Abstract

An overview of the current status of wideband wireless local access technologies is provided. Service scenarios and availability of the market and products for wireless LAN and wireless ATM technologies are discussed. Similarities among IEEE 802.11 and HIPERLAN standards for wireless LANs and the developing prototypes for wireless ATM are evaluated. An update on the status of the available unlicensed bands in the United States as well as status of the wideband wireless projects in the European Community and Japan is presented.

Wideband Local Access: Wireless LAN and Wireless ATM

Kaveh Pahlavan, Ali Zahedi, and Prashant Krishnamurthy
Worcester Polytechnic Institute

Although wireless local area networks (WLANs) and wireless asynchronous transfer mode (WATM) both provide wideband wireless local access (WWLA), there are differences between and similarities among the two. WLAN is a mature technology with available products and market, WATM is an evolving technology that has not yet tested the market. WATM is perceived to be a service provided by the operating company. WLANs are considered as products sold by the manufacturer for private use. WLANs provide an access to legacy LAN applications. WATM is expected to provide end-to-end ATM connectivity and quality of service (QoS) in the wireless channel. In this article we address these issues in further detail and provide an overview of the global WWLA activities.

We are emerging at the beginning of a new and exciting era for the WWLA industry. After a decade of self-realization for this industry, WLAN and inter-LAN bridges are finding their way into the health care, manufacturing, finance, and educational markets. According to the January 1997 Frost & Sullivans report on the North American wireless office hardware market, the total 1996 revenue for wireless offices was $390 million, of which $218 million was from WLANs. The IEEE 802.11 standard for WLANs is emerging as a mature standard presenting a well-defined technology that is being adopted by the manufacturers and accepted by the users. Chip sets have been developed according to the IEEE 802.11 standard, making software creativity easier for developing new applications toward expanding the market. The European Telecommunications Standards Institute's (ETSI's) RES-10 group has defined another alternative technology, High-Performance Radio LAN version 1 (HIPERLAN I), which is primarily focused on ad hoc networking applications and supports higher data rates. More recently, research around wireless ATM has spread like an epidemic, engaging numerous companies in examining the suitability of yet another alternative standard technology for WWLA.

The successful emergence of the market for WLANs operating in the unlicensed industrial, scientific, and medical (ISM) bands has underlined the need for additional unlicensed bands. The continual demand of the WWLA industry for additional unlicensed bands in useful spectrum, initiated by WINForum, has resulted in the release of a 20 MHz unlicensed band around 1.9 GHz for asynchronous and isochronous applications in 1994 and 300 MHz of unlicensed bands earlier this year at 5 GHz, referred to as the U-NII (unlicensed national information infrastructure) bands (formerly SUPERNet). On the other hand, the pan-European third-generation cellular service, Universal Mobile Telecommunications Services (UMTS), is considering connectionless packet-switched networks as class D bearer services. Under the research arm ACTS (Advanced Communications Technologies and Services), the MEDIAN, WAND, SAMBA, and AWACS projects are addressing WWLA services. The Japanese are engaged in developing their own WWLA technology, and at the same time several Japanese companies are involved in developing WLAN products for the U.S. market.

Wireless access cannot be discussed without considering issues related to the backbone. There are four options to interconnect the two air interfaces, WLAN and WATM, to the two wired backbones, legacy LANs and evolving ATM networks: WLAN-LAN, WATM-ATM, WLAN-ATM, and WATM-LAN. Figure 1 shows the protocol stack needed for the respective implementation of these interconnection techniques. The first option, shown in Fig. 1a, is addressed by the IEEE 802.11 community. The other two options are being considered in the WATM community. The second approach, shown in Fig. 1b, has more overhead, and is expensive and less scalable. At this stage this technique is considered only an interim solution for migration and proof of concept [1]. The fourth option, WATM-LAN, is not under consideration at all because a WATM air interface assumes that the backbone network employs ATM switches. Therefore, we are left with two options, WATM-ATM and WLAN-LAN, which we will refer to as WATM and WLAN in the rest of this article.

