

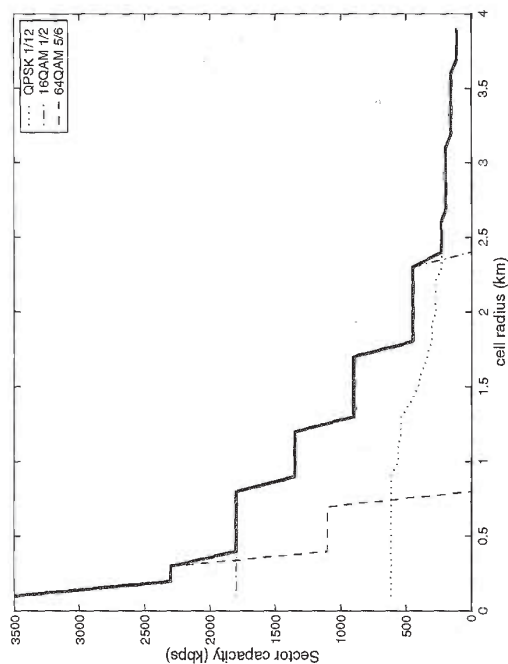


Figure 14-19: DL sector capacity per cell radius—ITU VehA (60 km/h)

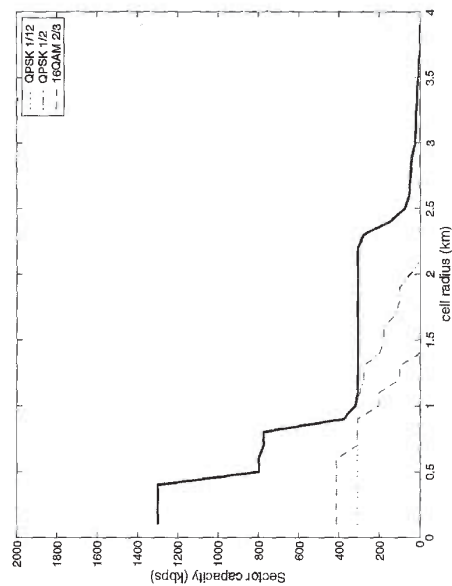


Figure 14-20: UL sector capacity per cell radius—ITU VehA (60 km/h)

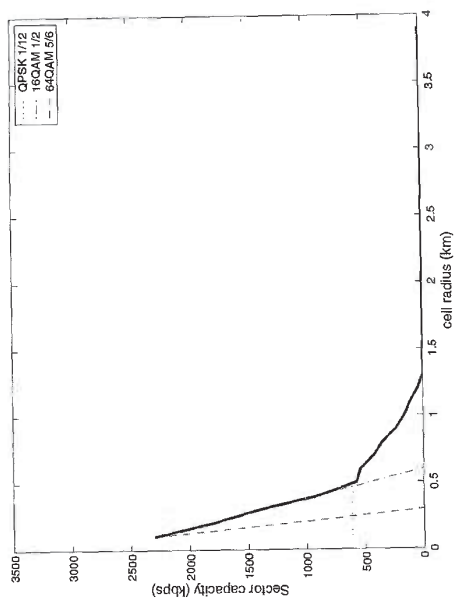


Figure 14-21: DL sector capacity per cell radius (ITU outdoor-indoor)

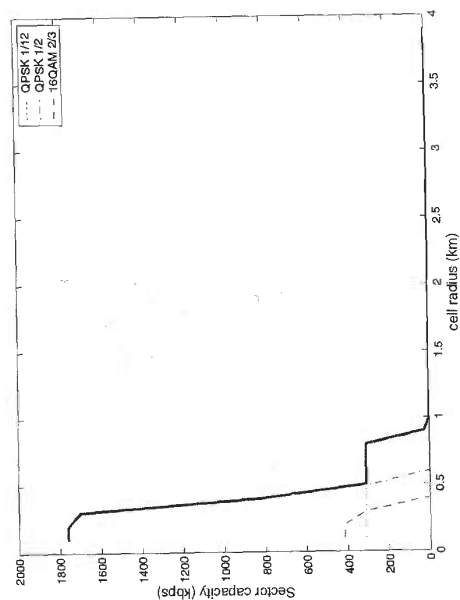


Figure 14-22: UL sector capacity per cell radius (ITU outdoor-indoor)

A 2005 paper by Kwon, et al., [B34] presents an alternative study of the system capacity. The modeled system is TDD using a 1024-FFT, 9 MHz bandwidth, 5 ms frame duration, and a 2/1 DL/UL frame split. The network is loaded with a number of applications spanning all four service types (UGS, rtPS, nrPS, and BE) defined in IEEE Std 802.16-2004 as well as the extended rtPS (ertPS) introduced in IEEE Std 802.16e for real-time flows generating variable packet sizes on a periodic basis, such as VoIP with silence suppression. The traffic load per user is as follows:

