Standards from IEEE 802 Unleash the Wireless Internet

Roger B. Marks
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80305-3328 USA
marks@boulder.nist.gov

Ian C. Gifford
M/A-COM, Inc.
1011 Pawtucket Blvd.
Lowell, MA 01853-3295 USA
giffordi@ieee.org

Bob O'Hara
Informed Technology, Inc.
1750 Nantucket Circle, Suite 138
Santa Clara, CA 95054-3822 USA
bob@informed-technology.com

Draft for submission to *IEEE Microwave Magazine*

1.0 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 technology. These standards are enabling the development of an infrastructure for the Wireless Internet.

2.0 Introduction

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 around the The Institute of Electrical and Electronics Engineers, Inc. (IEEE) and its IEEE 802 LAN MAN Standards Committee, which is the world leader in Local Area Network (LAN) and Metropolitan Area Network (MAN) standards. IEEE 802 is currently developing and enhancing standards for wireless Local Area Networks (Wireless LAN), Wireless Personal Area Networks (Wireless PAN), and Wireless Metropolitan Area Networks (WirelessMAN™).

The model of the Wireless Internet 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 base stations serving both highly-mobile users (at automotive speeds) at 144 kbit/s, with the theoretical capability to also serve fixed users at rates up to 2 Mbit/s. The standards were developed at a technical level by national or regional bodies so that, when worldwide standards were forged by the ITU-R, the voting members, which are national governments, were centrally involved in the negotiations. As a result, the standards debates turned into 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 brought in 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.

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 of the work is to succeed by bringing 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 entrepreneurs and innovations. IEEE 802 Wireless Internet technologies offer data rates much higher than those provided by even IMT-2000's projected fixed-user rates; for example, the currently-popular IEEE 802.11b standard supports 11 Mbit/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:

- 802.16 WirelessMAN™ standards will support high-rate Broadband Wireless Access services to buildings, mostly through rooftop antennas, from central base stations;
- 802.11 Wireless LAN standards support users roaming through homes, office buildings, campuses, hotels, airports, restaurants, cafes, etc.;
- 802.15 Wireless PAN standards will support short-range links among computers, mobile telephones, and other consumer electronics devices that are worn or carried.

3.0 Standardization in IEEE 802

3.1 The 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 <http://standards.ieee.org>). 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 of them, 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 carries out oversight of the standardization process through the IEEE-SA Standards Board. Project development is delegated to individual standard sponsors; these 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.

3.2 The IEEE 802 LAN MAN Standards Committee

The IEEE 802 LAN MAN Standards Committee <http://ieee802.org> is sponsored by the IEEE Computer Society. It first met in 1980 to develop a Local Area Network (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 (LLC) sublayer.[1] Together, these make up the two lowest layers of the OSI seven-layer model for data networks.

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 worldwide 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 standards and raising the supported data rates with 100BaseT and 1000BaseT. Optical media are supported, and 802.3 is currently developing a 10 Gbit/s standard. 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.

1. Overview and Guide to the IEEE 802 LMSC <http://ieee802.org/overview2000.pdf>.

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

3.3 The 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 of 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 it 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 change 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 suggestions. A 75% approval rate is required to pass. However, changes made in response to comments, and negative comments that have not been accepted by the editorial team, must be "recirculated" for approval 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. In the end, the approval margin is typically much higher than 75% at closure.
- The Working Groups 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 use interests. In addition to the vote, of course, critical comments are vital to the success of the process.

2. Operating Rules of IEEE Project 802 LAN MAN Standards Committee <http://ieee802.org/rules.pdf>

Experience has shown that the IEEE 802 process is extremely effective at engaging a wide array of interested parties, bringing forth 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 in a reasonable time.

4.0 The IEEE 802 Wireless Standards Program

The IEEE 802 wireless standards program comprises three Working Groups:

- The IEEE 802.11 Working Group develops the IEEE 802.11 standards for Wireless Local Area Networks (Wireless LAN)
- The IEEE 802.15 Working Group develops the IEEE 802.15 standards for Wireless Personal Area Networks (Wireless PAN™ or WPAN™)
- The IEEE 802.16 Working Group on Broadband Wireless Access develops the IEEE 802.16 standards for Wireless Metropolitan Area Networks (WirelessMAN™).

These groups work in a loose association to coordinate their activities. 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. 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.

Below, we summarize the status and technology of the projects in the IEEE 802 wireless standards program.