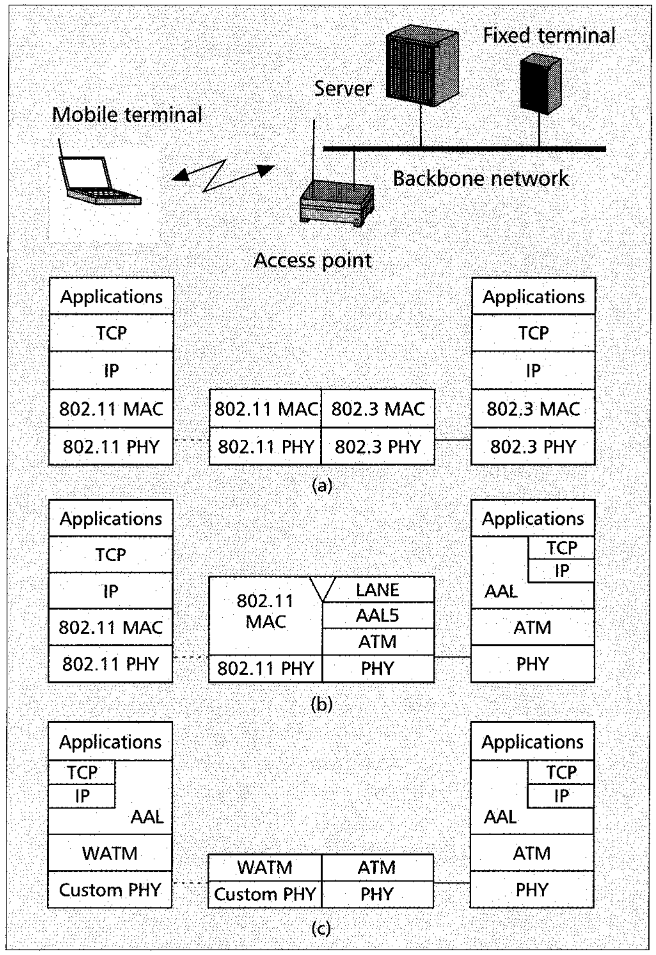
Service Scenarios

The success of WLANs or WATM depends on the availability of the corresponding backbone wired infrastructure and the evolution of the software applications. The backbone wired network consists of long-haul and local backbones. Today, it is commonly assumed that the future long-haul backbone networks will employ ATM transport, and ATM will also be the backbone of the third-generation wireless telecommunications networks. However, there is an ongoing

 0163-6804/97/$10.00 © 1997 IEEE

battle between connection-based ATM local backbones versus contention-based local legacy LAN backbones. Whether the backbone network of the future uses ATM only for long-haul and the legacy wired LAN technologies for local access or whether we will have an end-to-end wired ATM network will be a major deciding factor on the success of WLANs or WATM. The battle between ATM and gigabit Ethernet for wired local access is not yet resolved [2], and an unbiased prediction of the direction of this religious war is extremely challenging and beyond the scope of this article.

Service scenarios for the future WWLA can be categorized into private local networks in workplaces, universal access points in homes, and nomadic access in public places [3]. The existing WWLA market is almost exclusively for wireless office equipment using Transmission Control Protocol/Internet Protocol (TCP/IP)-based applications over WLANs. The WLAN technology provides wireless access to the legacy LANs which support TCP/IP applications with minimal overhead. ATM in general has been shown to be inefficient in supporting legacy TCP/IP applications [4, 5]. The ATM local backbone is expected to be suited for future multimedia applications supporting a variety of traffic categories with negotiable QoS. Using Resource Reservation Protocol (RSVP) for TCP/IP applications, the legacy LAN local backbone can support QoS for multimedia applications [6]. Potential wireless applications in the home include universal wideband access to a variety of services such as cordless telephony, Internet access, and flexible positioning of audio systems. The WLAN technology can support all these applications, but WATM could be more suitable for cordless telephone applications which may generate most of the in-home wireless traffic. Nomadic public access again depends on the availability of the backbone network. If the ATM networks are available in most public places, it may appear easier to provide traffic policing and charging mechanisms using WATM. If legacy wired LAN backbones are available, WLAN technology can also provide charging mechanisms, but it is rather challenging to enforce traffic policing.



■ **Figure 1.** *WLAN connection to the backbone.*

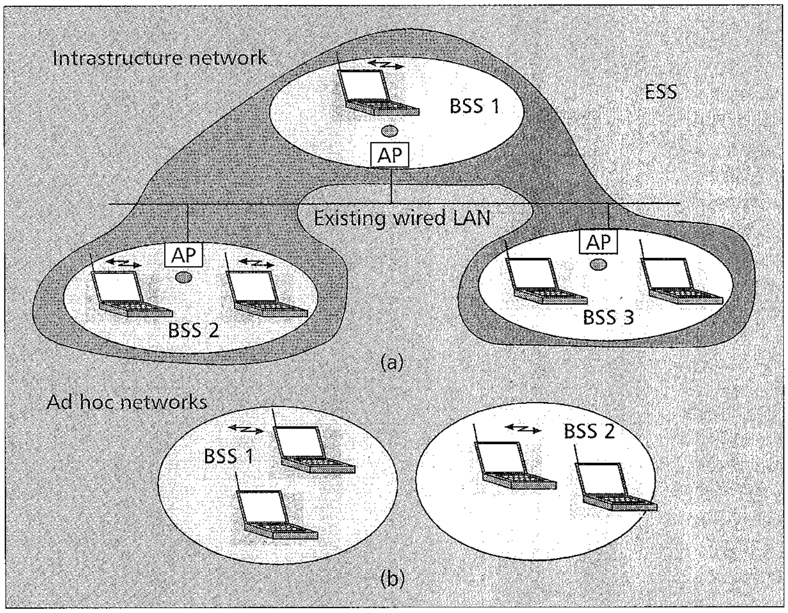
MARKET AND PRODUCTS

One of the most challenging issues facing the WLAN industry is expanding the market. Those involved in the traditional WLAN industry promote privately owned WLAN applications, such as campus-area networks — a market for PCMCIA cards and access points in large quantities. The more visionary service providers are eager to promote nomadic WWLA applications in public places such as airports to generate a new source of income through service charges. Today only WLAN products exist in the market; WATM services are expected to appear in the market only by the turn of the century.

In the past, the WLAN industry had a difficult time predicting the development of the market. In 1990 the first-generation WLAN products appeared in the market. These products, consuming around 20 W (not suitable for laptops), were considered an alternative that would avoid the expensive and troublesome installation and relocation costs of coaxial cable LANs. Under the assumption that WLANs would capture 10–15 percent of the coax LAN market, early market predictions for WLANs were around $0.5–2 billion for the mid-1990s. However, by the time WLAN products appeared in the market, less troublesome twisted pair wiring technology, similar to existing telephone wiring, had already replaced coax LAN technology, so the first-generation WLANs did not meet the market predictions.

