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| Abstract | Within the Institute of Electrical and Electronics Engineers, Inc. (IEEE), the IEEE 802 LAN MAN Standards Committee is developing air interface standards for wireless local area network (LAN), wireless metropolitan area network (MAN), and wireless personal area network (PAN) technology. These standards are enabling the development of an infrastructure for the Wireless Internet.<br>This article was published as "Standards from IEEE 802 Unleash the Wireless Internet, Roger B. Marks, Ian C. Gifford, and Bob O'Hara, *IEEE Microwave Magazine* 2, pp. 46-56, June 2001."<br><http://ieeexplore.ieee.org/iel5/6668/20011/00924918.pdf> |
| Purpose | This document may improve the effectiveness of standards developers by aiding their understanding of the wireless projects in the IEEE 802 LAN MAN Standards Committee. |
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Standards in IEEE 802 Unleash the

# Wireless Internet

**Roger B. Marks, Ian C. Gifford, Bob O'Hara**



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Within the Institute of Electrical and Electronics Engineers, Inc. (IEEE), the IEEE 802 LAN MAN Standards Committee is developing air interface standards for wireless local area network (LAN), wireless metropolitan area network (MAN), and wireless personal area network (PAN) technology. These standards are enabling the development of an infrastructure for the wireless Internet.

## Standards for the Convergence of Internet and Wireless Communications Technologies

The Internet and wireless communications networks revolutionized communications in the 1990s. The convergence of these two technologies leads naturally to the wireless Internet. Just as standards determined the development of the Internet and of wireless cellular telephony, so will standards influence the evolution of the wireless Internet as a social phenomenon. Both the cellular telephony industry and the Internet communications industry bring their own models for standardization, and the two offer contrasting visions. For low-level network issues, the Internet-based standardization model is currently centered in the IEEE and its IEEE 802 LAN MAN Standards Committee, the world leader in LAN and MAN standards. IEEE 802 is currently developing and enhancing standards for wireless LANs, PANs, and MANs.

The wireless Internet model based on cellular telephony is embodied in the International Mobile Telecommunications 2000 (IMT-2000) family of standards for third-generation wireless communications, published by the International Telecommunication Union Radiocommunication Sector (ITU-R). This set of standards foresees an evolution from circuit-switched mobile voice services to packet-switched mobile voice and data. The infrastructure is to be based on cellular basestations serving highly mobile users (at automotive speeds) at 144 kb/s, with the capability to also serve fixed users at rates up to 2 Mb/s. The standards were developed at a technical level by national or regional standards bodies so that, when world-wide standards were forged by the ITU-R, the voting members (national governments) were centrally involved in the negotiations. As a result, the standards debates became highly politicized events often publicized as "wars." The world now eagerly anticipates the economic success of this technology. For example, license auctions in Europe have garnered thousands of euros per resident. By the time these costly systems are engineered, constructed, and marketed, investors will have paid dearly and will be expecting a heavy return.

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In a contrast of broad proportions, IEEE 802 is developing an alternative series of wireless Internet standards. IEEE's global standardization effort involves no national bodies and therefore no national politics; the work proceeds on a technical and business basis. To a large degree, the intent is to bring to market low-cost products that serve customer needs. Much of the work involves license-exempt spectrum. This removes the spectrum acquisition costs from the economic picture. Furthermore, it weakens the concept of a monolithic "operator" with strong control over the provided services. Instead, it opens up the market to enterprise and innovation. IEEE 802 wireless Internet technologies offer data rates much higher than those provided by even the fixed user case in IMT-2000; for example, the currently popular IEEE 802.11b standard supports 11 Mb/s. The IEEE standards do not offer the mobility of IMT-2000 in the sense of providing services to moving vehicles, and they are not aimed at providing blanket coverage to users at arbitrary locations within a city. Instead:

**If IEEE 802 maintains its record of success in ushering technology into the economy and into society, then IEEE 802.16 will be the tool to make fixed broadband wireless access a mainstream application**

- IEEE 802.16 wireless MAN standards will support high-rate broadband-wireless-access services to buildings, mostly through rooftop antennas, from central basestations.
- IEEE 802.11 wireless LAN standards support users roaming within homes, office buildings, campuses, hotels, airports, restaurants, cafes, etc.
- IEEE 802.15 wireless PAN standards will support short-range links among computers, mobile telephones, peripherals, and other consumer electronics devices that are worn or carried.

## Standardization in IEEE 802

### IEEE Standards Association

The IEEE is a nonprofit transnational technical professional organization with over 350,000 members. IEEE supports many technical activities, including conferences, publications, and local activities. In addition, IEEE carries out an active program in standardization through the IEEE Standards Association (IEEE-SA). While many IEEE-SA activities are global in scope, its efforts are accredited by the American National Standards Institute (ANSI). ANSI oversight ensures that its guiding principles of consensus, due process, and openness are followed.

IEEE-SA standards are openly developed with consensus in mind. Participation in their development, and use is entirely voluntary. However, history has shown that standards developed in an open forum can produce high-quality, broadly accepted results that can focus companies and forge industries.

The IEEE-SA oversees the standardization process through the IEEE-SA Standards Board. Project development is delegated to individual standard sponsors that are generally units of the IEEE's technical societies. One of the most important of the IEEE-SA sponsor groups is the IEEE 802 LAN MAN Standards Committee.

### *IEEE 802 LAN MAN Standards Committee*

The IEEE 802 LAN MAN Standards Committee is sponsored by the IEEE Computer Society. It first met in 1980 to develop a LAN standard that evolved into separate technologies. It develops and maintains standards at the physical layer (PHY) and medium access control sublayer (MAC), each of which fits under a common logical link control sublayer (LLC) [1]. Together, these make up the two lowest layers of the Open Systems Interconnection (OSI) seven-layer model for data networks. The seven-layer model is a standard of the International Standards Organization (ISO).