4.1 The IEEE 802.11 Working Group for Wireless Local Area Networks

The IEEE 802.11 Working Group for Wireless Local Area Network (Wireless LAN or WLAN) Standards <http://ieee802.org/11> was the first wireless effort in IEEE 802. As with other standards in the 802 family, 802.11 describes a Medium Access Control (MAC) sublayer and multiple physical (PHY) layers. 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 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 layer amendments (802.11a and 802.11b). The existing standard and its amendments describe several WLAN PHYs:

- infrared at 1 and 2 Mbit/s
- frequency hopping spread spectrum radio at 1 and 2 Mbit/s in the 2.4 GHz band
- direct sequence spread spectrum radios with data rates up to 11 Mbit/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.

4.1.1 The 802.11 MAC

The 802.11 standard[3] describes two types of WLANs, an ad hoc network (an independent Basic Service Set (BSS), in the language of the standard) and an infrastructure network (comprised of infrastructure BSSs of one access point and the associated mobile stations). An ad hoc WLAN consists of only mobile stations. This type of WLAN 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 WLAN that integrates mobile stations into a large network infrastructure through the use of access points (APs) 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 WLAN, request encryption and power management services from the WLAN, 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), in the language of the standard) is carrier sense multiple access with collision avoidance (CSMA/CA). The DCF may be used in either the ad hoc or infrastructure WLANs. The DCF is quite similar to the carrier sense multiple access 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 with another transmission. 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.

Because it is more difficult to have a radio simultaneously transmit and receive on the same channel than would be the case for 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 about 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 will be deferred.

3. Bob O Hara and Al Petrick, *IEEE 802.11 Handbook: A Designers Guide*, IEEE Standards Press, 1999.

In an infrastructure WLAN, 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 WLAN, 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. It is upon this PCF that the current work in 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.

4.1.2 The 802.11 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), 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. It is still incumbent upon the manufacturer 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 expectations of approval as an amendment to the 802.11 standard 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 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 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 IR has seen the least use. This PHY uses baseband pulse position to transmit data at 1 and 2 Mbit/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 WLAN 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 2 Mbit/s. This PHY was suitable for operation under the U.S. FH spread spectrum rules for the 2.4 GHz Industry, Scientific, and Medical (ISM) band at the time of development; 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 Mbit/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, though transmit power may be as high as 1 W. The receiver sensitivity is –80 dBm. For 2 Mbit/s, the modulation used is four-level GFSK.

The Direct Sequence (DS) PHY, with the extension in the 802.11b amendment, provides data rates of 1, 2, 5.5, and 11 Mbit/s. In the U.S., 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 GHz 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 Mbit/s data rates use a fixed 11-chip spreading sequence, based on a Walsh code, to meet the minimum spreading requirements of the U.S. regulations. The modulation used for these rates is DBPSK and DQPSK, respectively. The 5.5 and 11 Mbit/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, though it is arguable whether it meets the letter of the DS spread spectrum rules of the regulations. However, it does pass the test in the regulations 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 Mbit/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 U.S. The OFDM PHY provides eight data rates: 6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s. It uses BPSK, QPSK, 16-QAM, 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 ms. 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 WLANs 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.

4.2 The IEEE 802.15 Working Group for Wireless Personal Area Networks

The IEEE 802.15 Working Group for Wireless Personal Area Networks (WPANs™) <http://ieee802.org/15> develops standards for WPANs, which 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 kbit/s range to beyond 20 Mbit/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.

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 WLAN and WPAN devices.
- Task Group 3 is developing a High Rate WPAN standard supporting at least 20 Mbit/s for applications such as digital imaging and multimedia.
- Task Group 4 is developing a Low Rate WPAN standard supporting rates of 2-200 kbit/s with extremely low power consumption and complexity for sensors, toys, etc.

4.2.1 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 (WPAN) Study Group within 802.11 in March 1998. At the time, no other WPAN 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.

4.2.2 Task Group 1: WPAN ™ Derived from Bluetooth™

IEEE 802.15's Task Group 1 (TG1) is deriving a draft standard from the Bluetooth™ Specification Version 1.1 under IEEE PAR 802.15.1. Bluetooth[4] 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 kbit/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.[5]

---

4. Bluetooth" is a trademark owned by Telefonaktiebolaget LM Ericsson, Sweden and licensed to promoters and adopters of the Bluetooth Special Interest Group.