The second-generation WLAN industry evolved in two directions. One group developed PCMCIA card WLANs for laptops to address the need for local mobility and its related applications. The other group added directional antennas to the first generation shoebox-type WLAN products and marketed them as inter-LAN bridges for outdoor applications [7–9]. The existing WLAN products available on PCMCIA cards are either direct-sequence spread spectrum (DSSS) or frequency-hopping spread spectrum (FHSS) operating in ISM bands. Diffused IR (infrared) technology is used for nomadic access in shorter distances for applications such as access for laptops to printers or in specific areas within hospitals, such as radiology departments, where radio signal use is not encouraged. In addition to spread spectrum technology, other technologies such as direct-beam IR (DBIR) and traditional radio are used for inter-LAN bridge applications. As mentioned in the introduction, the market size for these products is around $2–3 million.

The WLAN market currently aims at four categories of applications [10]: healthcare, factory floors, banking, and educational institutions. In the healthcare market, in addition to traditional equipment such as laptops, notebooks, and handheld terminals, special wireless services such as electronic thermometer and blood pressure monitoring devices are expected to be involved in wireless local communications. These devices are used to provide mobile access to clinical and pharmaceutical databases for the physician as well as to enter personal health data. In manufacturing floors and the factory environment, in addition to accessing databases and updating them, wireless networks enable rapid modification of assembly lines and provide instant network access, for example, to delivery trucks at dock stations. In the banking industry, WLANs facilitate extending network facilities to other branches, upgrading systems without disrupting banking operation, reorganizing and rearranging branches, and access to



■ **Figure 2.** *Network topologies supported by IEEE 802.11.*

the Internet. In the educational environment, WLANs facilitate distance learning using wireless classrooms, and provides access to the Internet, computational facilities, and database servers to students using notebook computers.

Standard Technologies

There are three standardization activities for WWLA: the IEEE standard (802.11), ETSI's HIPERLAN standard, and the ATM Forum's standard, WATM. We discuss these in this section in some detail.

The IEEE standard for WLANs started in 1988 as IEEE 802.4L, a part of the IEEE 802.4 token bus wired LAN standard. In 1990 the IEEE 802.4L changed its name to IEEE 802.11 to form a standalone WLAN standard in the IEEE 802 LAN standards organization. The technical aspects of this standard were completed this year. Throughout this unexpectedly long endeavor, the 802.11 group developed a framework to incorporate wireless-specific issues such as power control, frequency management, roaming, and authentication in a LAN standard. The IEEE 802.11 standard was developed based on existing products in the market, so it addresses both technical and marketing issues.

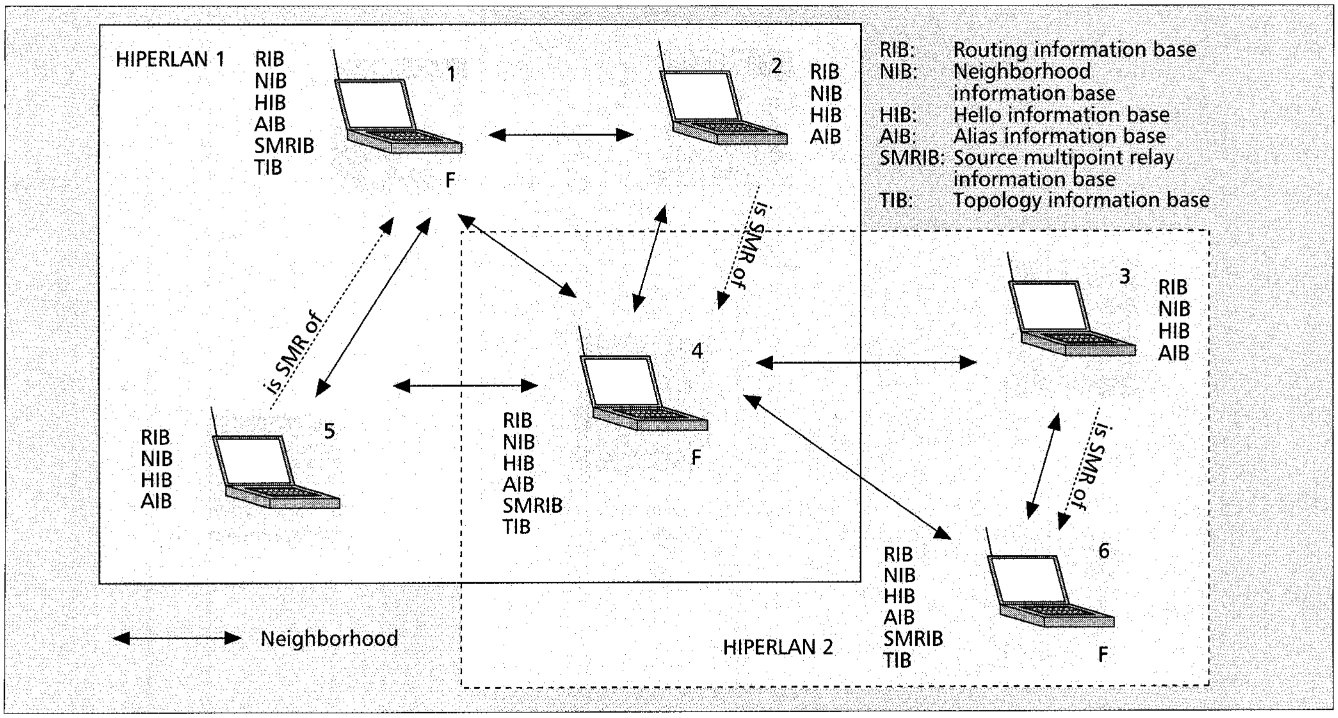
The 802.11 standard [11] specifies data rates up to 2 Mb/s using spread spectrum technology in the 2.4 GHz ISM bands. As wider U-NII bands with no restriction on modulation become available, it is possible to update the physical layer of the standard to support higher data rates and other modulation techniques. The 802.11 standard considers two network topologies: infrastructure-based and ad hoc (Fig. 2). In an infrastructure network (Fig. 2a), mobile terminals communicate with the backbone network through an access point (AP). The AP is a bridge interconnecting the 802.11 network to the backbone wired infrastructure. In this configuration, a distribution system interconnects multiple basic service sets (BSSs) through access points to form a single infrastructure network called an extended service set (ESS). A mobile terminal can roam among different BSSs in one ESS without losing connectivity to the backbone. In an ad hoc configuration (Fig. 2b), the mobile terminals communicate with each other in an independent BSS without connectivity to the wired backbone network. In this case some of the functions of the AP, such as release of a beacon with a defined ID and timing reference, which are needed to form and maintain a BSS are provided by one of the mobile terminals. The cells in both configurations shown in Fig. 1 can overlap with one another. In addition to the contention-based carrier sense multiple access with collision avoidance (CSMA/CA) access method suited for asynchronous data applications, the IEEE 802.11 also supports a contention-free prioritized point coordination function (PCF) mechanism to support time-bounded isochronous applications. The PCF mechanism supports limited assurance for providing QoS. The medium access control (MAC) services in IEEE 802.11 support authentication, encryption, frequency management, and power conservation mechanisms not available in the MAC layer of other 802 standards such as 802.3.

