Table 15.1: ▶
Comparison of WLAN Standards [15.23]
From R.L. Ashok and D.P. Agrawal, “Next Generation Wearable Networks,” *IEEE Computer*, November 2003, Vol. 36, No. 11, pp. 31–39.

Technology	**Wireless LAN**		
	802.11b (Wi-Fi)	**HomeRF**	**HiperLAN2**
Operational spectrum	2.4 GHz	2.4 GHz	5 GHz
Physical layer	DSSS	FHSS with FSK	OFDM with QAM
Channel access	CSMA–CA	CSMA–CA and TDMA	Central resource control/TDMA/TDD
Nominal data rate possible	22 Mbps	10 Mbps	32–54 Mbps
Coverage	100 m	>50 m	30–150 m
Power level issues	<350 mA current drain	<300 mA peak current	Uses low-power states like sleep
Interference	Present	Present	Minimal
Price/complexity	Medium (<$100)	Medium	High (>$100)
Security	Low	High	High

15.4 Wireless Metropolitan Area Networks (WMANs) using WiMAX and Mesh Networks

15.4.1 IEEE 802.16 based WiMAX

The IEEE 802.16 standard has been designed to evolve as a set of air interfaces based on a common MAC protocol but with physical layer specifications approved in 2001; it addresses frequencies from 10 to 66 GHz. A new project, currently in the balloting stage, expects to complete an amendment denoted IEEE 802.16a [15.24], also known as WiMAX. This document will extend the air interface support to lower frequencies in the 2–11 GHz band, including both licensed and license-exempt spectra. Compared to the higher frequencies, such spectra offer a less expensive opportunity to reach many more customers, although at generally lower data rates using an OFDM scheme.

MAC Layer

The IEEE 802.16 MAC protocol supports point-to-multipoint broadband wireless access. It allows very high bit rates in the range of 3.5–0 MHz in both the forward and reverse links, at the same time allowing hundreds of terminals per channel that may potentially be shared by multiple end-users. The versatile services required by these MSs include legacy TDM voice and data, IP connectivity, and packetized voice over IP (VoIP). The IEEE 802.16 MAC must therefore be able to accommodate both continuous and bursty traffic. Additionally, these services are expected to be assigned QoS in keeping with the traffic types. The IEEE 802.16 MAC provides a wide range of service types analogous to the classic ATM service categories as well as newer categories such as guaranteed frame rate (GFR) [15.25].

The IEEE 802.16 MAC protocol must also support a variety of backhaul requirements, including both ATM and packet-based protocols. Convergence sublayers are used to map the transport-layer–specific traffic to a MAC and offers features such as payload header suppression, packing, and fragmentation; the convergence sublayers and MAC work together in a form that is often more efficient than the original transport mechanism.

Issues of transport efficiency are also addressed at the interface between the MAC and the PHY layer. For example, modulation and coding schemes are specified in a burst profile that may be adjusted to each subscriber station adaptively for each burst. The MAC can make use of bandwidth-efficient burst profiles under favorable link conditions but shifts to more reliable, though less efficient, alternatives as are required to support the planned 99.999 percent link availability.

The request-grant mechanism is designed to be scalable, efficient, and self-correcting. The IEEE 802.16 access system does not loose efficiency when presented with multiple connections per terminal, multiple QoS levels per terminal, or a large number of statistically multiplexed users. It takes advantage of a wide variety of request mechanisms, balancing the stability of contentionless access with the efficiency of contention-oriented access.

Along with the fundamental task of allocating bandwidth and transporting data, the MAC includes a privacy sublayer; this provides authentication of network access, thereby avoiding theft of service and providing key exchange and encryption for data privacy. To accommodate more demanding physical environments and different service requirements of the frequencies between 2 and 11 GHz, the IEEE 802.16a project is providing a MAC to support automatic repeat request (ARQ) for mesh network architectures.

MAC Layer Details

The MAC includes service-specific convergence sublayers that interface to higher layers to carry out the key MAC functions. The privacy sublayer is located below the common part sublayer.

Service-Specific Convergence Sublayers

The IEEE 802.16 defines two general service-specific convergence sublayers for mapping services to and from the IEEE 802.16 MAC connections. The ATM convergence sublayer is defined for ATM services, and the packet convergence sublayer is defined for mapping packet services such as IPv4, IPv6, Ethernet, and virtual local area network (VLAN). The primary task of the sublayer is to classify service data units (SDUs) to the proper MAC connection, preserve QoS, and enable bandwidth allocation. The mapping takes various forms depending on the type of service. In addition to these basic functions, the convergence sublayers can also perform more sophisticated functions such as payload header suppression and reconstruction to enhance airlink efficiency.