- DL

Video: 32 kbit/s, 10 frames/s

IP traffic: ~90 kbit/s FTP and ~15 kbit/s HTTP traffic (according to 1xEV-DV traffic models; see [B8])

VoIP: 9.6 kbit/s with 0.403 activity factor

- UL

VoIP: 9.6 kbit/s with 0.403 activity factor

IP traffic: As needed to support UL FTP, HTTP, and video traffic

The analysis is performed in a hexagonal cellular environment considering interference from first and second tier cells with identical traffic distributions. Figure 14-23 shows the delay in transmitting VoIP data using rtPS, UGS, and ertPS. On the DL, the number of VoIP calls is limited to 92 when the delay limit is 60 ms. This figure shows that the introduction of ertPS in IEEE Std 802.16e is justified for voice with silence suppression since the call limit is similar to the DL limit using ertPS, but is significantly lower using rtPS and UGS.

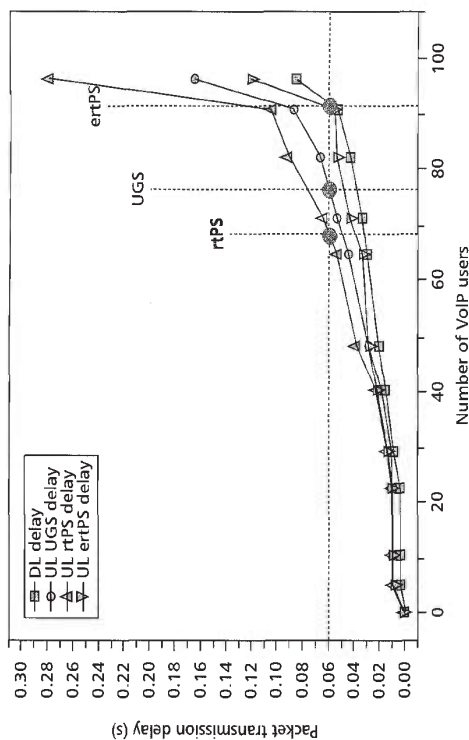


Figure 14-23: Delay for VoIP using rtPS, UGS, and ertPS

Figure 14-24 shows the average cell throughput both for UL and DL using various scheduling mechanisms, permutations, and feedback.

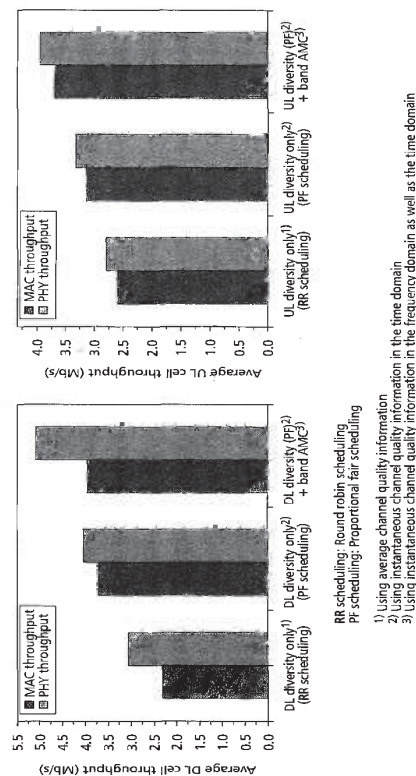


Figure 14-24: Average cell throughput for various schemes

WirelessMAN-OFDMA vs high-speed DL packet access (HSDPA)

A 2005 paper by Shin, et al., [B48] compares the capacity of a WiBro-compatible version of WirelessMAN-OFDMA (based on a preapproved draft of IEEE Std 802.16e) with that of HSDPA. The study concludes that the OFDMA approach has "much better performance." In particular, it finds that the spectral efficiency of WirelessMAN-OFDMA is close to double that of HSDPA for the ITU VehA channel model and also for the ITU Pedestrian A (PedA) channel at 10 km/h [B30]. For the ITU PedA channel model at 3 km/h, the spectral efficiency of WirelessMAN-OFDMA is found to be about one third greater than that of HSDPA. The authors ascribe the WirelessMAN-OFDMA advantage to two main factors:

- **TDD vs FDD:** Both systems work within a system bandwidth of 10 MHz. However, the OFDMA system under study uses TDD (with a fixed 2/1 DL/UL ratio) with signal bandwidth of 8.3 MHz. HSDPA uses FDD carried in two 5 MHz channels, but its effective signal bandwidth is just 3.84 MHz times two. The wider bandwidth of OFDMA is naturally not all positive, as it can result in a shrinkage of the coverage area due to the 3.4 dB higher thermal noise. In a noise-limited scenario, this coverage shrink is estimated at 19%, but the real situation may be interference-limited in both cases.
- **Multipath performance:** As discussed in Chapter 3 and Chapter 11, OFDM is very robust to multipath due to the use of the cyclic prefix and the cyclical nature of the FFT. Multipath channels that do not exceed the cyclic prefix duration will not significantly deteriorate the system performance (provided the sampling is adequate). CDMA, on the other hand, typically makes use of a rake receiver to extract the multipath energy. This results in deteriorated performance. The paper by Shin reports as much as 40% HSDPA capacity loss going from a single-path (multipath-free) channel to a three-path channel. Naturally, the move away from conventional rake receivers to more advanced receiver designs provides a means to reduce that capacity loss.

