single-vendor environment, it was noticed that wireless LAN users need the entire capacity of the channel for quick transmission of data bursts generated by each terminal, and CDMA is not suitable for this purpose [11]. As a result, the first wireless LANs in ISM bands that appeared in the market used spread spectrum without CDMA.

Using spread spectrum without CDMA, it can be argued that the maximum supportable data rate (bandwidth) is sacrificed to gain transmission reliability. But data rate is the most important technical feature appealing to a wireless LAN user. The transmission reliability of spread spectrum is due to the anti-multipath and anti-interference nature of this technology. Other techniques such, as decision-feedback equalization (DFE), multicarrier transmission, and sectored antennas [15], are also anti-multipath, but do not sacrifice bandwidth. These could be adopted as well. So far as the resistance to interference is considered, the low spreading factors used in the ISM band wireless LANs are insufficient to provide very much resistance. Another related important issue is the reliability of the delivered packets of data. In a wireless LAN, the delivery is checked with feedback acknowledgment in the communication software; this reduces the need for an extremely reliable transmission media. Due to the channel fading

Technique	Optical		RF		
	DF/IR	DB/IR	RF	DSSS	FHSS
Data rate (Mb/s)	1-4	10	5-10	2-20	1-3
Mobility	Stationary/ mobile	Stationary with LOS	Stationary/mobile		Mobile
Range (ft.)	50-200	80	40-130	100-800	100-300
Detectability	Negligible		Some	Little	Little
Wavelength/frequency	λ=800 - 900 nm		18 GHz or ISM	ISM bands	
Modulation technique	OOK		FS/QPSK	QPSK	GFSK
Radiated power	-		25 mW	<1W	
Access method	CSMA	Token Ring, CSMA	Reservation ALOHA, CSMA	CSMA	

■ **Table 1.** *Comparison of wireless LAN technologies.*

condition or interference, lost packets are simply retransmitted. Therefore, the reliability of transmission is not as necessary as it is in the case of real-time voice transmission in which there is no acknowledgment mechanism.

From the above discussion we conclude that the most practical reason for using spread spectrum in the ISM bands for multivendor wireless LAN applications is the availability of this band to host a high-speed, unlicensed data link. The main problem with this technique is the reduction in the maximum supportable data rate for a given bandwidth. To compensate for the loss in the maximum data rate in the ISM bands, some companies have adopted multiamplitude and multiphase modulation. Other companies have adopted single channel CDMA, in which each transmitter uses several orthogonal codes simultaneously in the same channels. Since all the codes are modulated over the same carrier, the received power for each code is the same. This is equivalent to having perfect power control in place. Using this method, some companies have been able to achieve data rates on the order of 20 Mb/s in an ISM band. The problem with this approach is the complexity of the design of the receiver and the transmitter.

The fact that without power control and in a multivendor environment spread spectrum is not appealing for wireless LAN applications does not imply that spread spectrum is not suitable for wireless data communications. Indeed, in a multimedia environment where various information sources have different requirements, CDMA is a promising technique. However, an efficient communication in that environment requires power control, which restricts the independence of the designs in a multivendor environment. Although the current trends in spread spectrum wireless LANs in the ISM bands have their own problems, spread spectrum technology will play an important role in the future multimedia wireless communication industry.

Trends in Products

Wireless LANs are designed for a small number of users, usually operating in indoor areas. The range of coverage is small, which leaves many options open for the transmission technology. Technologies used in the existing wireless LAN products are divided into five categories: diffused IR (DFIR), directed beam IR (DBIR), standard radio (RF), direct sequence spread spectrum (DSSS), and frequency hopping spread spectrum (FHSS). In each category several products with different specifications are available in the market. Table 1 shows a comparison among various features of the existing products in each of these categories. These technologies have evolved around the availability of the channel and the suitability of the transmission technique to provide a high data rate link in the wireless media. The IR products are designed to operate in the optical frequencies that are not regulated by the FCC. The spread spectrum LANs are designed to operate in the ISM bands. The RF products are either implemented in the 18-19 GHz licensed bands or in the ISM bands using very low power. The ISM bands allow non-spread spectrum transmission devices if the power is very low.