5. Tom Siep, *An IEEE Guide: How to Find What You Need in the Bluetooth Spec*, IEEE Press, 2000.

Figure 1 shows the protocol stacks in the Open Systems Interconnect (OSI) seven-layer network model (a standard of the International Standards Organization (ISO)) and their relationship to the Bluetooth™ reference model as it pertains to the 802.15.1 standard.

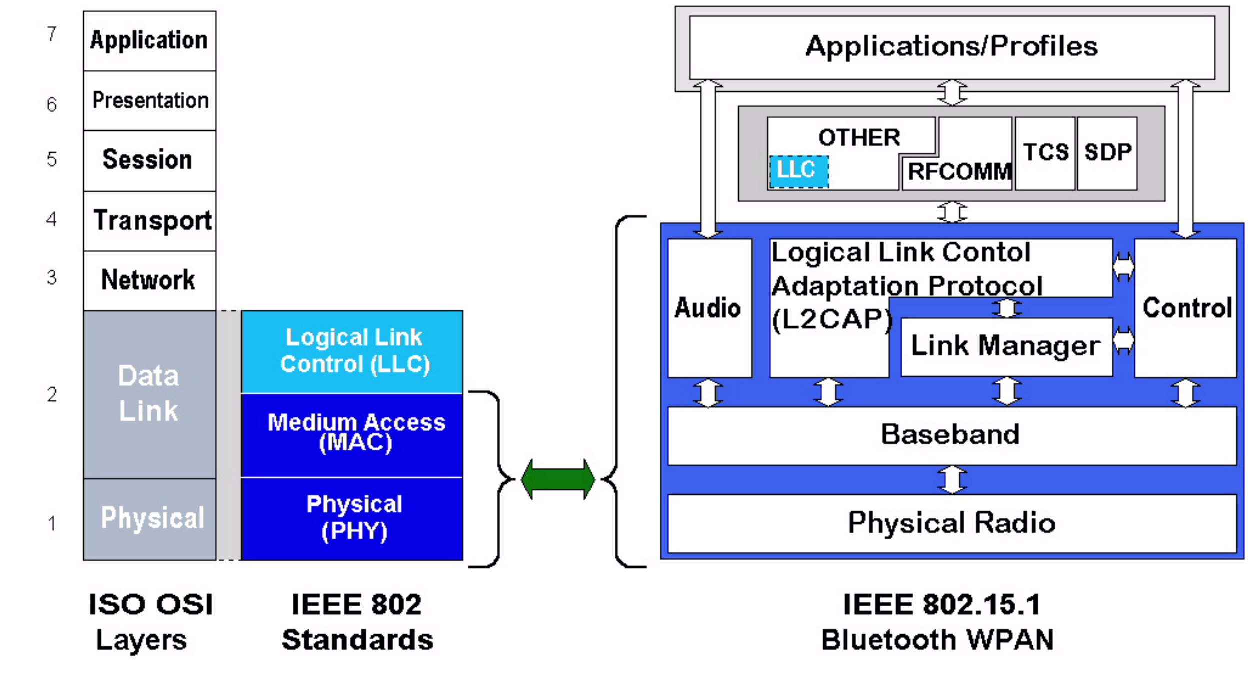

FIGURE 1. Mapping of ISO OSI model to scope of WPAN™ standard

4.2.3 Task Group 2: WPAN Coexistence

Task Group 2 (TG2) is developing, under IEEE PAR 802.15.2, a draft recommended practice for coexistence of WLAN and WPAN 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 nearby. TG2 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: physical layer (PHY), medium access control layer (MAC), RF propagation, and data traffic. The coexistence model is intend to predict the effects of a nearby 802.11 network on the performance of an 802.15.1 network, and vice versa. TG2 also plans to study the High Rate WPAN being developed in Task Group 3.

4.2.4 Task Group 3: High Rate WPAN™

Task Group 3 (TG3) is developing a standard for a high-rate WPAN under IEEE PAR 802.15.3, approved in March 2000. The goal is support data rates of at least 20 Mbit/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 PHYs and four candidate MAC proposals 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 Mbit/s. The group remains interested additional PHYs, possibly operating in unlicensed 5 GHz bands.

4.2.5 Task Group 4: Low Rate WPAN

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 TG3, Task Group 4 plans its own unique MAC. Potential applications include sensor and automation needs, interactive toys, and location tracking for smart tags and badges.