Basic WirelessMAN-OFDMA PHY performance

This section reports on unpublished studies of the basic WirelessMAN-OFDMA PHY performance. It assumes 10 MHz channelization at 2.5 GHz with a 1024-FFT; a 1/8 cyclic prefix; and practical levels of phase noise, mixer I/Q imbalance, and frequency offset. The reported $E_s N_0$ is equivalent to the SNR per subcarrier. For the repetition codes, postdetection combining of soft decisions is employed. All simulations shown use the mandatory CC.

Figure 14-25 and Figure 14-26 present the CBLER for the OFDMA modulation using the ITU VehA 3 km/h channel model. The first figure represents ideal synchronization and channel estimation, whereas the second represents a practical system of moderate complexity. The poor performance of QPSK-3/4 is a result of the mandatory interleaver problem discussed in Chapter 12.

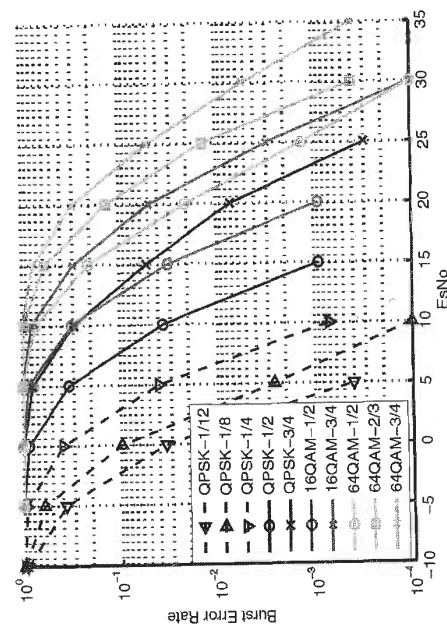


Figure 14-25: CBLER, UL PUSC, ITU VehA 3 km/h, CC, ideal

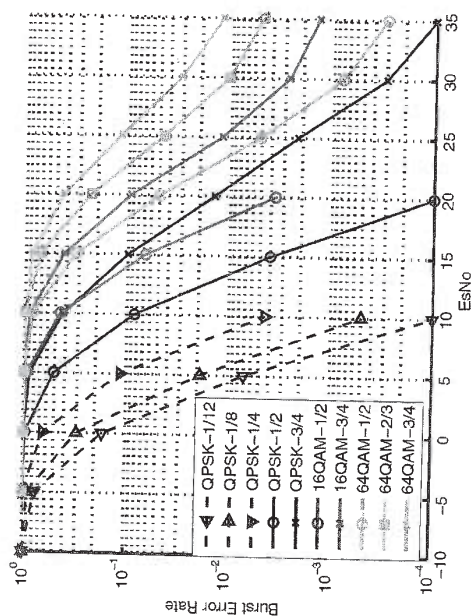


Figure 14-26: CBLER, UL PUSC, ITU VehA 3 km/h, CC, estimated

Figure 14-27 and Figure 14-28 provide similar data using the ITU VehA 120 km/h channel model. The ideal performance suffers only moderately as a result of the higher speeds, even for the higher modulation orders. However, the practical challenges of synchronization and channel estimation cause the performance at the higher modulation orders to degrade substantially, with error floors developing. For the lower order modulations, including the omitted repetition rates, the PHY is fairly robust to the rapidly changing channel.

Similar analysis for VehA 30 km/h channel shows no significant degradation compared to the VehA 3 km/h model, showing that the OFDMA PHY is substantially robust to practical speeds. On the other hand, the performance degrades substantially using the VehB 10 km/h model due the insufficient cyclic prefix duration compared to the impulse response in that model.