Data rate is an essential ingredient of local communication networks and the most important aspect for marketing and sale of the product. The higher the data rate, the more likely the impact of the product in the market. Another important feature affecting the market for wireless LANs is the mobility of the terminal, which is a function of the power consumption and the size of the product, except for DBIR, in which the terminal must stay stationary to keep the radiation pattern of the device effective. If the technology can be implemented with small batteries and light weight, it would be suitable for mobile applications and can be used for personal portable computers. Power consumption is a function of the electronic implementation of the device, and some technologies can be implemented either with or without battery operation for mobile and stationary applications, respectively. Most wireless LANs use a version of CSMA, and some use reservation slotted ALOHA or token ring.

Current Trends in Standards

Although none of the standards for wireless LANs are completed, there are numerous wireless LAN products on the market. Wireless LANs are stand-alone products that can be man-

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ufactured without a widely accepted standard. As the penetration of wireless LANs in the market grows and the standards are completed, this situation will change.

Currently, all standard activities for wireless LANs use unlicensed bands, and there are two approaches to regulate an unlicensed band. One approach is to develop a standard that will allow different vendors to communicate with one another using a set of interoperable rules. This approach is taken by IEEE 802.11 and ETSI's RES10, HIPERLAN. The second approach is to provide a minimum set of rules or "Spectrum Etiquette" [14] that allow terminals designed by different vendors to use a fair share of the available channel frequency-time resources and coexist in the same band. The second approach does not preclude the first approach and it is pursued by the WINFORUM. In a coexisting environment a vendor can interoperate with another vendor by using the same protocol and transmission scheme. The future of this industry is toward interoperability. However, a discovery period in which the technology and the market settles itself is being planned. An analogy existed in the development of voiceband modems: at the beginning there was no standard, and as the industry evolved CCITT adopted successful modems as the standard [17].

The three major activities related to wireless LANs are IEEE 802.11, HIPERLAN, and WINFORUM. IEEE 802.11 is developing a standard for DSSS, FHSS, and DFIR technologies and uses the ISM bands as the radio channel. The HIPERLAN standard is concerned with the recently released 5.2 and 17.1 GHz bands in the EC. It is expected that HIPERLAN will adopt non-spread spectrum modulation techniques. To achieve high data rates in multipath fading, HIPERLAN may resort to techniques such as adaptive equalization [18-20], sectored antenna [21] or multicarrier modulation [22-24]. The WINFORUM goal is to obtain parts of the PCS band for unlicensed data and voice applications and develop a "spectrum etiquette" for them.