Common Part Sublayer

Introduction and General Architecture: The IEEE 802.16 MAC is designed to support a point-to-multipoint architecture with a central BS handling multiple independent sectors simultaneously. On the downlink (DL) (forward channel), data to the subscriber stations (SSs—essentially the MSs) are multiplexed in TDM fashion. The uplink (UL) (reverse channel) is shared between SSs in TDMA fashion.

The IEEE 802.16 MAC is connection oriented. All services, including inherently connectionless services, are mapped to a connection. This provides a mechanism for requesting bandwidth, associating QoS and traffic parameters, transporting and routing data to the appropriate convergence sublayer, and all other actions associated with the contractual terms of the service. Connections are referenced with 16-bit connection identifiers (CIDs) and may require continuous availability of bandwidth or bandwidth on demand.

Each SS has a standard 48-bit MAC address, but this serves mainly as an equipment identifier, since the primary addresses used during operation are the CIDs. Upon entering the network, the SS is assigned three management connections in each direction. These three connections reflect the three different QoS requirements used by different management levels. The first of these is the basic connection, which is used for the transfer of short, time-critical MAC and radio link control (RLC) messages. The primary management connection is used to transfer longer, more delay-tolerant messages such as those used for authentication and connection setup. The secondary management connection is used for the transfer of standard-based management messages such as dynamic host configuration protocol (DHCP), trivial file transfer protocol (TFTP), and simple network management protocol (SNMP).

The MAC reserves several connections for other purposes. One connection is reserved for contention-based initial access. Another is reserved for broadcast transmissions in the forward channel as well as for signaling broadcast contention-based polling of SS bandwidth needs. Additional connections are reserved for multicast, rather than broadcast, contention-based polling. SSs may be instructed to join multicast polling groups associated with these multicast polling connections.

MAC PDU Formats: The MAC PDU (protocol data unit) is the data unit exchanged between the MAC layers of the BS and its SSs. A MAC PDU consists of a fixed-length MAC header, a variable-length payload, and an optional cyclic redundancy check (CRC). Two header formats, distinguished by the HT field, are defined: the generic header (see Figure 15.7) and the bandwidth request header. Except for bandwidth containing no payload, MAC PDUs have either MAC management messages or convergence sublayer data.

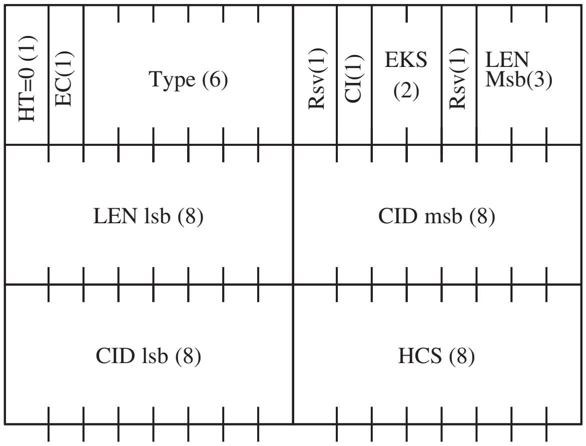

Figure 15.7 Generic header for MAC PDU.

Three types of MAC subheader may be present. A grant management subheader is used by the SS to convey bandwidth management needs to its BS. A fragmentation subheader indicates the presence and orientation within the payload of any fragments of the SDUs. The packing subheader is used to indicate packing of multiple SDUs into a single PDU. The generic header follows a grant management, and fragmentation subheaders may be inserted into MAC PDUs. The packing subheader may be inserted before each MAC SDU if shown by the type field.

Transmission of MAC PDUs: The IEEE 802.16 MAC supports various higher-layer protocols such as ATM or IP. Incoming MAC SDUs from corresponding convergence sublayers are formatted according to the MAC PDU format, possibly with fragmentation and/or packing, before being conveyed over one or more connections in accordance with the MAC protocol. After traversing the airlink, MAC PDUs are reconstructed back into the original MAC SDUs so that the format modifications performed by the MAC layer protocol are transparent to the receiving entity.

IEEE 802.16 takes advantage of packing and fragmentation processes, and their effectiveness, flexibility, and efficiency are maximized by appropriate bandwidth allocation. Fragmentation is the process by which a MAC SDU is divided into one or more MAC SDU fragments. Packing is the process by which multiple MAC SDUs are packed into a single MAC PDU payload. Both processes may be initiated by either a BS for a DL or for a SS for an UL connection. IEEE 802.16 allows simultaneous fragmentation and packing for efficient use of the bandwidth.