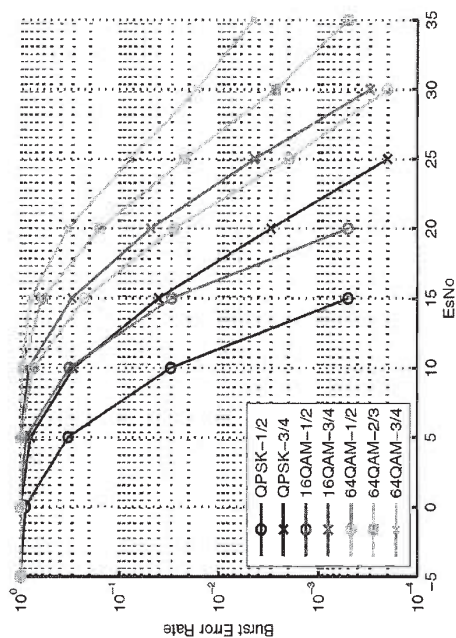


Figure 14-27: CBLER, UL PUSC, ITU VehA 120 Km/h, CC, ideal

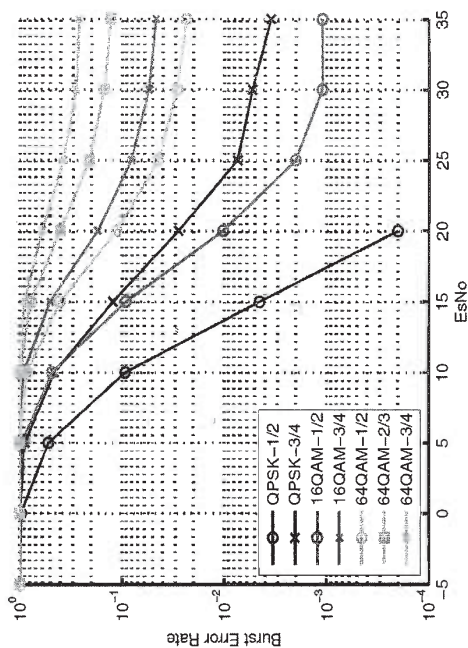


Figure 14-28: CBLER, UL PUSC, ITU VehA 120 km/h, CC, estimated

Figure 14-29 shows the ideal performance using the optional CTC codec, which is the optional codec of choice within the WiMAX profiles. The improvement over the CC codec varies from 1 dB to 1.5 dB although it need be noted that in this analysis only the longest code word is used. Use of shorter code words can result in a loss of up to 2 dB (compared to the longest code word).

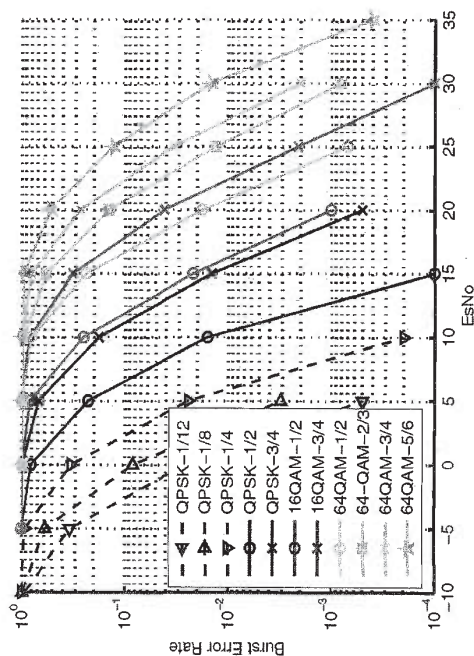


Figure 14-29: CBLER, UL PUSC, ITU VehA 3 km/h, CTC, ideal

Figure 14-30 shows the ideal performance of the DL modulations, including that of the DLFP. It is best to protect the DLFP since it constitutes a single point of failure within the frame.

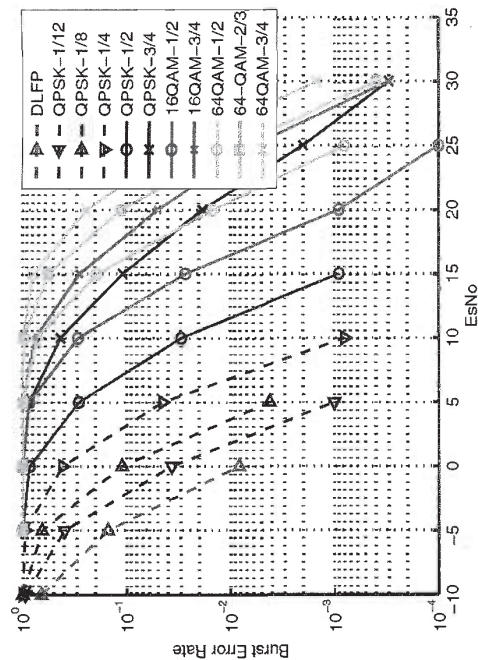


Figure 14-30: CBLER, DL PUSC, ITU VehA 3 km/h, CC, ideal

In Figure 14-31, the performance of the DL repetition coding as a function of channel impulse response (CIR) is shown. This result is important to determine which repetition code can be used at the cell edge. As may be observed from the figure, the use of QPSK-1/4 (QPSK-1/2, repetition rate 2) or QPSK-1/8 (QPSK-1/2, repetition rate 4) has sufficient CIR performance to make usage at the cell edge feasible. The large gap between the solid (ideal synchronization) and dashed (practical synchronization) curves is the result of the general difficulty of achieving good synchronization under low signal to noise-plus-interference ratio, regardless of the method used.