IEEE 802 holds week-long plenary meetings three times a year under the leadership of a Sponsor Executive Committee (SEC), chaired since 1996 by Jim Carlo. In between these plenaries, most of its active Working Groups hold interim meetings.

Historically, 802 has been best known for the IEEE 802.3 standard, informally known as Ethernet, which is a tremendous world-wide success. Ethernet is the foundation of so many of the world's LANs that, for most practical purposes, LAN simply means a connection of Ethernet devices. Like all successful 802 standards, however, IEEE 802.3 continuously evolves, moving from shared coaxial media to twisted pair with the 10BaseT standard and raising the supported data rates with 100BaseT and 1000BaseT. Optical media are also supported, and 802.3 is currently developing a 10 Gb/s standard. IEEE 802's portfolio of active projects in the cabled realm grew in late 2000 with the approval of the 802.17 Working Group on Resilient Packet Rings.

While Ethernet has been its greatest success, 802 is now the home of a number of wireless network standardization projects that take advantage of the highly successful system of standards development it pioneered. Before continuing with detailed discussion of the IEEE 802 Wireless Standards Program, it will be useful to overview this process.

### *IEEE 802 Standardization Process*

IEEE 802 process is designed for quick development of standards with broad consensus. The demand for consensus helps to ensure that standards are technically superior and meet market needs.

The development process in IEEE 802 follows the chronological steps outlined below. The process is overseen by 802's SEC and defined by a set of rules and procedures [2]. In brief:

- A study group is chartered to study the prospects for a standard in a field and potentially to develop a project authorization request (PAR) requesting IEEE-SA approval of a new project. The SEC also requires that each PAR be accompanied by a statement addressing 802's "Five Criteria for Standards Development," demonstrating that the intended standard has broad market potential, compatibility with other 802 standards, distinct identity within 802, technical feasibility, and economic feasibility.
- The SEC assigns each approved project to an existing or new working group. Technical decisions are made by the working group by vote of at least 75% of its members. Working group membership belongs to individuals, not to companies or other entities, and is awarded on the basis of participation at meetings. Nonmembers participate actively as well.
- The initial draft development method varies among groups, but the typical process is to delegate the problem to a subordinate task group and issue a public call for contributions for documented input. Eventually a baseline draft is selected and then developed.
- Before the SEC will advance the draft, it must be approved in a working group letter ballot in which the members are asked to approve the document. Any vote against the document must be accompanied by specific comments on what changes are required in order that the voter will approve it. This process forces constructive suggestions and helps drive the process to quick improvement after a few cycles. Members voting to approve, and nonmembers as well, are also solicited for comments. An approval rate of 75% is required to pass. However, changes made in response to comments, and negative comments that have not been accepted by the comment resolution team, must be recirculated for review by the voters. In effect, the ballot cannot close until those voting negative have had their say and failed to attract other voters to their argument. The approval margin is typically much higher than 75% at closure.
- The working group's final task is to see the draft standard through "sponsor ballot," in which it is put before a broad group of interested individuals. This is similar to a rerun of the working group letter ballot except that the ballot group is not restricted to members of the working group. IEEE requires a balanced ballot group, which ensures that is it not dominated by producer or user interests. In addition to the vote, critical comments are, of course vital to the success of the process. It is of-

ten said that, in 802, the purpose of balloting is not to approve the draft but to improve it.

Experience has shown that the IEEE 802 process is extremely effective at engaging a wide array of interested parties, fostering comments, and making constructive changes. As a result, 802 drafts are in a continual state of improvement. When a standard finally makes it through the system, users have solid confidence in it. With careful attention and the will of the developers, it is possible to drive the draft through the system within a reasonable time.

## IEEE 802 Wireless Standards Program

The IEEE 802 Wireless Standards Program comprises three working groups:

- IEEE 802.11 working group develops the IEEE 802.11 standards for wireless LANs
- IEEE 802.15 working group develops the IEEE 802.15 standards for wireless PANs
- IEEE 802.16 working group on broadband wireless access develops the IEEE 802.16 standards for wireless MANs.

These groups work in a loose association to coordinate their activities. IEEE 802.11 and 802.15 have worked particularly closely since they both address unlicensed bands. 802.16 has historically dealt with licensed bands and been more independent. However, a new license-exempt project in 802.16 now requires it to coordinate more closely with the other two working groups. Some of this coordination takes place through the IEEE 802 regulatory ombudsman, who oversees interactions with regulatory activities that affect any or all of the working groups.

The following sections summarize the status and technology of the projects in the IEEE 802 wireless standards program.

### *Wireless LANs*

The IEEE 802.11 working group for wireless LAN standards was the first wireless effort in IEEE 802. As with other standards in the 802 family, 802.11 describes a MAC sublayer and multiple PHYs. For the first time in an 802 standard, 802.11 also describes MAC management functionality.

The initial base standard, published in 1997, describes the requirements for a LAN implementation using both infrared and spread spectrum radio frequency (RF) communications designed in accordance with rules for unlicensed operation. Since then, the base standard has been revised (as 802.11-1999), and the working group has published two additional PHY amendments (802.11a and 802.11b). The existing standard and its amendments describe several WLAN PHYs:

- Infrared at 1 and, optionally, 2 Mb/s
- Frequency hopping spread spectrum radio at 1 and, optionally, 2 Mb/s in the 2.4 GHz band
- Direct sequence spread spectrum radios with data rates up to 11 Mb/s in the 2.4 GHz band
- Orthogonal frequency division multiplexing radios in the 5-6 GHz band.

Current work includes extending the MAC and MAC-management functionality to provide expanded international operation and roaming, improved support for quality of service, enhanced security, dynamic channel selection, transmit power control, and standardized communication between 802.11 access points. Work is also proceeding to increase the data rate of one of the existing PHYs.