The HIPERLAN standard was developed by the RES-10 group of the ETSI as a pan-European standard for high-speed wireless local networks. The so-called HIPERLAN I, the first technology defined by this standard group, began in 1992 and was completed this year. It supports data rates of 2–23 Mb/s using traditional radio modulation techniques in the 5.2 GHz band. The HIPERLAN I network [12, 13] supports a multihop ad hoc configuration (Fig. 3). Multihop routing extends HIPERLAN communication beyond the radio range of a single node. Each HIPERLAN node is either a forwarder or a nonforwarder. A nonforwarder node simply accepts the packet intended for it. A forwarder node retransmits the received packet, if the packet does not have its own node address, to other terminals in its neighborhood. Each nonforwarder node should select at least one of its neighbors as a forwarder. Inter-HIPERLAN forwarding needs bilateral cooperation and agreement between two HIPERLANs. To support routing and maintain the operation of a HIPERLAN, the forwarder and nonforwarder nodes need to periodically update six and four databases, respectively. These databases are identified in Fig. 3. The nonpreemptive multiple access (NPMA) protocol used in HIPERLAN is a listen-before-talk protocol that supports both asynchronous and isochronous transmissions. The HIPERLAN defines a priority scheme and lifetime for each packet which facilitates QoS control. In addition to routing, the MAC layer also handles encryption and power conservation.

Other versions of HIPERLAN for accommodating wireless ATM and other alternatives are currently under consideration [14]. During the standardization process a couple of HIPERLAN I prototypes were developed, but as of now no manufacturer has adopted this standard for product development. The bands assigned for HIPERLAN in the European Community (EC) were one of the motives of the FCC for releasing the U-NII bands, discussed in the next section.

In the past couple of years several companies and projects have developed infrastructure-based prototypes to implement WATM technology [1, 15–18]. Of these, three major prototypes were developed at Lucent, NEC, and the Magic WAND project of the ACTS research program in Europe. Table 1 summarizes the technical aspects of IEEE 802.11 and HIPERLAN I with the three major WATM prototypes. To merge these WATM studies, last year the WATM Working Group of the ATM Forum was formed to define a standard for WWLA using WATM technology. The work of this group started recently; it is planning to develop specifications for radio access, MAC layer, and mobility support for WATM. The standard is aiming for completion in 1999, so products could appear in the market by the turn of the century.

There are significant challenges for employing ATM in a mobile wireless link that must be resolved before this technol-



■ **Figure 3.** *HIPERLAN ad hoc network configuration.*

ogy is identified as a legitimate standard. ATM was essentially designed for high-bandwidth, highly reliable, static optical fiber channels; wireless channels are inherently unreliable and time-varying with limited available bandwidth. ATM is a connection-oriented transmission scheme that operates based on an initial negotiation with the network for a virtual channel with a specific QoS. In a mobile environment management of the virtual channel and the QoS is not simple because the route has to be continually modified as terminals move during the lifetime of a connection.

Several proposals have been submitted for consideration by the WATM Working Group [19–23], but no official technical specification has been released by the group. We refer to the overview material provided by the chairman of the committee in [24]. Figure 4 provides an overall architecture perceived for future WATM services. Similar to the IEEE 802.11 standard, the architecture is perceived to support both infrastructure and ad hoc networking. Unlike IEEE 802.11, wireless connection is expected to be performed through wired ATM switches. WATM APs are expected to communicate with one another to provide facilities to support a dynamic topology. WATM in this figure is shown to be part of an integrated multimedia network over a variety of links which includes standard wired networks as well as dedicated microwave and satellite links.