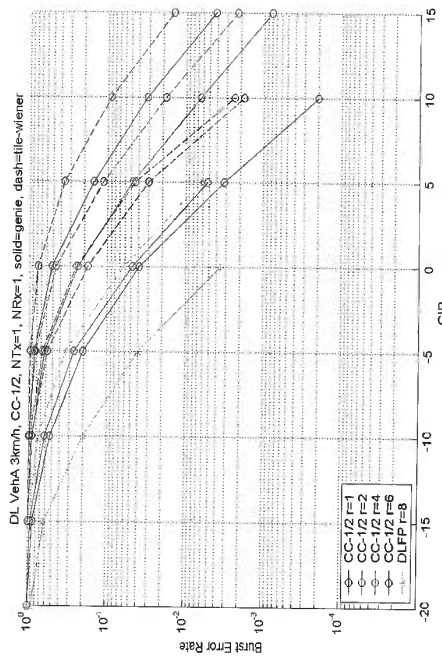


Figure 14-31: CBLER, DL PUSC, ITU VehA 3 km/h, CC, ideal

Finally, Table 14-1 shows the cell ranges that may be achieved with the DL modulations with a 20 W transmitter, 10 dB backoff, 15 dB antenna gain, and a 10 dB noise figure. For this case, the mobile is assumed to have two antennas on which it performs MRC. Achievable cell ranges are shown both with and without a 10 dB shadowing margin using the Cost 231 Hata channel model [B11].

Table 14-1: Cell-ranges DL PUSC

Modulation/ code rate	Max. PHY throughput (Mbit/s)	SNR @ 0.01 CBLER (dB)	Cell range (m)	Cell range with fade margin (m)
QPSK-1/12	1.19	-1.1	1586	825
QPSK-1/8	1.79	0.7	1410	733
QPSK-1/4	3.57	2.0	1259	674
QPSK-1/2	7.14	6.0	997	512
QPSK-3/4	10.71	9.2	809	421
16-QAM-1/2	14.28	10.3	753	392
16-QAM-3/4	21.42	14.9	557	290
64-QAM-1/2	21.42	15.5	536	279
64-QAM-2/3	28.56	19.0	426	222
64-QAM-3/4	32.13	21.2	369	192

MIMO capacity

This section discusses the capacity gain achieved by the use of MIMO. The capacity is analyzed at link level for a full-buffer FTP stream in an OFDMA network with 19 cells, each having three sectors, using 10 MHz bandwidth at 2.5 GHz. The channel models are a mix of stationary/pedestrian, pedestrian, mobile, and highly mobile models in analogue to the 1xEV-DV evaluation methodology (see [B8]). Some capacity results, in megabits per second, are shown in Table 14-2, where the notation $m \times n$ indicates m transmitter chains and n on the receiver. Note that the results are indicative only of the relative capacity gain, as a full-buffer FTP analysis provides an overly optimistic result for achievable capacity. The use of 2x1 STC on the DL, for which no simulation data were available for this specific scenario, would be expected to result in values between those of 1x1 SISO and 2x2 MIMO, but relatively closer to the 2x2 MIMO results.

Table 14-2: Relative performance benefit of MIMO and virtual MIMO^a

DL/UL ratio	DL				UL	
	Reuse	1x1	2x2 MIMO	2x4 MIMO	1x2 V-MIMO	2x2 MIMO
1/2	1	3.80	7.97	11.76	3.20	7.04
	3	1.52	3.98	7.06		6.72
1/1	1	5.75	12.08	17.83	2.40	5.28
	3	2.30	6.04	10.70		
2/1	1	7.67	14.00	20.67	1.60	2.40
	3	3.07	7.00	12.40		3.36

^a Data courtesy of Nortel Networks.

In Table 14-3, the spectral efficiency and capacity are shown for various antenna configurations in the same system, with DL/UL ratio of 2/1 and using the ITU PedA 3 km/h channel model.

Table 14-3: Performance using MIMO^a

	1x1	1x2	2x2	2x4	4x2	4x4
(bit/s)/Hz per sector	1.2	1.8	2.8	4.4	3.7	5.1
Aggregate sector throughput (Mbit/s)	7.6	11.6	17.8	27.7	23.6	32.6

^a Data courtesy of Nortel Networks.