PHY Support and Frame Structure: The IEEE 802.16 MAC supports both TDD and FDD. In FDD, both continuous and burst DLs are possible. Continuous DLs allow for certain robustness enhancement techniques, such as interleaving. Burst DLs (either FDD or TDD) allow the use of more advanced robustness and capacity enhancement techniques, such as subscriber-level adaptive burst profiling and advanced antenna systems.

The MAC builds the DL subframe starting with a frame control section containing the DL-MAP (downlink MAP) and UL-MAP (uplink map) messages. These indicate PHY transitions on the DL as well as bandwidth allocations and burst profiles on the UP. The DL-MAP is always applicable to the current frame and is always at least two FEC blocks long. To allow adequate processing time, the first PHY transition is expressed in the first FEC block. In both TDD and FDD systems, the UL-MAP provides allocations starting no later than the next DL frame. The UL-MAP can, however, start allocating in the current frame, as long as processing times and round-trip delays are observed.

Radio Link Control: The advanced technology of the IEEE 802.16 PHY requires equally advanced RLC, particularly a capability of the PHY to change from one burst profile to another. The RLC must control this capability as well as the traditional RLC functions of power control and ranging. RLC begins with periodic BS broadcast of the burst profiles that have been chosen for the UL and DL. Among the several burst profiles used on a channel, one in particular is chosen based on a number of factors, such as rain region and equipment capabilities. Burst profiles for the DL are each tagged with a DL interval usage code (DIUC), and those for the UL are tagged with an UL interval usage code (UIUC).

During initial access, the SS performs initial power leveling and ranging using ranging request (RNG-REQ) messages transmitted in initial maintenance windows. The adjustments to the SS's transmit time advance, as well as power adjustments, and are returned to the SS in ranging response (RNG-RSP) messages. For ongoing ranging and power adjustments, the BS may transmit unsolicited RNG-RSP messages instructing the SS to adjust its power or timing. During initial ranging, the SS can also request service in the DL via a particular burst profile by transmitting its choice of DIUC to the BS. The selection is based on received DL signal-quality measurements performed by the SS before and during initial ranging. The BS may confirm or reject the choice in the ranging response. Similarly, the BS monitors the quality of the UL signal it receives from the SS. The BS commands the SS to use a particular UL burst profile simply by including the appropriate burst profile UIUC with the SS's grants in UL-MAP messages.

After initial determination of UL and DL burst profiles between the BS and a particular SS, RLC continues to monitor and control the burst profiles. Harsher environmental conditions, such as rain fades, can force the SS to request a more robust burst profile. Alternatively, exceptionally good weather may allow an SS to temporarily operate with a more efficient burst profile. The RLC continues to adapt the SS's current UL and DL burst profiles, ever striving to achieve a balance between robustness and efficiency. Because the BS is in control and directly monitors the UL signal quality, the protocol for changing the UL burst profile for an SS is simple: the BS merely specifies the profile's associated UIUC whenever granting the SS bandwidth in a frame. This eliminates the need for an acknowledgment, since the SS will always receive either both the UIUC and the grant or neither. Hence, there exists no chance of UL burst profile mismatch between the BS and the SS.

In the DL, the SS is the entity that monitors the quality of the receive signal and therefore knows when its DL burst profile should change. The BS, however, is the entity in control of the change. There are two methods available to the SS to request a change in DL burst profile, depending on whether the SS operates in the grant per connection (GPC) or grant per SS (GPSS) mode. The first method would typically apply (based on the discretion of the BS scheduling algorithm) only to GPC SSs. In this case, the BS may periodically allocate a station maintenance interval to the SS. The SS can use the RNG-REQ message to request a change in DL burst profile. The preferred method is for the SS to transmit a DL burst profile change request (DBPC-REQ). In this case, which is always an option for GPSS SSs and can be an option for GPC SSs, the BS responds with a DL burst profile change response (DBPC-RSP) message confirming or denying the change.

Because messages may be lost due to irrecoverable bit errors, the protocols for changing SS's DL burst profile must be carefully structured. The order of the burst profile change actions is different when transitioning to a more robust burst profile than when transitioning to a less robust one. The standard takes advantage of the fact that any SS is always required to listen to more robust portions of the DL as well as the profile that has been negotiated.

Channel Acquisition: The MAC protocol includes an initialization procedure designed to eliminate the need for manual configuration. Upon installation, SS begins scanning its frequency list to find an operating channel. It may be programmed to register with one specific BS, referring to a programmable BS ID broadcast by each. This feature is useful in dense deployments where the SS might hear a secondary BS due to selective fading or when the SS picks up a side-lobe of a nearby BS antenna.