As far as the radio access specifications are concerned, the WATM community argues that the short packet size (53 bytes), high data rates (~20 Mb/s), and short header (5 bytes) in WATM ideally suit the on-off fading characteristics of local radio channels, providing efficient usage of the band [24]. It should be noted that the IEEE 802.11 MAC layer provides packet segmentation facilities which shorten the packets; if this is utilized properly, the same advantages can be gained. High data rates can also be provided by the IEEE 802.11 MAC layer if we migrate to higher frequency bands (e.g., U-NII) and adopt other modulation techniques. However, in either case, WLAN or WATM, migration to higher frequencies will reduce AP coverage and increase the cost of the infrastructure. In the past decade products with smaller coverage have not survived the market test.

Global Activities

Today's global market for WLANs primarily belongs to the United States. For manufacturers aiming at the WWLA market, the two most important issues are the availability of unlicensed bands for future product development and a spectrum etiquette that secures a minimum bandwidth availability for users in different scenarios. The relationship between a licensed band and an unlicensed band is similar to that between a privately owned backyard and a public park. If you can afford a backyard you can have a barbecue there; otherwise, you may go to a public park and, depending on the availability of space, enjoy similar benefits without any investment in property. WLANs are new products developed by small companies in the midst of large companies. None of them can afford backyards in the expensive neighborhoods of 1–2 GHz where a big market for voice applications exists. As an increasing number of people realize the benefits of a public park and use it, the need for an etiquette increases to control the crowd of barbecue fans and prevent the smoke from overwhelming everyone.

In 1994, the FCC released 20 MHz of spectrum between two parts of licensed bands in the 1.9 GHz band for operation of unlicensed personal communications services (U-PCS). This spectrum is shown in Fig. 5.

The unlicensed nature of the frequency bands necessitated a coexistence etiquette which was developed by WINTech, the technical subcommittee of the WINForum industry association. This spectrum etiquette forms the basis for the rules adopted by the FCC for operation in the U-PCS bands. The interesting point about the WINForum etiquette is the assignment of two separate bands for asynchronous and isochronous transmissions. This separation implies that, in the view of WINForum, voice and bursty data transmissions are incompatible enough to require the use of separate channels in the air. This separation is in contrast with the view of those working in wired communications such as integrated services digital network (ISDN) and ATM, where the trend is toward integration of voice and bursty data on the same channel. There are three basic principles adopted for the spectrum etiquette in the U-PCS bands:

- Listen before talk (or transmit) (LBT) protocol

	Frequency band	Modulation technique	Data rate	Access method	Topologies	MAC services	QoS	Availability
				Wireless LAN				
802.11	Spread spectrum direct sequence: 2.4–2.4835 GHz; frequency hopping: 2.4–2.4835 GHz; diffused infrared: 850–950 nm	Spread spectrum direct sequence: DBPSK, DQPSK; spread spectrum frequency hopping: 2GFSK, 4GFSK BT=0.5; diffused infrared: 16 and 4 PPM	1 and 2 Mb/s	Basic CSMA/CA, RTS/CTS, PCF with polling list, 20 frames	Ad hoc, infrastructure	Authentication, encryption, power conservation, time-bounded services	No explicit support for QoS, but includes infrastructure topology and priority scheme in PCF that are useful for quality assurance	Technical standard finalized. Final administrative approval under progress. Products (e.g., DEC Roamabout) and chip sets (e.g., Harris PRISM and Raytheon RAYLINK) are available
HIPERLAN	5.15–5.30 GHz	Low bit rate: FSK; high bit rate: GMSK (BT=0.3)	1.47 and 23.53 Mb/s	Nonpreemptive multiple access (NPMA), 10 PDU	Ad hoc	Encryption, power conservation, routing and forwarding time-bounded services	Advanced user priority scheme and packet lifetime mechanism to support QoS	Standard is finalized. No product in the market. Two prototypes: HIPERION, fully standards compliant, and LAURA, not fully compliant [14]
				Wireless ATM				
MII Bahama	900 MHz (proposed 5 GHz U-NII bands)	OFDM or GMSK with LMS or RLS equalization	2–20 Mb/s between laptop and PBS, and Gb/s between PBSs	Distributed queue reservation updated multiple access (DQRUMA): reservation and piggybacking	Infrastructure, ad hoc base station placement (optional)	Scheduling, piggybacking, and so on	Base station responsible for checking and guaranteeing QoS, connections with or without QoS guarantees possible	Prototype at Bell Labs, Lucent Technologies
NEC	2.4 GHz ISM bands	$\pi/4$-QPSK with decision feedback equalization	8 Mb/s	TDMA/TDD with slotted ALOHA	Infrastructure-based	Scheduling multiplexing and demultiplexing of VCs	ABR, UBR, VBR, and CBR slots are available but QoS support is not finalized	Prototype at NEC USA's C&C Research Laboratories, Princeton, NJ
Magic WAND	5.2 GHz	16-channel OFDM	>24 Mb/s	Reservation, slotted ALOHA: mobile access scheme based on contention and reservation (MASCARA)	Infrastructure-based	Scheduling, radio resource managment; under further study	Worst case QoS estimate (cell delay or cell loss) to be used for determining the connection	Prototyping under the European ACTS AC085 project