Chapter 15 Conformance and interoperability

Conformance standards and testing

In this chapter, we discuss the IEEE 802.16 conformance standards and the WiMAX Forum[®] interoperability and certification procedures. The conformance standards are essentially comprehensive test plans to evaluate whether a particular vendor's implementation meets the requirements defined in IEEE Std 802.16. The WiMAX Forum is an industry alliance, analogous to the Wi-Fi Alliance for IEEE Std 802.11, that defines interoperability tests and certifies IEEE 802.16 BSs and SSs that pass these tests.

THE WIMAX FORUM

By the end of 2000, even before the original IEEE Std 802.16-2001 was approved, it became clear that the standard would include a plethora of options. For instance, the high-frequency WirelessMAN-SC mode has literally more than 4000 possible combinations of FEC and modulation alternatives, while in practice four or five would suffice. While most options have at least one corresponding proponent who can argue for its benefits under certain circumstances, implementing all of the options would clearly be an onerous and expensive task. Conversely, if equipment vendors independently chose which options to implement, full interoperability would be precluded, and IEEE Std 802.16 would be a standard in name only. Systems would be, for all intents and purposes, proprietary through the choice of options. In March of 2001, the outline of Clause 12 was added to the IEEE 802.16 draft standard.

It also became clear that full interoperability would require proper conformance testing, lest two vendors pick the same profile but interpret it differently. In IEEE 802, standards rarely include test specifications; in most cases, they stop with functional specifications. In the 2000 time frame, intense

debate surrounded IEEE Std 802.16 versus ETSI BRAN HiperACCESS as the standard of choice for PMP broadband wireless access above 10 GHz. ETSI BRAN HiperACCESS was a simpler but less efficient standard than IEEE 802.16 WirelessMAN-SC. ETSI BRAN HiperACCESS advocates criticized IEEE Std 802.16, citing the plethora of options and the impact on interoperability. They also cited the ETSI mandate for a full set of test documentation based on the ISO/IEC 9646 standards series (identical to the ITU x.290 series) specifying test documentation. In response, several companies involved in IEEE Std 802.16 were determined to eliminate this as a source of discredit to IEEE Std 802.16 so the two standards could be compared on a head-to-head technical basis.

These companies decided to take the concept a step further and initiate a certification body and process modeled as a hybrid of Wi-Fi and GSM type approval. In April 2001, representatives of Nokia, Ensemble Communications, Harris Corporation, and Crosspan (a division of Raytheon) met in Antibes, France, alongside an ETSI BRAN HiperACCESS meeting in neighboring Sophia Antipolis; and the WiMAX Forum was born. Unlike the WiMAX Forum of today, the original group was concerned with single-carrier systems above 11 GHz. This was due to the facts that this aspect of IEEE Std 802.16 was much further developed than the lower frequency specifications and that it was ETSI BRAN HiperACCESS to which they were reacting.

By the way, "WiMAX" is derived from the expression *worldwide interoperability for microwave access*. Jay Klein, who chaired the WirelessMAN-SC PHY Task Group, has been credited with creating the name.

The initial task of the early WiMAX Forum was to develop system profiles for WirelessMAN-SC operation. These were submitted during the development of IEEE Std 802.16c, which specified detailed system profiles in Clause 12. Following draft development and balloting, these profiles, with minor changes, were approved; and IEEE Std 802.16c was approved in December 2002. The WirelessMAN-SC profiles are shown in Table 15-1.

Table 15-1: WirelessMAN-SC system profiles

Identifier	Description
profM1	Basic ATM MAC profile
profM2	Basic packet MAC profile
profP1	25 MHz channel PHY profile
profP1f	25 MHz channel PHY profile—FDD
profP1t	25 MHz channel PHY profile—TDD
profP2	28 MHz channel PHY profile
profP2f	28 MHz channel PHY profile—FDD
profP2t	28 MHz channel PHY profile—TDD

Once this task was accomplished, the next step was to deal with the issue of test specifications. With the aid of other companies such as Nera, Intracom, Hewlett-Packard, and Hughes Network Systems, the founders of the WiMAX Forum started to create the test specification necessary to be on par with the ETSI test specifications. Four documents were identified:

1. Protocol implementation conformance statement (PICS) proforma:
A document that serves two purposes. First, it lists the features that are mandatory, optional, conditionally mandatory, forbidden, etc., for each of the system profiles. Second, it serves as a form that vendors fill out to specify which features they implement and for what sets or ranges of allowed values.
2. Test suite structure and test purposes (TSS&TP): A test plan for covering the features outlined in the PICS proforma.
3. Abstract test suite (ATS): Equipment-independent test procedures for implementing the tests identified in the TSS&TP.
4. Radio conformance test (RCT) specification: Tests for the radio portion of the system that could not be specified as protocol tests.