After deciding on which channel or channel pair to start communicating, the SS tries to synchronize to the DL transmission by detecting the periodic frame preambles. Once the physical layer is synchronized, the SS looks for periodic DCD (DL channel descriptor) and UCD (UL channel descriptor) broadcast messages that enable the SS to learn the modulation and FEC schemes used on the carrier.

IP Connectivity: After registration, the SS acquires an IP address via the DHCP and establishes the time of day via the Internet time protocol. The DHCP server also provides the address of the TFTP server from which the SS can request a configuration file. This file provides a standard interface for providing vendor-specific configuration information.

Physical Layer

From C. Eklund, R. B. Marks, K. L. Stanwood, and S. Wang, "IEEE Standard 802.16: A Technical Overview of the WirelessMANT Air Interface for Broadband Wireless Access," *IEEE Communications Magazine*, June 2002.

10–66 GHz: For the deployment of single-carrier modulation in the air interface "WirelessMAN-SC" (WMAN–SC), a precondition is that line-of-sight (LOS) conditions should exist. This is provided in the design of the PHY specification for 10–66 GHz. The point-to-point communication is enabled through a TDM scheme whereby a BS transmits the signal sequentially to each MS in its allocated slot. Access in the UL direction is by TDMA.The burst design selected allows coexistence of both TDD and FDD forms of communication. In the TDD scheme, both the UL and DL are possible over the same channel but not at the same time.

In FDD, the uplink and downlink occur over separate channels and could occur together. At the cost of increasing hardware complexity, half-duplex FDD support was added, and this resulted in making the technology cheaper by a small margin. In order that modulation and coding can be programmed dynamically, both TDD and FDD alternatives support adaptive burst profiles.

2–11 GHz: The standards for both licensed and license-exempt in the 2–11 GHz bands are being formulated, and the final draft has not yet been completed [15.25]. IEEE project 802.16a addresses these issues, and three air interfaces are defined in Table 15.2. One of these has to be implemented by each system compliant with 802.16a. All the three interfaces can provide interoperability. It is envisaged that outdoor application, especially in urban areas could involve non–light-of-sight (NLOS) links between a BS and the user. Owing to the expected multipath propagation, the design of the 2–11 GHz physical layer is driven by the need for NLOS. The hardware expense and installation costs involved in outdoor-mounted antennas are other factors that need further consideration.

Table 15.2: ▶
Three 2–11 GHz Air Interfaces of the IEEE 802.16a Draft 3 Specifications

Air Interface	Specification
WMAN–SC2	A single-carrier modulation is used.
WMAN–OFDM	License-exempt bands necessarily use this TDMA access interface. OFDM is present with a 256-point transform.
WMAN–OFDMA	Each receiver is assigned a set of multiple carriers to enable multiple access. OFDM is present with a 2048-point transform.

It is important to note that the IEEE 802.16a amendment has not yet been completed and hence could exhibit significant changes. The propagation requirements necessitate the use of advanced antenna systems. Notwithstanding the reasonably stable draft that has been achieved, modes could be added or deleted; hence, the specifications could be changed through the ballot.

Physical Layer Details

In the PHY specification, burst single-carrier modulation with adaptive burst profiling is used for the 10–66 GHz frequency band. The channel bandwidths are 20, 25 MHz (typical U.S. allocation) or 28 MHz (typical European allocation). The systems use Nyquist square-root raised cosine pulse shaping with a roll-off factor of 0.25. By using this adaptive burst profiling, each SS may adjust the transmission parameters such as the modulation and coding schemes, individually frame by frame. Both the TDD variant and the burst FDD variant are defined in this specification.

The data bits are randomized to minimize the possibility of transmission of an unmodulated carrier and to ensure adequate numbers of bit transitions to support clock recovery. The data is also FEC coded using Reed-Solomon GF (256), which allows variable block size and has appropriate error correction capabilities. An inner block convolutional code is used to robustly transmit critical data such as frame control and initial accesses. The FEC coded data is mapped to a QPSK, 16-state QAM (16-Quadrature Amplitude Modulation) or 64-state QAM (64-Quadrature Amplitude Modulation) to form burst profiles with varying robustness and efficiency. The block may be shortened if the last FEC block is not filled.