Table 1. *Comparison of WLAN standard technologies.*

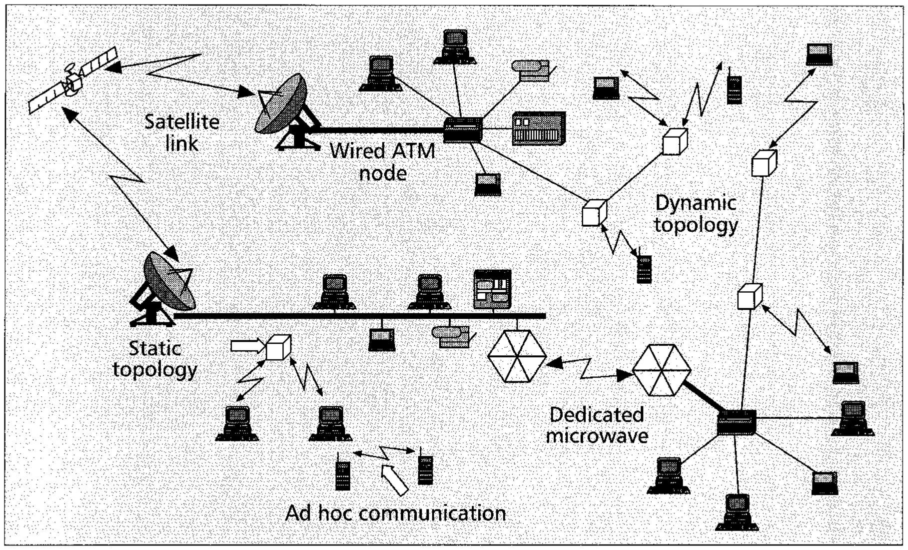
- Low transmitter power
- Restricted duration of transmissions

The requirements on timing accuracy are quite rigid, making this protocol unsuitable for ATM transport. Further details about this protocol are available in [25].

The U-NII initiative started with WINForum filing a petition before the FCC requesting allocation of 250 MHz of spectrum for high-speed devices providing 20 Mb/s in May 1995. This was followed by a petition by Apple Computer requesting allocation of 300 MHz of spectrum in the same frequency bands for promoting full deployment of the so-called national information infrastructure (NII).[1] These bands and devices were referred to as shared unlicensed personal radio network (SUPERNet) bands and devices. On January 9, 1997, the FCC released 300 MHz of unlicensed spectrum around 5 GHz for use by a new category of radio equipment, U-NII devices. This decision of the FCC makes a large amount of spectrum available for wireless LAN applications which can provide data rates up to several tens of megabits per second, needed for multimedia applications. The frequencies allocated

[1] *The FCC describes the NII as a group of networks, including the public switched telephone network (PSTN), radio and television networks, and other networks yet to be built, which together will serve the communications and information processing needs of the people of the United States in the future.*

are compatible with those specified earlier by the Conference of European Postal and Telecommunications Administrations (CEPT) for HIPERLAN. The WINForum spectrum etiquette was also suggested by the FCC for U-NII devices, but was not adopted because of concerns about its suitability to accommodate WATM services. The FCC believes that this spectrum would enable opportunities for providing advanced telecommunications services to educational institutions, health care providers, libraries, and others [26], thereby significantly helping to meet universal service goals [27] as set forth in the Telecommunications Act of 1996 [28].



■ **Figure 4.** *Wireless ATM architecture [24].*

The frequency bands and their respective technical restrictions are shown in Table 2. To encourage maximum flexibility in developing new technologies, minimum technical restrictions have been adopted. Detailed restrictions or standards can only delay the implementation of appropriate products able to attract commercial applications.

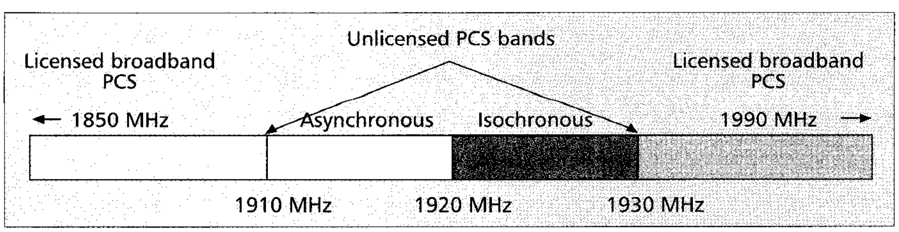
Although no devices have been developed yet for U-NII bands, several activities for developing standards and products in these bands have already started. The Mobile Information Infrastructure (MII), an ongoing research project at Bell Laboratories which is partially funded by the National Institute of Standards and Technology (NIST), is considering wireless ATM applications in this band [1]. IEEE 802.11 has set up a study group for higher-speed physical-layer standards development in the 5 GHz band with the same MAC protocol currently used for the 2 Mb/s standard with spread spectrum technology in the ISM bands. Data rates beyond 20 Mb/s as well as the capability of the MAC layer to support data, voice, and video services are to be examined by this study group. In the U-NII, as opposed to ISM bands, there is no restriction to use only spread spectrum technology, and other modulation techniques such as orthogonal frequency-division multiplex (OFDM) and Gaussian minimum shift keying (GMSK) have been suggested. At higher U-NII frequencies the LAN adapter is expected to be more expensive, but the cost/performance ratio is expected to improve.

Although the WLAN market is primarily in the United States, there are significant WWLA related activities in the EC and Japan. In the EC under the ACTS projects, several research programs are devoted to examining a variety of technologies for wideband local applications. The intention is to integrate these technologies into the evolving third-generation cellular systems. Also, ETSI has announced a new standardization project, BRAN (Broadband Radio Access Networks), which will take over the current HIPERLAN activities. The BRAN project will address issues related to wireless access systems with bit rates larger than 25 Mb/s. Close relationships are being established with the ATM Forum, IEEE 802.11, the Internet Engineering Task Force (IETF) and ITU — Radiocommunication Standardization Sector (ITU-R) to ensure overall coherence with other existing and emerging technologies.