4.3 IEEE 802.16 Working Group on Broadband Wireless Access Standards

The IEEE Working Group 802.16 on Broadband Wireless Access (BWA) Standards <http://WirelessMAN.org> 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 Metropolitan Area Networks. The Working Group's projects are co-sponsored by the IEEE Microwave Theory and Techniques (MTT) Society as well as the IEEE Computer Society.

802.16 is addressing applications of wireless technology to link commercial and residential building 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. 802.16's work has aimed at a point-to-multipoint topology with a cellular deployment of base stations, 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, though 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.

802.16 has three active projects to develop air interface standards. Task Group 1 (TG1) 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 (TG3) is developing a PHY for licensed bands from 2-11 GHz and supporting MAC extensions. This work is planned as an amendment to the baseline 802.16 standard. The TG1 and TG3 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 GHz region, sometimes known as U-NII bands due to their U.S. designation. Again, the plan is for an amendment to the base 802.16 standard, with a PHY and with MAC extensions.

Finally, Task Group 2 is finalizing the IEEE 802.16.2 *Recommended Practice on Coexistence of Fixed Broadband Wireless Access Systems*. The emphasis is on supporting deployment of systems built according to the TG1 standard, primarily in the range 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.

Historically, 802.16 was initiated by activity of the National Wireless Electronics Systems Testbed (N-WEST <http://nwest.nist.gov>) 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 TG1 PAR. The Working Group's Session #1 took place in July 1999. At that meeting, the TG2 PAR was approved by 802; Leland Langston chaired the project. In November 1999, 802.16 created the Study Group which, under the leadership of Brian Kiernan, developed the TG3 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 TG3 PAR was approved in December 2000. The original TG1, TG3, and TG4 chairs remain in place; in addition, Carl Eklund and Jay Klein serve as MAC and PHY chairs, respectively, in TG1. The TG2 project is chaired by Phil Whitehead, following a brief stint by Andy McGregor. At the time of this report, 802.16 has 124 members, 76 Potential Members, and 91 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 maintain close working relationship with standards bodies in the International Telecommunications Union and the European Telecommunications Standards Institute (ETSI), particularly with the HIPERACCESS program of ETSI's Broadband Radio Access Networks (BRAN) project and with ETSI Working Group TM4.

The 802.16 technology is summarized below. Several publications[6] [7] provide additional detail.

4.3.1 802.16 MAC

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 TG1 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, with extensions, support all three projects.

The 802.16 MAC (Figure 2) draws from the Data-Over-Cable (DOCSIS[8]) standard 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. 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

6. Jeff Foerster and Glen Sater, LMDS Standards Architectural Issues, 2000 IEEE Wireless Communications and Networking Conference.

7. Brian Petry, Broadband Wireless Access: High Rate, Point to Multipoint, Fixed Antenna Systems, in *The RF and Microwave Handbook*, CRC Press, 2001, pp. 2-41 to 2-51.

8. Cable Television Laboratories, Inc., Radio Frequency Interface Specification (version 1.1), Data-Over-Cable Service Interface Specifications.

station to manage its bandwidth allocation among its users. This can make for more efficient allocation.