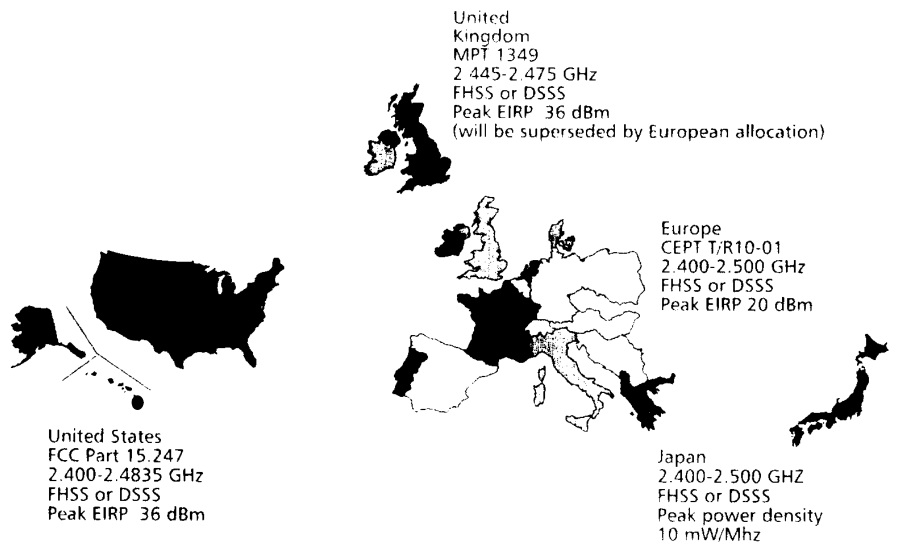
IEEE 802.11 and ISM Bands

IEEE 802.11 focuses on the physical and media access protocol (MAC) layers for peer-to-peer and centralized topologies accommodating DFIR, DSSS and FHSS. Both spread spectrum systems operate in the 2400-2483.5 MHz ISM band. This band is selected over the 902-928 MHz and 5725-5850 MHz ISM bands because it is widely available in most leading countries. Figure 4 shows the map of four major geographic areas with their position toward the ISM bands at 2.4-2.5 GHz. In this band, more than 80 MHz of bandwidth is available that is suited to high-speed data communication. The implementation in this band is also more cost effective as compared with implementation in frequencies that are a few GHz higher. IEEE 802.11 supports DSSS with BPSK and QPSK modulation for data rates of 1 and 2 Mb/s, respectively; FHSS with GFSK modulation and two hopping patterns with data rates of 1 and 2 Mb/s; and DFIR with OOK modulation with a data rate of 1 Mb/s. For DSSS the band is divided into five overlapping 26 MHz sub-bands centered at 2412, 2442, 2470, 2427 and 2457 MHz, with the last two overlapping the first three. This setup provides five orders of frequency selectivity for the user, which is very effective in improving the transmission reliability in the presence of interference or severe frequency selective multipath fading. For FHSS, the channel is divided into 79 subbands, each with 1 MHz bandwidth, and three patterns of 22 hops are left as options for the users. A minimum hop rate of 2.5 hops/s is assigned to provide an opportunity for slow frequency hopping in which each packet can be sent in one hop and, if it is destroyed, the following packet can be sent from another hop for which the channel condition would be different. This approach will provide a very effective time-frequency diversity that takes advantage of a retransmission scheme to provide a robust transmission. The standard supports CSMA and intends to provide interoperability among all users.

WINFORUM and PCS Bands

An important issue that was not addressed in the ISM bands was the enforcement of a time limit for the air time of a terminal. Suppose that a wireless LAN and another device operate in the ISM bands near one another. Further assume that the other device serves an application that constantly radiates a signal in the band. The wireless LAN is a data communication device and it communicates with bursts of information. In this situation, all information bursts generated from the wireless LAN will suffer from the interference caused by the other device, while the wireless LAN only produces bursts of interference to the device. This is not fair to the wireless LAN because it is not getting a fair share of the available resources. A fair method to allow several devices to operate in the same band is to restrict their frequency-time share of the channel according to their transmission power. This issue is addressed by WINFORUM.

WINFORUM was initiated by Apple Computer to form an alliance in the industry to obtain frequency bands for the so called data-PCS. Today, WINFORUM has approximately 40 members from leading information technology companies, and its objective is to obtain and effectively employ radio spectrum for unlicensed user-provided voice and data personal communication services referred to as User-PCS. Currently, WINFORUM intends to foster technical advances in applications such as wireless LANs and wireless PBX services. Originally, WINFORUM was looking for a 40 MHz unlicensed band for the data-PCS, and the FCC has shown some indications to provide them with a 20 MHz band divided into two 10 MHz separate sub-bands for voice and data applications. The technical innovation initiated by the WINFORUM is the development of the so-called "spectrum etiquette" that is a means to provide fair access to an unlicensed band to widely different applications and devices [14]. The etiquette does not intend to preclude any common air interface standards or access technologies. Spectrum etiquette demands listen-before-talk (LBT), which means a device may not transmit if the spectrum it will occupy is already in use within its range. The power is limited to keep the range short. That allows operation in densely populated office areas. The power and connection time is related to the occupied bandwidth to equalize the



■ **Figure 4.** *Worldwide wireless LAN spectrum allocation in the 2400-2500 MHz band.*

interference and provide a fair access to frequency-time resources. In May 1993 WINFORUM filed its spectrum etiquette with the FCC.

In the view of WINFORUM, there are two classes of information type generated from the asynchronous and the isochronous transmissions. The asynchronous transmission, typified by wireless-LAN-like applications is bursty, begins transmission within milliseconds, uses short bursts that contain large amounts of data, and releases the link quickly. The isochronous transmission, typified by voice services such as wireless PBX, exhibits long holding times, periodic transmissions, and flexible link access times that may be extended up to a second. The asynchronous sub-bands may range from 50 KHz to 10 MHz, while the isochronous sub-bands may be divided into 1.25 MHz segments. The two types are technically contrasting and cannot share the same spectrum.