The ACTS program in Europe is involved in several wideband wireless activities. In the wireless customer premises network/mobile broadband system (WCPN/MBS) domain there are four major wideband projects [29, 30]. The MEDIAN project is evaluating and implementing a wireless LAN capable of operating at 60 GHz and providing 155 Mb/s. The prototype will demonstrate one base station at 155 Mb/s and two portables, one at 34 Mb/s and the other at 155 Mb/s. The Magic WAND project (Table 1) demonstrates WATM transmission at 5 GHz. The System for Advanced Mobile Broadband Applications (SAMBA) develops an MBS trial of two base and two mobile stations operating at 40 GHz. The Advanced Wireless ATM Communications Systems (AWACS) is a cooperative project between Europe and Japan (ACTS and NTT). It is based on a 19 GHz ATM wireless LAN testbed already available through NTT, and targets the development and demonstration of wireless access to broadband ISDN (B-ISDN) services through this testbed. The terminals are low-mobility and operate at 19 GHz with data rates up to 34 Mb/s. The demo is expected to be ready by the end of 1997. This projects aims to investigate super high frequency (SHF) bands due to the shortage of spectrum in the lower frequencies in Japan. The interesting observation here is that all these activities are considering WATM in some form for the wireless access.

In Japan [31] the Ministry of Post and Telecommunications (MPT) is the primary agency involved in future wideband wireless networks. Radio regulation was updated to provide 26 MHz of bandwidth in the 2.4 GHz band for low-power data communications that fits IEEE 802.11. The major problem with this band appears to be the small bandwidth of 26 MHz compared to 84 MHz available in the ISM bands in the United States. There is another 80 MHz of spectrum available for licensed local-area radio stations at 19 GHz, similar to the frequencies used by Motorola's ALTAIR product.

More recent activity in Japan in local wideband wireless networks is related to the Multimedia Mobile Access Communication (MMAC) committee, which has proposed two systems for a mobile communication infrastructure that works seamlessly with fiber optic networks. Terminals that can



■ **Figure 5.** *Spectrum allocated for unlicensed PCS [26].*

Band of operation	Maximum Tx power	Max. power with antenna gain of 6 dBi	Maximum PSD	Applications: suggested and/ or mandated	Other remarks
5.15–5.25 GHz	50 mW	200 mW	2.5 mW/MHz	Restricted to indoor applications	Antenna must be an integral part of the device
5.25–5.35 GHz	250 mW	1000 mW	12.5 mW/MHz	Campus LANs	Compatible with HIPERLAN
5.725–5.825 GHz	1000 mW	4000 mW	50 mW/MHz	Community networks	Longer range in low-interference (rural) environments

■ **Table 2.** *FCC requirements for the U-NII frequency bands.*

operate both indoors and outdoors at 6–10 Mb/s (high-speed wireless access) and those that operate only indoors without handoffs (ultra-high-speed radio LAN) systems, both operating in millimeter-wave frequencies, are being investigated by MMAC. Equipment development in system design and fundamental RF technologies and standardization are expected to be completed by 2000 with commercial services expected to start by the year 2002.

Conclusions

The recent release of the U-NII bands, the growth of the WLAN industry, and the interest of service providers in wideband wireless local access encourage further research and development in this field. However, the most challenging task for WLAN companies will remain developing new applications to expand the market. In the same way that connectionless and connection-based wired networks offer two alternatives for the wired backbone networks, WLANs and WATM offer two alternatives for wideband wireless access to the backbone. In the next few years we will witness the development of wideband access technologies under these two categories. The WLAN community will pursue alternatives for integrating itself with the evolving third-generation services by adding features to make WLANs suitable for this integration. The WATM community will pursue a revolutionary path to define a new wideband access technology that is embedded in the future ATM networks. There are significant overlaps between these activities which may lead to one unique standard that combines the two.

Acknowledgments

The authors would like to express their appreciation to TEKES and Nokia of Finland for supporting this project. We also thank Jari Vallstrom, Jaakko Talvitie, Savo Glisic, and Pentti Leppanen, our collaborators at CWC, University of Oulu, Jorma Lilleberg and Sakari Vikamaa at Nokia, and Sanjay Bagchi and Jacques Beneat of CWINS, WPI. We also appreciate reviews and comments from Allen Levesque and Brian Sylvester.