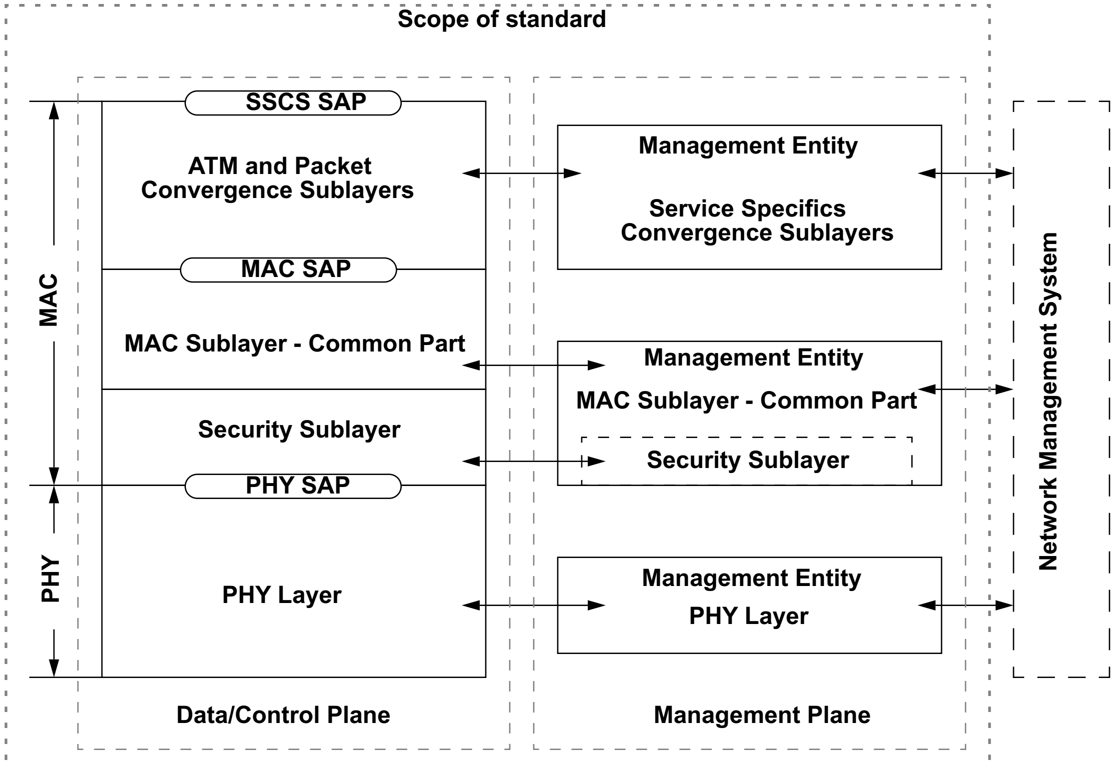

FIGURE 2. IEEE 802.16 Reference Model and Protocol Stack

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 base station.

4.3.2 10-66 GHz Physical Layer (PHY)

The 10-66 GHz PHY assumes line of sight propagation with little multipath. Either of two basic modes may be used. The Continuous Mode uses frequency division duplexing (FDD), with the uplink and downlink on separate frequencies simultaneously. 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 trade-off of capacity versus robustness again offers vendors opportunities to implement sophisticated algorithms to differentiate their approach while retaining interoperability.

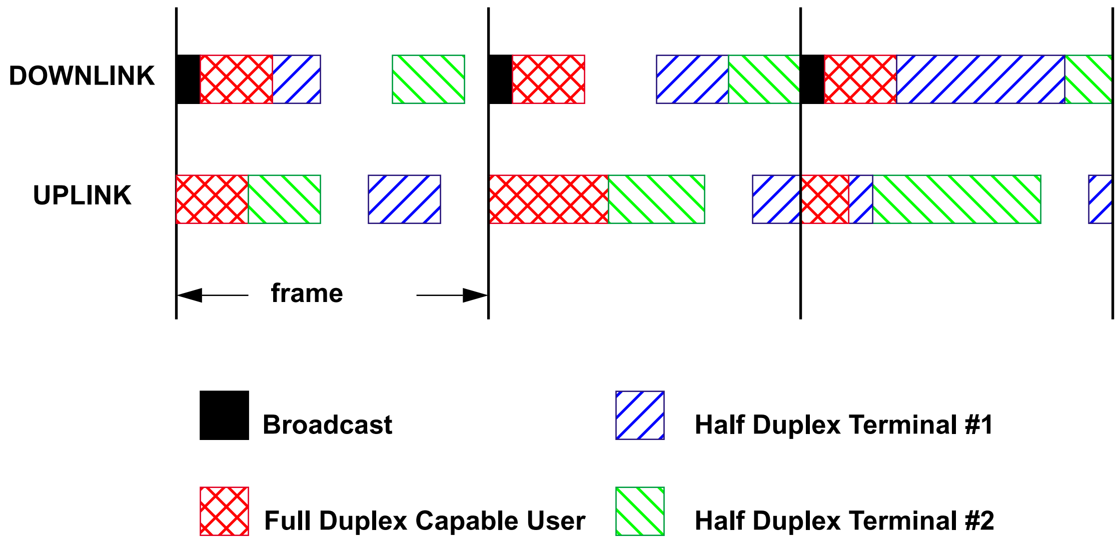

FIGURE 3. Example of Burst FDD Bandwidth Allocation

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

4.3.3 Licensed Bands, 2-11 GHz

802.16's Task Group 3 has been developing a standard for 2-11 GHz BWA. In the U.S., the primary targeted frequencies are in the Multichannel Multipoint Distribution Service (MMDS) bands, mostly from 2.5-2.7 GHz. Worldwide, 3.5 GHz 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. The Task Group 1 has considered a number of physical layer approaches and was scheduled to select a baseline draft in the spring of 2001. MAC enhancements are also under development.