CONFORMANCE TEST STANDARDS FOR WIRELESSMAN-SC

The WiMAX Forum played a key role in the development of PICS proforma, TSS&TP, and RCT documents in IEEE Std 802.16. In each case, a new IEEE 802.16 project was proposed and initiated for each test specification, each to lead to an independent published standard. Once the project was underway, an open call for contributions was issued; in each case, a single proposal, developed within the WiMAX Forum, was received.

These proposals were unchallenged primarily because of the involvement of the same participants in both the WiMAX Forum and the IEEE 802.16 Working Group. Nonetheless, the documents proceeded through the official IEEE 802 process of working group review, working group letter ballot, and sponsor ballot, with comments addressed along the way. The result was three official IEEE standards: IEEE Std 802.16/Conformance01-2003 [B21], IEEE Std 802.16/Conformance02-2003 [B22], and IEEE Std 802.16/Conformance03-2004 [B23], each in accordance with ISO/IEC 9646.

By the time the RCT document was initiated, relations between companies participating only in ETSI BRAN HiperACCESS and those interested in both ETSI BRAN HiperACCESS and IEEE Std 802.16 had improved, and the ETSI BRAN HiperACCESS RCT was used as the foundation of the WirelessMAN-SC RCT document. Unfortunately, before the ATS document could be initiated, the bottom fell out of the market for high-frequency broadband wireless access equipment. Consequently, the WirelessMAN-SC ATS standards project was never initiated.

THE WIMAX FORUM'S MOVE TO LOWER FREQUENCIES

In April 2002, as the specifications for systems below 11 GHz were solidifying, entities interested in operation below 11 GHz began to join the WiMAX Forum. The first was the OFDM Forum in April, followed by Wi-LAN and Fujitsu in November 2002. Then, in January of 2003, the WiMAX Forum jumped to twelve "charter member" companies and, fueled by the efforts of Intel Corp., started expanding rapidly. The WiMAX Forum, with well over 300 member companies, is now certifying fixed-access WirelessMAN-OFDM systems through independent laboratory conformance

testing and overseeing interoperability "plug-fests." The WiMAX Forum is devoting great energy to the development of system profiles and test specifications for mobile systems based on the enhancements in IEEE Std 802.16e.

LOWER FREQUENCY PROFILES AND TEST SPECIFICATIONS

The WirelessMAN-OFDM, WirelessMAN-OFDMA, and WirelessMAN-SC PHY specifications were the first foray of IEEE Std 802.16 into the lower frequencies (less than 11 GHz). These were first defined in IEEE Std 802.16a. In late 2002, as IEEE Std 802.16a was nearing completion, the IEEE 802.16 Working Group opened the amendment project IEEE P802.16d, which was intended to develop profiles in support of the low-frequency modes. Eventually, IEEE P802.16d was dropped as a project to amend IEEE Std 802.16, replaced by a broader revision project that eventually led to IEEE Std 802.16-2004 [B20]. That revised standard does include the low-frequency profiles.

IEEE Std 802.16-2004 specifies profiles for all three PHY mode alternatives. However, for this fixed-access case, WirelessMAN-OFDM was of the greatest interest for two reasons:

1. The parallel ETSI BRAN HiperMAN standard initially supported a mode compatible with WirelessMAN-OFDM only.
2. The WiMAX Forum contributed only to the development of the WirelessMAN-OFDM and developed fixed-access interoperability tests only for that mode.

The low-frequency profiles are considerably more complex set than those for WirelessMAN-SC. In the case of WirelessMAN-OFDM, a system profile consists of four components: a MAC profile, a PHY profile, a duplexing selection, and a power class. The IEEE 802.16 standard defines two MAC profiles (PMP and mesh), six PHY profiles (1.75, 3.5, 7, 3, 5.5, and 10 MHz channel bandwidth, with the last one specified in the license-exempt case only), two duplexing alternatives (TDD and FDD), and five power classes.

In the case of WirelessMAN-OFDMA, only one MAC profile (PMP-based) is specified, along with nine PHY profiles (1.25, 3.5, 7, 8.75, 14, 17.5, 28,

10, and 20 MHz channel bandwidth, with the last two specified in the license-exempt case only), two duplexing alternatives (TDD and FDD), and four power classes.

The ATM CS is not included in either the WirelessMAN-OFDM or the WirelessMAN-OFDMA profiles. In both cases, RF profiles are mentioned, but not specified except in the license-exempt case.