HIPERLAN and 5.2 and 17.1 GHz Bands

Europeans are approaching wireless LAN development from a different angle. They intend to establish a standard first and then develop the products based on the standard. ETSI has asked the Sub-Technical Committee RES10 to develop a standard for High Performance Radio Local Area Networks (HIPERLAN). The committee has secured two bands at 5.12-5.30 GHz and 17.1-17.3 GHz for the development of the HIPERLAN to operate at a minimum useful bit rate of 20 Mb/s for point-to-point data communications with a range of 50 m. They expect that at this rate and range they can provide 500-1000 Mb/s for a standard building floor of approximately 100 meters square that is comparable with FDDI [25]. RES10 is chartered to define a radio transmission technique that includes type of modulation, coding, and channel access, as well as the specific protocols. The first meeting of the HIPERLAN took placed in December 1991. They secured the bands in 1992-93 and they expect to receive ETC approval this year.

Trends in Research

Research today is directed toward enabling the average person to access vast compute power and an enormous amount of information through a "cloud" comprised of a synergistic fusion of communications and distributed computers. The student, nurse, business person, or firefighter dealing with a hazardous materials incident will be able to tap into an enormous quantity of information and computing power assembled to benefit all.

From the Past to the Present

In the view of many, computers and communications are perceived as complementary technologies: related, but different, and not integrated. This is borne out by the focus of research during the past 20 years.

An earlier direction of U.S. government spending for computer research was directed toward supercomputers applied to complex problems, the so-called "grand challenges." The object was to apply massive computing power to solve complex tasks. Wireless networks were not a factor in these programs. Over the past decade, the supercomputer market has been eroded by the emergence of cost effective high-performance desktop workstations and personal computers [26]. This is partially responsible for an expansion in research direction to the "national challenges," which includes wireless networks.

Yielding to the demands of businesses, healthcare, digital libraries, and other interests and applications, the U.S. government has broadened its focus from the "grand challenges" to the "national challenges." The expanded goal now includes funding to provide computational power to the average person in a meaningful way through the National Information Infrastructure (NII) [27]. Support for the range of applications envisioned for the NII requires a fusion of computers and

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networks with wireless access. The network can no longer be thought of as simply a pathway for the transmission of files from one computer to another. The network must meld with the computer, enabling a new paradigm referred to as a "cloud."

Fusion of Computer and Communications

In the simplest sense, networks provide the ability for computers to communicate. However, the integration of computers and networks can provide more than file transfers. In an increasing number of applications, the network is providing computation resources through the communications pathway. One need only look at the burgeoning Internet to see this trend. This coupling has made the Internet more than a vehicle for electronic mail. It has enabled information and provided computational power independent of geographical location. This trend promises to fuel a huge demand for widely distributed computers seamlessly networked together.

The ultimate challenge is to exploit wasted computing cycles and provide location-independent access to the computational resources. If the number of personal computers is 50 million and each is capable of 2 MIPS, then the combined computing power is 10^{14} MIPS with, perhaps, 95 percent of that idle. When one considers workstations, minicomputers and mainframes, the combined computing power is immense. The difficulty is how to put this incredible resource to productive work and provide ubiquitous local wireless access to the cloud anytime and from anywhere.

Impact of the Cloud

To illustrate how the fusion of computers and wireless LANs will impact the future, we present three applications under development or envisioned: a military application, the military concept applied to the office or hospital, and a community emergency services response.

Digitalization of the Battlefield — Command, control, communications, and intelligence (C^3I) are a difficult task in the hostile environment of a battlefield. The field commander needs to know the location and situation of the troops under his command, and have all available intelligence as well, in order to make the appropriate decisions. The lives of the troops and the success of the mission depend on the commander and his C^3I. If the commander along with all support and communications is at one site, the battalion is vulnerable. To reduce the battalion's exposure and assure the integrity of the chain of command, the integrated wireless digital battlefield has been proposed.

In the digitized battlefield, each soldier carries a backpack computer connected through a wireless LAN to all others in the battalion. Through the network, each soldier's physical condition and location can be monitored through the use of a personal network [28], and instructions can be given accurately and without delay. Visual data can be relayed to the commander. More importantly, the backpack computers form a distributed, fault-tolerant computer, survivable after the loss of one or more nodes. The wireless LAN enables the unencumbered movement of troops and machines, as well as providing a communication infrastructure. The commander, or his chain of command, can monitor the health of the troops, monitor movements, gather intelligence, communicate with neighboring commanders or superiors, and give orders.