**Wireless MAN standards will support high-rate broadband-wireless-access services to buildings, mostly through rooftop antennas, from central basestations**

#### Medium Access Control

The 802.11 standard [3] describes two types of wireless LANs, an ad hoc network (an independent basic service set (BSS)) and an infrastructure network (comprised of infrastructure BSSs of one access point and the associated mobile stations). An ad hoc wireless LAN consists only of mobile stations. This type of wireless LAN is often set up for a very specific purpose, such as exchanging files during a single meeting, and its lifetime is usually limited. The infrastructure BSS, on the other hand, is typically a long-lived wireless LAN that integrates mobile stations into a large network infrastructure through the use of access points (AP) that perform a bridging function between wired and wireless LANs. The MAC and MAC-management functions allow the mobile stations to find other mobile stations and APs, register with the wireless LAN, request encryption and power management services from the wireless LAN, and exchange data with other mobile stations and APs. The MAC and MAC-management functions operate over any and all of the PHYs.

The 802.11 MAC incorporates mechanisms to increase the reliability of exchanging information in the wireless medium. The basic access mechanism of 802.11 (distributed coordination function (DCF)) is carrier sense multiple access with collision avoidance (CSMA/CA). The DCF may be used in either the ad hoc or infrastructure wireless LANs. The DCF is quite similar to the CSMA with collision detection (CSMA/CD) used in IEEE 802.3 Ethernet. CSMA/CA works by sensing the medium for activity before every transmission and deferring the transmission if the medium is active. As in 802.3, 802.11 uses a binary exponential backoff mechanism to spread transmission opportunities in time and minimize the likelihood of subsequent collisions.

## Web Sites

**IEEE-SA**
http://standards.ieee.org

**IEEE 802 LAN MAN Standards Committee**
http://ieee802.org

**IEEE 802.11 Working Group**
http://ieee802.org/11

**IEEE 802.15 Working Group**
http://ieee802.org/15

**IEEE 802.16 Working Group**
http://WirelessMAN.org

**Regulatory Ombudsman**
http://ieee802.org/Regulatory

**N-WEST**
http://nwest.nist.gov

Because simultaneous transmission and reception on the same channel is more difficult using radio than using a wired medium, 802.11 uses a collision avoidance mechanism rather than physical collision detection. Every frame transmitted by 802.11 is part of a frame exchange sequence that includes an acknowledgement from the destination. Each frame includes information on the duration remaining in the sequence of frames being exchanged. Every station processes this duration information and maintains a network allocation vector (NAV) indicating how much longer the medium will be occupied by the frame exchange. The NAV is used to reduce the problem caused by "hidden nodes," in which a station receives only one side of the frame exchange; the potential for this problem makes physical carrier sense an unreliable means of detecting activity on the medium. Thus, a station senses the medium using both its physical carrier sense and a virtual carrier sense derived from the NAV. If either of these indicate that the medium is in use, a station's transmission is deferred.

In an infrastructure wireless LAN, the 802.11 standard provides an optional access mechanism, called the point coordination function (PCF), where the AP acts as a central coordinator for the wireless LAN, scheduling nearly all of the transmissions. The PCF offers a significant boost in efficiency since almost all collisions are eliminated. Of course, this efficiency comes at an increased cost due to the higher complexity of the AP and its required scheduling algorithms. Based upon this PCF, the 802.11e task group is proceeding to build improved support for quality of service. This work is in the very early stages of development. The resulting 802.11e amendment may be available by early 2002.

### PHY: Spread Spectrum, OFDM, and Infrared

The 2.4 GHz PHYs of the current standard describe the requirements for operating in a limited number of areas of the world: the United States, Canada, Europe (within the domain of the European Telecommunications Standards Institute (ETSI)), France, Spain, and Japan. In no other locations can a device that implements the 802.11 standard using these PHYs be called compliant with 802.11. The 802.11d task group has addressed this shortcoming of the standard by describing a protocol that will allow an 802.11 device to receive the regulatory information required to configure itself properly to operate anywhere on planet Earth. The manufacturer is still obligated to obtain any required certifications before allowing its equipment to operate in locations requiring certification. In the winter of 2001, 802.11d was in sponsor ballot, with approval as an amendment to the 802.11 standard expected in the spring of 2001.

Because a wireless medium offers even less protection from eavesdropping than a wired medium, 802.11 incorporates encryption into the MAC. Called the wired equivalent privacy (WEP) mechanism, this encryption function is intended to prevent "casual eavesdropping." It is not a guaranteed privacy mechanism but is intended to provide only basic protection to the information transmitted over the air. The 802.11e task group is working to improve this capability significantly. The capability envisioned by 802.11e will provide a simple upgrade path, based on the current WEP, to offer better security for current implementations. It will also offer a new encryption function based on the recently selected Advanced Encryption System (AES), the result of a years-long selection process by the U.S. Department of Commerce. The work of 802.11e is in the very early stages of development and could be completed late in 2001.

Of the three initial PHYs in the 802.11 standard, the infrared (IR) has seen the least use. This PHY uses baseband pulse position to transmit data at 1 and, optionally, 2 Mb/s. It provides the greatest physical security of the 802.11 PHYs, since most walls and windows block IR radiation. For the same reason, the number of APs required to provide wireless LAN coverage for a given area is often significantly greater than that required for the radio PHYs. This is the likely reason that the IR PHY has been used so infrequently.

The frequency hopping (FH) PHY also provides data rates of 1 and, optionally, 2 Mb/s. At the time of development, this PHY was suitable for operation under the U.S. FH spread spectrum rules for the 2.4 GHz band designated for industry, scientific, and medical (ISM) applications; it remains usable under the rules as liberalized in 2000 to allow wideband FH spread spectrum systems. The 802.11 FH PHY provides 79 channels with a channel bandwidth of 1 MHz. For 1 Mb/s, the modulation used is two-level Gaussian frequency shift keying (GFSK) with a nominal bandwidth bit period of 0.5. Minimum transmit power is 10 mW, although transmit power may be as high as 1 W. The receiver sensitivity is -80 dBm. For 2 Mb/s, the modulation used is four-level GFSK.