4.3.4 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 physical layer based on the 802.11a OFDM and/or HIPERLAN/2 PHYs. It is working closely with TG3 to ensure harmony, and it is developing MAC enhancements. Coordination of base stations under independent operators in unlicensed spectrum is an important issue for this group to face. 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.

5.0 Coexistence and Regulatory Issues Across 802

As 2.4 GHz 802.11 products proliferate, 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 TG3 has had discussions about a PHY in the same bands, and 802.16's TG4 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 WLAN 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.

The IEEE 802 wireless projects have also increasingly focussed on Radio Regulations. Again, the unlicensed bands cause the most concern, for here 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 <http://ieee802.org/Regulatory> and elected Vic Hayes to fill this position.

6.0 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 Gbit/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 the 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 worldwide 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 opens 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 Mbit/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."[9] This has dramatically shifted Wireless LAN applications. While the original target was primarily businesses who wanted to save on LAN installation costs, 802.11 products are now significantly penetrating home networking markets. Even more significant is 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.”[10] An accompanying article on the standard[11] 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.” The success of 802.11 products is based on only on the price drops but also on the increasing ubiquity of the service, a result that is also driven by standardization. The *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 standards.

One major roadblock remains to be addressed in order to complete this picture of a Wireless Internet based on IEEE 802. Namely, 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. Fiber optic links offer very broadband rates, but only about 5% of commercial buildings have access to fiber optic 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 to make fixed broadband wireless access a mainstream application. IEEE 802 will have unleashed the Wireless Internet.

---

9. P. Mannion, Ad Hoc Networks Ascend to the Airwaves, *EE Times*, pp. 85-86, February 26, 2001.

10. Glenn Fleishman, The Web, Without Wires, Wherever, *The New York Times,* February 22, 2001.

11. Glenn Fleishman, Protocol Wars: A Standard Emerges, but Watch Out for Those Microwave Ovens, *The New York Times,* February 22, 2001.

7.0 About the Authors

Roger B. Marks initiated an effort in 1998 to standardize fixed broadband wireless access within the IEEE 802 LAN/MAN Standards Committee. This effort led to creation, in March 1999, of the IEEE 802.16 Working Group on Broadband Wireless Access, which Marks has chaired since inception. Marks received his A.B. in Physics in 1980 from Princeton University and his Ph.D. in Applied Physics in 1988 from Yale University. Following a postdoctoral appointment at the Delft University of Technology (The Netherlands), his professional career has been with U.S. Commerce Department's National Institute of Standards and Technology (NIST) in Boulder, Colorado, USA. A Fellow of the IEEE and the author of over 70 journal and conference publications, Marks has received many awards, including the 1995 Morris E. Leeds Award (an IEEE Technical Field Award). He currently serves as an IEEE Distinguished Lecturer. He participates in many professional activities; for example, developed the IEEE Radio and Wireless Conference (RAWCON) and chaired it from 1996 through 1999.

Ian Gifford was born in Framingham, Massachusetts, USA. He received a Bachelors in Economics from Boston University, Boston Massachusetts, USA, in 1981. He is Director of Standards at M/A-COM, Inc., a Tyco Electronics Company, in Lowell, Massachusetts, USA. For the past 15 years he has worked on wireless solutions for wide area, local area and personal area networks. Additionally, he is an active member in Standards Development Organizations such ITU-R, TIA, and Committee T1 as well as a few Industry Special Interest Groups and Alliances including the Bluetooth™ Special Interest Group. He serves as Vice Chair of the IEEE 802.15 Working Group for WPANs.

Bob O'Hara is the president of Informed Technology, Inc., a company that specializes in strategic, technology, and network consulting. He is actively involved in the development of networking, telecommunications and computing standards and products. His areas of expertise are: network and communication protocols and their implementation, operating systems, system specification and integration, standards development, cryptography and its application, strategy development, and product definition. Bob has been involved with the development of the IEEE 802.11 WLAN standard since 1992. He is the technical editor that standard and chairman of the revisions (802.11rev) and regulatory extensions (802.11d) task groups. Prior to starting Informed Technology, Bob worked for Advanced Micro Devices in both senior engineering and management positions for the I/O and Network Products Division and in the Advanced Development Lab, as well as engineering positions at Fairchild Space and Communications and TRW Defense and Space Systems Group. Bob Graduated with a BSEE from the University of Maryland in 1978.