The wireless digital battlefield provides a significant strategic advantage. The enemy is no longer able to destroy the effectiveness of a battalion by striking a central command site. The C^3I function is more difficult to compromise. Command is spread over a larger area, with each soldier a part of the distributed C^3I structure.

Jacquard — The Jacquard project[2] [29] fuses computers and communications into a scalable, real-time, distributed, fault-tolerant architecture. Jacquard provides for both shared-memory and message-passing distributed-processor paradigms with wireless access. It is essentially a scalable local *cloud* connectable to a global *cloud*. Processes on the system can be run on processors with available compute cycles, thus putting wasted resources to use. If a machine fails, the process can be automatically restarted on another machine under control of the operating system. The user need not be aware of the intricacies of this computational backbone, only that his mission-critical process will run on the available cycles, thus increasing resource utilization. Consider the battleship captain needing to compute missile trajectories to launch a counter-attack after suffering damage to the weapons control. The Jacquard architecture will still allow the ship to compute and launch a retaliatory strike by utilizing the remaining processors distributed throughout the ship. The captain keeps informed of the situation through his personal digital assistant (PDA), connected to the ship's Jacquard framework, regardless of where he roams on the ship.

In the office or campus environment, an individual is able to access the Jacquard *cloud* through a PDA with ubiquitous wireless communications. The PDA is of limited processing capability to conserve battery power, and has a user-friendly graphical interface [30, 31]. The businessperson, student, or engineer can access vast quantities of data, run simulations, utilize decision support software, and teleconference through their PDA. Beyond ad hoc networks, the PDA provides mobility to the user by maintaining connectivity throughout the local area. Discussions in a conference room, hallway, or associate's office can be more productive by testing hypothesis, running simulations, searching databases, or calculating projections quickly, utilizing the heretofore wasted compute cycles of traditional computers through wireless LANs.

Emergency Service Response — The local fire department is called to respond to a hazardous material spill on a busy highway in the community. Speed is critical to mitigate the situation and to insure citizen safety and protect property. Upon arrival at a safe distance from the spill, the highly-trained response team dons protective clothing and attaches a PDA with wireless LAN. The incident commander and his assistants monitor the vital signs of the response team and observe the situation through video, audio, and data transmitted over the wireless LANs. As the team leader nears the spill, he observes the placard on

[2] *Funded by ARPA under contract #DABT63-91-C-0016.*

the trunk and on the leaking drums.

The chemical identification is entered into the PDA and, through the *cloud*, identification, health and fire hazards, recommendation for evacuation, and containment and neutralization procedures are relayed to the team. Additionally, the mixture of different chemicals is relayed to a network of computers that quickly analyzes the resultant chemical compound, which may not be contained in any reference material, and suggests a course of action.

This represents a vast improvement over the current method of limited voice-only communications. Similar technologies can be effectively applied to emergency medical services, law enforcement, highway workers, and so on.

Technical Challenges

This vision of the future, the integration of computers and communications into one entity or *cloud*, must overcome significant technical obstacles before becoming a reality. The communications technologist is faced with providing a ubiquitous wireless LAN for connectivity anywhere, anytime. The computer technologist is faced with the problem of integrating the computers into a cohesive distributed network through the operating system and software applications.

The communications problems to be overcome include limited bandwidth, latency, dropout, limited available power, and secure communications. In distributed computing applications, latency is one of the biggest problems.

The computer component of the *cloud* has its hurdles to overcome. The speed of the processor is not the limiting factor. Density, power requirement, performance, and cost of memory are limiting factors. Display technology is another area where improvement must be made. Resolution, power, size, and cost are areas for improvement in PDA display technology.

The system issue of resource management must be considered and may be intractable. Imagine allocating resources on 10 different computers or processors to run 48 different applications or processes. There are on the order of 10^{48} different allocation assignments or possibilities, each with its own system-wide performance implications. The complexities of efficient, fair, and equitable allocation will be a challenge for the future.

The fusion of computers and communications into a unified entity may appear a subtle distinction from the computers and networks popular today. However, the impact of the fusion along with wireless LANs will be profound. It will affect everything from the way we do business to the way we live. It will be the harbinger of an information wave.

The system issue of resource management may be intractable. Imagine allocating resources on 10 different computers or processors to run 48 different applications or processes.

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