The direct sequence (DS) PHY, as extended in the 802.11b amendment, provides data rates of 1, 2, 5.5, and 11 Mb/s. In the United States, this PHY operates under the DS spread spectrum rules for the 2.4 GHz ISM band. The standard provides for 14 overlapping channels of 22 MHz between 2.4 and 2.5 GHz. Not all channels are usable in all regulatory areas; e.g., only channels 1 through 11 may be used in the United States. Channel centers are spaced 5 MHz apart. The 1 and 2 Mb/s data rates use a fixed 11-chip Barker sequence to meet the minimum spreading requirements of the U.S. regulations. The modulation used for these rates is differential binary phase shift keying (DBPSK) and differential quadrature phase shift keying (DQPSK), respectively. The 5.5 and 11 Mb/s data rates use complementary code keying (CCK) as the spreading mechanism. With CCK, a data symbol is created from 8 data bits that select one quaternary (4-level) code from a universe of $2^{16}$ possible codes. This provides some coding gain, although whether it meets the letter of the DS spread spectrum rules of the regulations is arguable. However, it does pass the regulatory test to determine the minimum coding gain. The work currently proceeding in the 802.11g task group is to increase the data rates for the DS PHY beyond 20 Mb/s. This task group is working cooperatively with the Office of Engineering Technology (OET) at the U.S. Federal Communications Commission (FCC) to identify potential rule changes for this band that can increase its utility.

The orthogonal frequency division multiplexing (OFDM) PHY, described in 802.11a, is defined to operate only in the 5-6 GHz Unlicensed National Information Infrastructure (U-NII) bands in the United States. This band offers three subbands of 100 MHz each, at 5.15-5.25, 5.25-5.35, and 5.725-5.825 GHz. Some of these bands are available in Europe, with similar regulatory requirements, though the standard does not define operation outside of the United States. The OFDM PHY provides eight data rates: 6, 9, 12, 18, 24, 36, 48, and 54 Mb/s. It uses binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-QAM (quadrature amplitude modulation), and 64-QAM modulation schemes coupled with forward error correction coding of rates 1/2, 2/3, and 3/4. The OFDM symbol has a period of 4 μs. It uses 48 data subcarriers and 4 pilot subcarriers. The data subcarriers are all modulated using the same modulation scheme; the pilot subcarriers are always modulated using BPSK. Products based on the 802.11a standard are not yet commercially available but are expected in 2001.

An 802.11 study group is currently investigating an extension of 802.11a in order to achieve compliance with ETSI regulations for the corresponding frequency bands in Europe. There is significant industry support to harmonize 802.11a with a similar ETSI standard (HIPERLAN/2) so that the market for high-speed wireless LANs is not fragmented in those bands. The study group is investigating means to allow the two standards to coexist in the same band as well as means to merge the best of both 802.11 and HIPERLAN/2 into a single new standard. This work is in its early stages, and its outcome is uncertain.

### *Wireless PANs*

The IEEE 802.15 working group for wireless PANs develops standards to link pervasive computing devices that may be portable or mobile and could be worn or carried by individuals. Communication with nearby static devices is also included. The work is exclusively in unlicensed bands (primarily at 2.4 GHz), with ranges up to 10 meters and data rates from the kb/s range to beyond 20 Mb/s. Low power consumption, small size (less than 10 ml), and low cost relative to target devices are primary considerations. The goal is to develop interoperability standards that have broad market applicability and offer coexistence with wireless LANs.

**Wireless LAN standards support users roaming through homes, office buildings, campuses, hotels, airports, restaurants, cafes, etc.**

The group has four authorized projects underway:

- Task Group 1 is developing a standard derived from Bluetooth Specification Version 1.1.
- Task Group 2 is developing a recommended practice for coexistence of wireless LAN and wireless PAN devices.
- Task Group 3 is developing a high-rate wireless PAN standard supporting at least 20 Mb/s for applications such as digital imaging and multimedia.
- Task Group 4 is developing a low-rate wireless PAN standard supporting rates of 2-200 kb/s with extremely low power consumption and complexity for sensors, toys, etc.

### History of IEEE 802.15

The chain of events leading to the formation of IEEE 802.15 began in June 1997 when the IEEE Ad Hoc Wearables Standards Committee was initiated during the IEEE New Opportunities in Standards Committee meeting in June 1997. The purpose of the Committee was to "encourage development of standards for wearable computing and solicit IEEE support to develop standards." The wearables committee met three more times, agreed to focus on wireless PAN standards, and decided to approach IEEE 802. IEEE 802.11 welcomed the initiative and launched the Wireless Personal Area Network Study Group within 802.11 in March 1998. At the time, no other wireless PAN initiatives had been publicized. However, by March 1999, when the study group and 802.11 submitted a PAR to 802, the Bluetooth™ special interest group (SIG) had over 600 adopter companies and HomeRF™ had over 60. The PAR was approved and placed in the hands of a new Working Group 802.15. Bob Heile was named chair and continues in that position. The working group has 74 members.

### Wireless PAN Derived from Bluetooth

IEEE 802.15's Task Group 1 is deriving a draft standard from the Bluetooth Specification Version 1.1 under IEEE PAR 802.15.1. Bluetooth is a technology for small form-factor, low-cost wireless communication and networking between computers, mobile telephones, and other portable devices. The specification supports data rates up to 721 kb/s as well as three voice channels and targets low power consumption: 30 µA in "hold" mode and 8-30 mA (less than 0.1 W) during transmission. Bluetooth technology will provide an easy and robust way for a variety of mobile devices to communicate with one another and remain synchronized without the need for wires or cables.