References

[1] E. Ayanoglu *et al.*, "Mobile Information Infrastructure," *Bell Labs Tech. J.*, Autumn 1996, pp. 143–63.
[2] J. McGarvey, "Crossroads: ATM or Gigabit Ethernet?" *Interactive Week*, Oct. 7, 1996.
[3] D. Gilmurray *et al.*, "Wireless ATM Service Scenarios," ATM Forum Proposal doc. ATMForum/96-1056/WATM, Baltimore, MD, Aug. 1996.
[4] R. P. Lipschutz, "ATM on the Move," *PC Mag.*, Apr. 23 ,1996.
[5] C. Fang, H. Chen, and J. Hutchins, "A Simulation Study of TCP Performance in ATM Networks," *Proc. IEEE GLOBECOM '94*, pp. 1217–23.
[6] P.Lambert, "RSVP and ATM: Shotgun Wedding at Hand," *Interactive Week*, July 21, 1997.
[7] K. Pahlavan and A. Levesque, *Wireless Information Networks*, New York: Wiley, 1995.
[8] K. Pahlavan, T. H. Probert, and M. E. Chase, "Trends in Local Wireless Networks," *IEEE Commun. Mag.*, Mar. 1995.
[9] K. Pahlavan, "Wireless Communications for Office Information Networks," *IEEE Commun. Mag.*, Sept. 1985.
[10] D. Woznicki, "Wireless LANs in Education, Health, and Finance," *2nd IEEE Wksp. Wireless LANs*, Worcester Polytech. Inst., Oct. 24–25, 1996.
[11] IEEE 802.11D3, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE Stds. Dept., Jan. 1996.
[12] ETSI TC-RES, "Radio Equipment and Systems (RES); High Performance Radio Local Area Network (HIPERLAN); Type 1; Functional Specification, Technical Correction," France, Dec. 1996.
[13] ETSI TC-RES, "Radio Equipment and Systems (RES); High Performance Radio Local Area Network (HIPERLAN); System Definition," France, July 1994.
[14] T. Wilkinson, "HIPERLAN," *2nd IEEE Wksp. Wireless LANs*, Worcester Polytech. Inst., Oct. 24–25, 1996.
[15] P. Agrawal *et al.*, "SWAN: A Mobile Multimedia Wireless Network," *IEEE Pers. Commun.*, Apr. 1996, pp. 18–33.
[16] K. Y. Eng *et al.*, "BAHAMA: A Broadband Ad-Hoc Wireless ATM Local Area Network," *Proc. IEEE ICC '95*, 1995, pp. 1216–23.
[17] D. Raychaudhuri *et al.*, "WATMNet: A Prototype Wireless ATM System for Multimedia Personal Communication," *IEEE JSAC*, vol. 15, no. 1, Jan. 1997, pp. 83–95.
[18] WAND Annual Project Rev. Rep. AC085/NMP/MR/I/035/1.0, Feb. 1996.
[19] S. N. Hulyalkar *et al.*, "Extension to the Charter, Scope and Work Plan for the WATM Working Group for Ad Hoc Network Architectures," ATM Forum proposal doc. ATMForum/96-0991, Baltimore, MD, Aug. 1996.
[20] J. Deane, "WATM Interim Mobility Protocol (WIMP) Proposal," ATM Forum proposal doc. ATMForum/96-1118, Baltimore, MD, Aug. 1996.
[21] A. Acharya *et al.*, "Primitives for Location Management and Handoff in Mobile ATM Networks," ATM Forum proposal doc. ATMForum/96-1121, Baltimore, MD, Aug. 1996.
[22] M. Barton and F. C. Liu, "Supporting PCS on an ATM Switching and Control Infrastructure," ATM Forum proposal doc. ATMForum/96-1368, Baltimore, MD, Aug. 1996.
[23] A. Acharya *et al.*, "Comparison of Location Management Schemes for Wireless ATM," ATM Forum proposal doc. ATMForum/97-0161, Feb. 1997.
[24] L. Dellaverson, "High Speed Wireless ATM," Congress ATM '96.
[25] D. G. Steer, "Coexistence and Access Etiquette in the United States Unlicensed PCS Band," *IEEE Pers. Commun.*, 4th qtr., 1994, pp. 36–43.
[26] "Notice of Proposed Rulemaking: In the Matter of Amendment of the Commission's Rules to provide for Unlicensed NII/SUPERNet Operations in the 5 GHz Frequency Range," FCC ET docket no. 96-102, FCC 96-193, May 1996.
[27] H. Hudson, "Universal Service in the Information Age," *Telecommun. Policy*, vol.18, no. 8, Nov. 1994, pp. 658–67.
[28] FCC, *Telecommunications Act of 1996*, Pub. LA. No. 104-104, 110 Stat. 56, 1996, available at http://www.fcc.gov/telecom.html.
[29] H. Aghvami, "Wireless Data in Europe," *Proc. 2nd IEEE Wksp. Wireless LANs*, Worcester Polytech. Inst., Oct. 24–25, 1996
[30] ACTS home page: http://www.infowin.org/ACTS96 (see Mobile Domain D4).
[31] Japan Ministry of Post and Telecommunications: http://www.mpt.go.jp/index-e.html; press releases, July, Oct. and Nov. 1996.
Additional information is available at http://www.cwins.wpi.edu.

Biographies

Kaveh Pahlavan [F] (kaveh@wpi.edu) is a professor of electrical and computer engineering and director of the Center for Wireless Information Networks Studies at the Worcester Polytechnic Institute (WPI), Massachusetts. His recent research has been focused on indoor radio propagation modeling and analysis of multiple access and transmission methods for wireless local networks. He is editor-in-chief and founder of the *International Journal of Wireless Information Networks*, the principal author of *Wireless Information Networks*, and has contributed to numerous technical papers and two patents. He has been program chair and organizer of IEEE conferences and workshops. Details are available at the Web site.

Ali Zahedi (azahedi@wpi.edu) is a research assistant at the Center for Wireless Information Networks Studies at WPI. His recent research has focused on performance evaluation of wireless networks, in particular integration of voice and data in TCP/IP environments. He also participated in deployment of the wireless campus testbed and development of the wireless benchmark.

Prashant Krishnamurthy (prashant@wpi.edu) is a research assistant at the Center for Wireless Information Networks Studies at WPI. His recent research has been focused on statistical indoor radio propagation modeling for signal coverage prediction and urban geolocation, and also developing tools for deployment of wireless LANs and wireless information networks.