The frame size can be 0.5, 1, or 2 ms. There are UL subframes and DL subframes in each frame. A frame is divided into physical slots, and the physical slot is the unit for bandwidth allocation and identification of PHY transitions. A physical slot has 4QAM symbols. For the TDD variant and the FDD variant, different framings are defined. In the TDD variant, a frame starts with a DL subframe followed by a UL subframe. In the FDD variant, UL and DL are using different frequencies. The BS controls the UL and DL in the UL-MAP and DL-MAP. In the DL-MAP, the first part is a frame control section which contains control information for all SSs. Following the frame control section is the TDM portion. A negotiated burst profile is used to provide synchronization with the DL. For the FDD variant, a TDMA segment is used to transmit data to half-duplex SSs. This permits some SSs to transmit data earlier than they were scheduled. The synchronization with the DL may get lost because of the half-duplex nature. However, the TDMA preamble provides a way to get synchronization back. Because the bandwidth requirements may vary from time to time, the mixture and duration of burst profiles and the presence or absence of the TDMA portion may vary from frame to frame. The recipient SS is included in the MAC headers not in the DL-MAP; therefore, all of the DL subframes are listened to by all SSs for the potential reception. For full-duplex SSs, this means they receive all burst profiles of equal or greater robustness than they would have by negotiating with the BS. Unlike the DL, specific SSs are granted bandwidth by UL-MAP. Now the SSs start transmitting, using the burst profile specified by the UL interval usage code (UIUC) in UL-MAP entry, in their assigned allocations, thus granting them bandwidth. Contention-based allocations are also provided in the UL subframe for initial system access and broadcast or multicast bandwidth requests. Properly sized access opportunities for initial system access are allowed extra guard time for these SSs, which have not yet been resolved with the transmit time advances necessary to offset the round-trip delay to the BS.

The transmission convergence (TC) sublayer resides between the PHY and MAC layers. This layer delivers the transformation of variable length MAC PDUs into the fixed-length FEC blocks (with possibly a shortened block at the end) of each burst. A sized PDU contained in the TC layer fits in the FEC block currently being filled. As shown in Figure 15.8, the pointer indicates to the next MAC PDU header that starts within the FEC block. The TC PDU format allows resynchronization to the next MAC PDU in the event that the previous FEC block had irrecoverable errors. In the absence of the TC layer, a receiving SS or BS would potentially lose the entire remainder of a burst with the occurrence of an irrecoverable bit error.

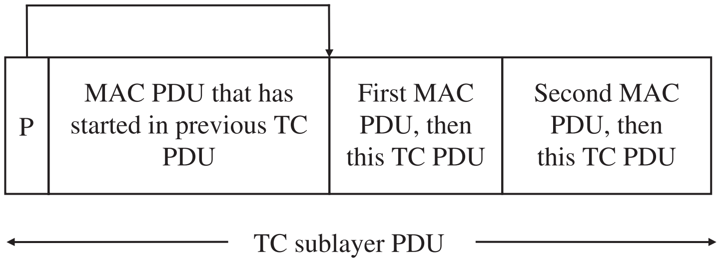

Figure 15.8
TC PDU format.

WMAN has been envisioned to be a data network that covers an entire city. Network access is provided by WMAN to buildings through exterior antennas, communicating with central radio BSs (base stations). It further offers an option to cabled access networks, such as fiber-optic links, coaxial systems using cable modems, and DSL links. The nomadic access is explicitly handled by its fundamental design. The Ricochet [15.5] network can be thought of as the only pure WMAN commercial service. The air interfaces for WMANs, WirelessMAN IEEE 802.16, were published on April 8, 2002 [15.24]. In the following two sections we will look at these two technologies in more detail.

15.5 Mesh Networks

Over the past few years wireless mesh networks (WMNs) have steadily emerged as a feasible and economical method for provisioning broadband wireless internet service to users. WMNs are capable of providing attractive services in a wide range of application scenarios, such as broadband home/enterprise/community networking and disaster management. Some key advantages of WMNs include their self-organizing ability, self-healing capability, low-cost infrastructure, rapid deployment, scalability, and ease of installation. The mesh-networking technology attracted both academia and industry, stirring efforts for their real-world deployment in a variety of applications. Improvements in processor capacity, wireless standards developments, carrier deployments, and growing competition amongst the technology vendors are driving the rapid adoption of wireless mesh technology into various application scenarios.

WMNs, illustrated in Figure 15.9 [15.26], consist of internet gateways (IGWs), mesh routers (MRs), and mesh clients (MCs). MRs seamlessly extend the network connectivity to mesh clients (MCs) as end users by forming a wireless backbone of MRs and IGWs that requires minimal infrastructure. This multihop backbone network of MRs could use 802.11-based access points or WiMAX routers or a combination of them and is responsible for providing services to the MCs by transporting traffic either to or from IGWs by cooperatively relaying each other's traffic and facilitating interconnectivity.

WMNs usually operate in the unlicensed ISM bands, and this leads to several issues. Due to the unpredictable nature of the unlicensed spectrum, wireless