Figure 1 shows the protocol stacks in the OSI seven-layer network model and their relationship to the Bluetooth reference model as it pertains to the 802.15.1 standard.

### Wireless PAN Coexistence

Task Group 2 is developing, under IEEE PAR 802.15.2, a draft recommended practice for coexistence of wireless LAN and wireless PAN devices.

In the context of this project, multiple wireless devices are said to "coexist" if they can be collocated without significantly impacting their performance. Since the 802.15.1 standard addresses the same license-exempt 2.4 GHz band as 802.11's DS and FH PHYs, mutual interference is a concern when they operate near each other. Task Group 2 is developing a coexistence model that quantifies the effect of the mutual interference, with coexistence mechanisms to follow. The final model will consist of four elements: PHY, MAC, RF propagation, and data traffic. The coexistence model is intended to predict the effects of a nearby 802.11 network on the performance of an 802.15.1 network, and vice versa. Task Group 2 also plans to study the high-rate wireless PAN being developed in Task Group 3.

### High-Rate Wireless PAN

Task Group 3 is developing a standard for a high-rate wireless PAN under IEEE PAR 802.15.3, approved in March 2000. The goal is to support data rates of at least 20 Mb/s for applications such as digital imaging and multimedia. In a break with 802 tradition, the plan is to create a second MAC within the working group.

In November 2000, six candidate proposals for the PHY and four for the MAC were reduced to a single working version of the standard. In January 2001, an eight-state, trellis-code modulated, 16/32/64-QAM PHY operating in the 2.4 GHz band was selected. The proposed system provides adaptive data rates from 22-55 Mb/s. The group remains interested in additional PHYs, possibly operating in unlicensed 5 GHz bands.

### Low-Rate Wireless PAN

Following the December 2000 approval of PAR 802.15.4, Task Group 4 held its first meeting and began by assessing eight contributions in response to a call for applications. Like Task Group 3, Task Group 4 plans its own

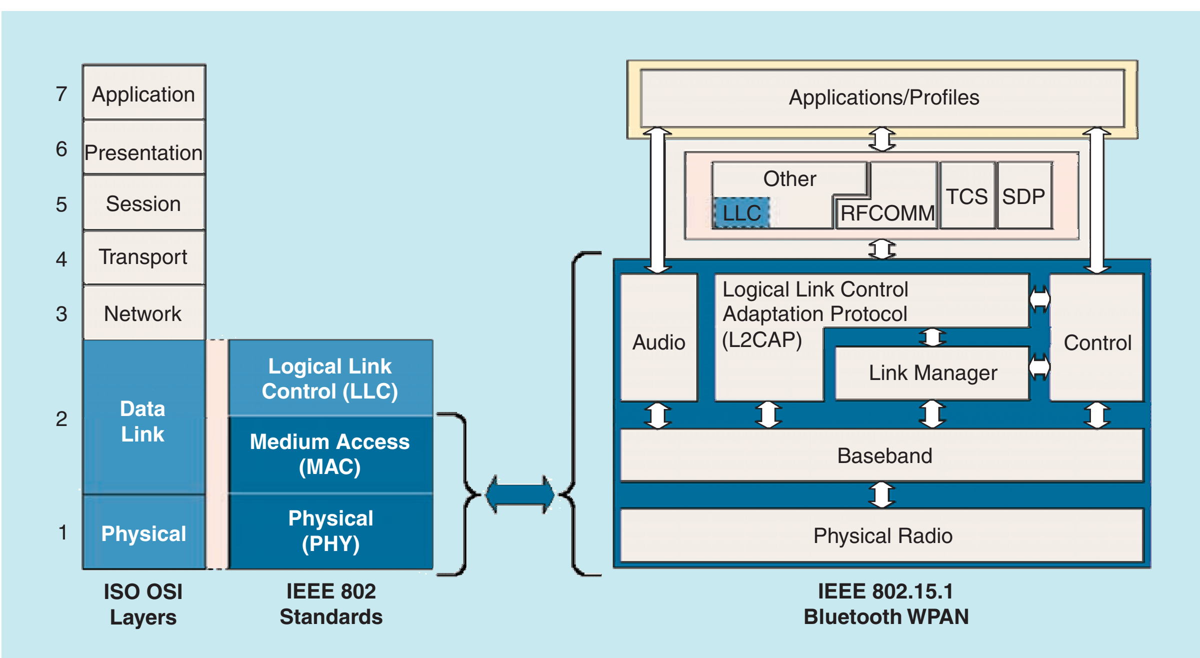


**Figure 1.** *Mapping of ISO OSI model to scope of IEEE 802.15.1 WPAN™ standard.*

unique MAC. Potential applications include sensor and automation needs, interactive toys, and location tracking for smart tags and badges.

### *Broadband Wireless Access Standards*

The IEEE Working Group 802.16 on broadband wireless access (BWA) standards develops standards and recommended practices to support the development and deployment of fixed broadband wireless access systems. It refers to its products as the IEEE 802.16 family of WirelessMAN™ standards for wireless MANs. The working group's projects are cosponsored by the IEEE Microwave Theory and Techniques (MTT) Society as well as the IEEE Computer Society.

Working group 802.16 is addressing applications of wireless technology to link commercial and residential buildings to high-rate core networks and thereby provide access to those networks; this link is sometimes known colloquially as the "last mile," though the term "first mile" is more appropriate for data flowing out of the customer site. The work has aimed at a point-to-multipoint topology with a cellular deployment of basestations, each tied into core networks and in contact with fixed wireless subscriber stations. The subscriber stations typically include rooftop-mounted antenna/radio units connected to indoor network interface units, although in some cases both units could be indoors or both outdoors. Initial work has aimed at businesses, with much of the market focus on small-to-medium-sized enterprises. Attention has increasingly turned toward residential opportunities, particularly at the lower frequencies.

The working group has three active projects to develop air interface standards. Task Group 1 is completing the IEEE 802.16 *Standard Air Interface for Fixed Broadband Wireless Access Systems*. This project addresses a PHY to support licensed bands from 10-66 GHz. The document will include an accompanying MAC. The standard is not yet final, but the draft is stable and in working group letter ballot.

Task Group 3 is developing a PHY for licensed bands from 2-11 GHz and the supporting MAC extensions. This work is planned as amendment 802.16a to the baseline 802.16 standard. Task Group 1 and Task Group 3 projects are 802's only work targeted at licensed bands. 802.16's newest project, led by Task Group 4, looks at license-exempt applications in the 5-6

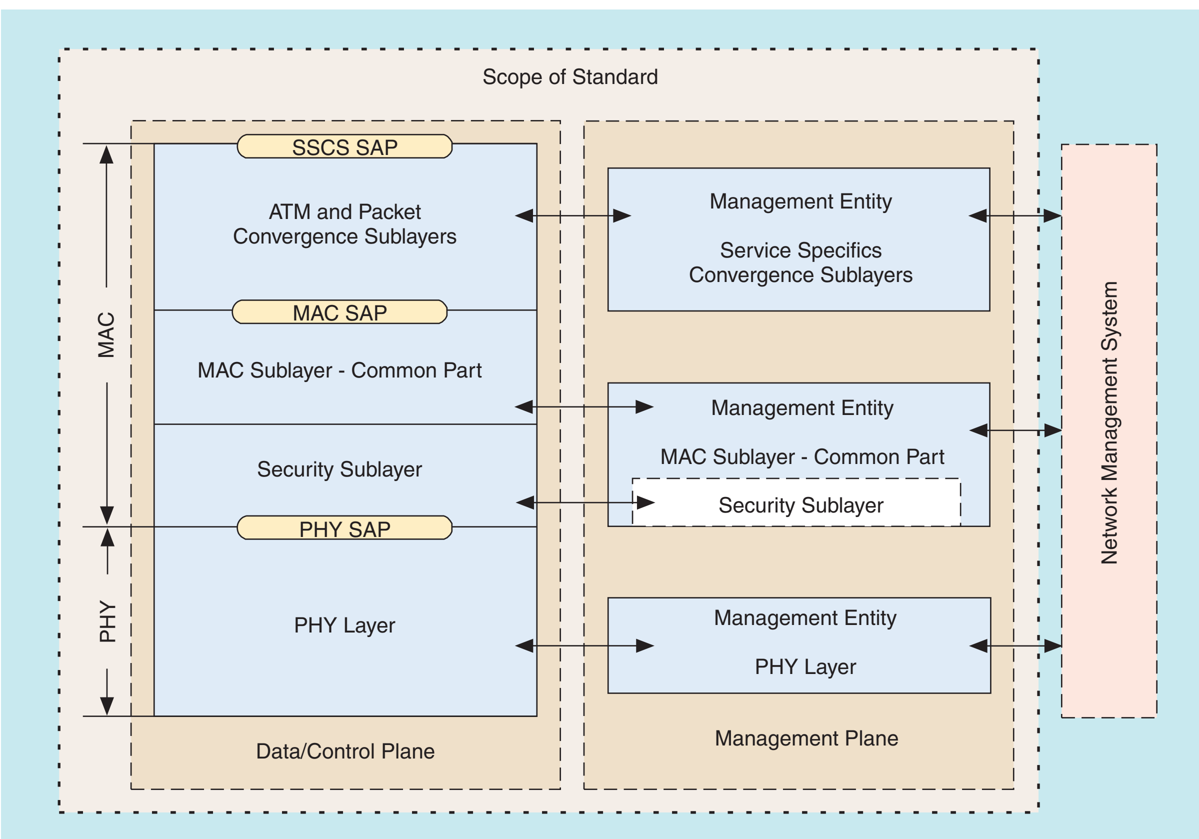


**Figure 2.** *IEEE 802.16 Reference Model and Protocol Stack.*

GHz region, sometimes known as U-NII bands due to their U.S. designation. Again, the plan is for an amendment (802.16b) to the base 802.16 standard, with a PHY and with MAC extensions.

Finally, Task Group 2 is completing the IEEE 802.16.2 *Recommended Practice for Coexistence of Fixed Broadband Wireless Access Systems*. The emphasis is on supporting deployment of systems built according to the Task Group 1 standard, primarily in the range of 23.5 to 43.5 GHz. This is the first document to have completed 802.16 working group letter ballot, and publication is anticipated for the summer of 2001.

## History of IEEE 802.16

The activities of 802.16 were initiated by activity of the National Wireless Electronics Systems Testbed (N-WEST) at the U.S. National Institute of Standards and Technology. N-WEST organized a kickoff meeting at the 1998 IEEE Radio and Wireless Conference (RAWCON). The group of 45 accepted an invitation to meet along with IEEE 802 in November, and 802 then approved the formation of a study group under chair Roger Marks. That group met twice and wrote the Task Group 1 PAR. The working group's Session #1 took place in July 1999. At that meeting, the Task Group 2 PAR was approved by 802; Leland Langston chaired the project. In November 1999, 802.16 created the study group that, under the leadership of Brian Kiernan, developed the Task Group 3 PAR that was approved in March 2000. At that time, a study group for the license-exempt bands was set up under chair Durga Satapathy, who developed the acronym WirelessHUMAN™ (Wireless High-Speed Unlicensed Metropolitan Area Network) to describe the standard effort. The Task Group 3 PAR was approved in December 2000. The original Task Group 1, Task Group 3, and Task Group 4 chairs remain in place; in addition, Carl Eklund and Jay Klein serve as MAC and PHY chairs, respectively, in Task Group 1. The Task Group 2 project is chaired by Phil Whitehead, following a brief stint by Andy McGregor. At the time of this report, 802.16 has 137 members, 74 potential members, and 59 official observers. Its work has been closely followed; for example, the IEEE 802.16 Web site received over 2.8 million file requests in the year 2000.

IEEE 802.16 maintains close working relationship with standards bodies in the ITU and the ETSI, particularly with the HIPERACCESS and HIPERMAN programs of ETSI's Broadband Radio Access Networks (BRAN) project and with ETSI Working Group TM4.

The technical accomplishments of IEEE 802.16 are summarized below. Several publications provide additional detail [5], [6].

## Medium Access Control

The 802.16 working group follows the traditional 802 approach of developing multiple PHY options supported by a common MAC. The MAC was developed by Task Group 1 along with the original 10-66 GHz PHY. Although the service requirements of the other air interface projects differ, the original MAC design is flexible enough to support, with extensions, all three projects.

The 802.16 MAC (Figure 2) draws from the data-over-cable (DOCSIS) standard [7] that has been successfully deployed in hybrid-fiber coaxial (HFC) cable systems, which have a similar point-to-multipoint architecture. However, the MAC protocol engine is a new design. It is a connection-oriented MAC able to tunnel any protocol across the air interface with full quality-of-service (QoS) support. Asynchronous transfer mode (ATM) and packet-based convergence layers provide the interface to higher protocols. While extensive bandwidth allocation and QoS mechanisms are provided, the details of scheduling and reservation management are left unstandardized and provide an important mechanism for vendors to differentiate their equipment.

An important MAC feature is the option of granting bandwidth to a subscriber station rather than to the individual connections it supports. This provides the option of allowing a smart subscriber station to manage its bandwidth allocation among its users. This can make for more efficient allocation.

The 802.16 MAC is versatile and flexible. For example, it supports several multiplexing and duplexing schemes; some possibilities are described below. In general, the point-to-multipoint architecture is implemented with a controlling base station interacting with many subscriber stations. The downlink from the base station may be channelized and sectorized but, within a channel and sector, all subscriber stations receive the same signal and retain only messages addressed to them. The uplink from the subscriber stations is shared, with access assigned by the basestation.

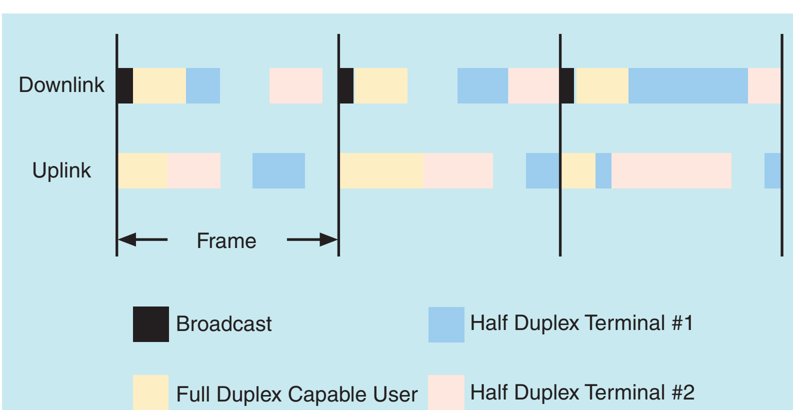


**Figure 3.** *Example of Burst FDD Bandwidth Allocation.*

## 10-66 GHz PHY

The 10-66 GHz PHY assumes line-of-sight propagation with no significant concern over multipath propagation. Either of two basic modes may be used. The continuous mode uses frequency division duplexing (FDD), with simultaneous uplink and downlink on separate frequencies. A continuous time division multiplexed downstream allows a powerful concatenated coding scheme with interleaving. The Burst Mode allows time division duplexing (TDD), with the uplink and downlink sharing a channel but not transmitting simultaneously. This allows dynamic reassignment of the uplink and downlink capacity. This mode also allows "burst FDD," which supports half-duplex FDD subscriber stations that do not simultaneously transmit and receive (see Figure 3) and may therefore be less expensive. Both TDD and Burst FDD support adaptive burst profiles in which modulation (QPSK, 16-QAM, or 64-QAM) and coding may be dynamically assigned on a burst-by-burst basis. This real-time tradeoff of capacity versus robustness again offers to vendors opportunities to implement sophisticated algorithms to differentiate their approach while retaining interoperability.

The choice of continuous or burst mode may depend on the available channel allocations and other regulatory issues. Because the standard is intended for world-wide use, the channelization is left flexible. Recommendations are included, however. These suggest symbols rates as high as 43.4 MBd in a 50 MHz channel, which, assuming 64-QAM, translates to data rates as high as 260 Mb/s in that channel.

## Licensed Bands, 2-11 GHz

Task Group 3 has been developing a standard for 2 to 11 GHz BWA. In the United States, the primary targeted frequencies are in the Multichannel Multipoint Distribution Service (MMDS) bands, mostly from 2.5-2.7 GHz. World-wide, 3.5 and 10.5 GHz are likely applications. Because non-line-of-sight operation is practical and because of the lower component costs, these bands are seen as good prospects for residential and small-business services. The spectrum availability is suitable to these uses. Task Group 1 has considered a number of PHY layer approaches and was scheduled to select a baseline draft in the spring of 2001. MAC enhancements are also under development.

## Unlicensed Bands, 5-6 GHz

In order to provide for rapid development, Task Group 4 is working under a narrow charter. It is tasked to develop a PHY layer based on the 802.11a OFDM and/or HIPERLAN/2 PHYs and is developing MAC enhancements. It works closely with Task Group 3 to ensure harmony. Coordination of basestations under independent operators in unlicensed spectrum is an important issue facing this group. One proposal is to consider an optional mesh architecture in addition to a point-to-multipoint topology. Some participants have proposed MAC enhancement to support a mesh; this is testimony to the flexibility of the 802.16 MAC.

## Coexistence and Regulatory Issues Across 802

As 802.11 products proliferate at 2.4 GHz, the prospect of a large number of 802.15 products operating in the same spaces and in the same unlicensed bands prompts significant concern about coexistence. In the 5-6 GHz bands, products based on the 802.11a OFDM standard are expected soon. 802.15's Task Group 3 has had discussions about a PHY in the same bands, and 802.16's Task Group 4 is firmly engaged in developing a fixed wireless access standard at the same frequencies. Meanwhile, 802.11 is working with European and Japanese standards groups with the goal of harmonizing the world's 5 GHz wireless LAN standards or, failing that, to ensure that the systems can coexist. These overlaps have brought about discussions of a coexistence coordinating group that would interact with all of 802's development projects addressing those unlicensed bands.

**Wireless PAN standards will support short-range links among computers, mobile telephones, and other consumer electronics devices that are worn or carried**

The IEEE 802 wireless projects have also increasingly focussed on radio regulations. Again, the unlicensed bands cause the most concern, because the operation rules strongly impact the allowed technology and vary from country to country. In March 2000, the SEC assigned regulatory matters to a regulatory ombudsman and elected Vic Hayes to fill this position. The regulatory ombudsman prepares and submits unified 802 positions in regard to spectrum sharing and in support of harmonized global rules. Much of the focus is on the World Radiocommunications Conference (WRC) and the ITU-R. For example, the WRC in 2003 has three agenda items related to extension, sharing studies, and harmonization of the 5 GHz band.

## Applications

The IEEE 802 wireless standards program builds on the success of IEEE 802.3 (Ethernet), since much of the success of the Internet is based on the availability of low-cost Ethernet equipment. In 2000, the Dell'Oro Group projected revenue from Ethernet switch equipment to grow at 20% per year to over $23 billion in 2004. Dell'Oro also projected 10 Gb/s Ethernet, the most advanced Ethernet technology, to reach revenue of $1 billion by 2004 and said "One of the most important trends in networking is the extension of the economics (i.e., price/performance) of the LAN to the metro and wide area (MAN/WAN)."

While IEEE 802.15-based products are not yet available, they promise to extend the wireless Internet to a wide range of devices. One driver will be cost, as Bluetooth radios are often projected to fall from the $20 range to around $5. Another critical success factor is low power consumption, which will significantly expand the range of applications as compared to current wireless technology. IEEE 802.15 is addressing the true consumer electronics industry, from mobile telephones and handheld devices to sensors and toys. The number of units deployed based on the 802.15 standards may be enormous. For example, market research firm Cahners In-Stat Group has projected over 670 million Bluetooth-enabled devices world-wide by 2005.

The IEEE 802.11 wireless LAN standard was initially published in 1997, with the important 802.11a and 802.11b amendments in 1999. It has already been emulating Ethernet's success, demonstrating that standardization does open new markets. As a recent publication noted, "The curve of wireless interest over time shows three key turning points. The first was the finalization of the IEEE 802.11b standard for 11 Mb/s direct-sequence radios. The rate itself wasn't the key, though. Standardization was. This allowed interoperability among vendors and helped bring the cost down to where it is today, with a bill of materials of less than $40 for the radio" [8]. This has dramatically shifted wireless LAN applications. While the original target was primarily businesses that wanted to save on LAN installation costs, 802.11 products are now significantly penetrating home networking markets. Even more significant is the surge in public deployments, a trend strong enough to receive recent treatment in the mainstream press. *The New York Times*, in a major article on the topic, wrote, "Wireless high-speed Internet access, a longtime dream of the technophile and business traveler, is finally arriving at hundreds of access points in public and private places across the United States. With a laptop computer equipped with a wireless card, anyone within a few hundred feet or so of one of these access points, or hot spots, can tap into a wireless network that is in turn connected to the Internet via a broadband connection. The user can then send e-mail or surf the Web at speeds in the megabit range... By late this year, industry experts say, the hundreds of hot spots will become thousands as service providers and entrepreneurs install the necessary equipment—generally, a small transceiver and a broadband connection—in all major airport terminals, sports arenas, and other business and consumer sites. By sometime next year, one company expects to have access points in 5,000 Starbucks stores. Some of these services may be free, run by volunteers intrigued by the community-building prospects of wireless networking... But most access points are and will be commercial, run by companies that will charge for the services" [9]. An accompanying article on the standard said "The protocol called IEEE 802.11b has been put in place by so many companies offering wireless short-range networks that it is emerging as the standard for the field" [10]. The success of 802.11 products is based not only on the price drops but also on the increasing ubiquity of the service, a result that is also driven by standardization. *The New York Times* expressed this by quoting one industry manager as saying that this new wireless access is about "giving you the ability to roam from one network to another and be blissfully ignorant" of the technical intricacies and quoted a user as saying, "It's the kind of thing that's such a fundamental capability that it starts feeding on itself." With the user of a portable computer now able to access the Internet at work, home, restaurants, cafes, hotels, and airports, all with the same equipment and all at blazing speed, the wireless Internet is arriving, and it is based on IEEE 802 standards.

One major roadblock remains to be addressed in order to complete this picture of a wireless Internet based on IEEE 802. How will all of those access points be connected with fast access to the Internet itself? Cable modems provide service in some residential neighborhoods but are available in very few commercial districts; furthermore, their uplink capacity may be too narrow for this purpose. Digital subscriber line (DSL) can provide broadband service but is limited in range. Fiberoptic links offer very broadband rates, but only about 5% of U.S. commercial buildings have access to fiberoptic links, and the cost of laying cable is extremely high. In many cases, the most efficient means of reaching the many widely dispersed sites providing license-exempt wireless Internet access based on IEEE 802 standards will be fixed broadband wireless access. If IEEE 802 maintains its record of success in ushering technology into the economy and into society, then IEEE 802.16 will be the tool that makes fixed broadband wireless access a mainstream application. IEEE 802 will have unleashed the wireless Internet.

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