The IEEE P802.16/Conformance04 project, to specify PICS proforma for the low-frequency modes, was initiated in March 2004. Draft 6, which entered IEEE-SA sponsor ballot in January 2006, includes no specification for WirelessMAN-SCa, which had lost support by the time the project got underway. The draft does include a detailed PICS specification for WirelessMAN-OFDMA. It should be noted that this PICS proforma concerns only fixed systems, not any mobile systems. In the case of WirelessMAN-OFDM, the draft simply makes normative reference to ETSI 102 385-1 V1.2.1, entitled "Broadband Radio Access Networks (BRAN); HiperMAN; Conformance testing for the Data Link Control Layer (DLC); Part 1: Protocol Implementation Conformance Statement (PICS) proforma." Since ETSI BRAN HiperMAN has long supported a PHY compatible with WirelessMAN-OFDM and since ETSI is recognized for its expertise in conformance test specifications, it is natural to defer to the ETSI standard on this issue. It is worth noting, however, that ETSI defers to IEEE standards as well. In fact, the ETSI test specifications have, in many cases, pointed not to ETSI air interface standards but to IEEE Std 802.16 for their references.

WIMAX FORUM CONFORMANCE TESTING FOR FIXED ACCESS

The only publicized industry activities related to the testing of conformance to IEEE Std 802.16 have been developed in the WiMAX Forum. In January 2006, the WiMAX Forum announced that four products (two BSs, one BS "solution," and one SS "solution") had been certified for 3.5 GHz operation following testing at its laboratory in Malaga, Spain. It also announced plans to test an additional 26 products. Protocol conformance, radio conformance, and basic interoperability were certified. Some additional capabilities, including QoS and security, were not tested. Certification testing of these features is

expected later in 2006. Testing of systems operating in the 5.8 GHz bands is also in development.

WIMAX FORUM AND MOBILE BROADBAND WIRELESS ACCESS

With the progress of the amendment project IEEE P802.16e, the WiMAX Forum developed an interest in this work also. The WiMAX Forum eventually came to the conclusion that it would strongly support the evolution of the IEEE 802.16 standard from fixed to mobile applications and would commit itself to the development of test specifications for mobile systems defined in IEEE Std 802.16e. Most of the WiMAX Forum effort on mobility has been directed at the WirelessMAN-OFDMA mode. Work to create the test specifications is well underway. This work is being undertaken jointly between ETSI and the WiMAX Forum based on agreement between the two. An activity related to the mobile enhancement of WirelessMAN-OFDM is also underway, but this has seen considerably less support among the member companies of the WiMAX Forum.

Chapter 16 Related standards

Other wireless standards with similar applications

This chapter opens by comparing the IEEE 802.16 (WirelessMAN) standard to the IEEE 802.11 (WLAN) standard. It next overviews progress in two IEEE 802 working groups, IEEE 802.20 and IEEE 802.22, that are engaged in developing standards, but have not at this time completed any. The chapter reviews some history and the status of related projects in ETSI's BRAN activity, briefly adding reports on the relation between the IEEE 802.16 Working Group and two other regional standardization activities: the Korean Telecommunication Technology Association (TTA) and the China Communications Standards Association (CCSA). We close the chapter with a review of the important relationships between IEEE Std 802.16 and the ITU, particularly those leading to the international recommendation of IEEE Std 802.16 through the ITU.

IEEE STD 802.11

The IEEE 802.11 standard defines MAC, PHY, and management protocols for WLANs. A LAN typically has a range on the order of 100 m and serves a space the size of a home, an office building, or a small campus. The distinction between LANs and MANs is especially important in the wireless case because the choices for MAC and PHY protocols and parameters essentially dictate the type of network that can be built. WLANs and wireless MANs have widely different requirements, and a MAC or PHY designed for one type of network may be unsuitable for the other.

Since its initial ratification in 1997, IEEE Std 802.11, and its later amendments, have become the foundation for a large and growing market. WLANs based on IEEE Std 802.11 are an essential network technology. With their standardization and subsequent widespread adoption in homes and enterprises, IEEE 802.11 devices—known as *Wi-Fi* to the general public, due

to the certification mark of the Wi-Fi Alliance—have become commodities in recent years. The following subsections summarize the IEEE 802.11 MAC and PHY and discuss the similarities and differences between IEEE Std 802.11 and IEEE Std 802.16.

IEEE 802.11 MAC

Medium access control layer (MAC)

The IEEE 802.11 MAC is based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol, in which IEEE 802.11 devices primarily follow a “listen before talk” rule, with random backoff to avoid collisions. The fundamental premise of CSMA is that all devices sharing the channel can hear each other. Most IEEE 802.11 devices have omnidirectional antennas and, in the local area of primary application, can hear each other. Some mechanisms [e.g., the request to send and clear to send (RTS/CTS) mechanism] do exist, albeit at a higher overhead, to partially address the “hidden node” case in which some nodes are within range of the AP (analogous to an IEEE 802.16 BS), but not within range of each other.

The IEEE 802.11 CSMA/CA protocol is similar to the CSMA/CD protocol of Ethernet. In the wireless case, carrier sensing is possible, except in the hidden node situation. However, collision detection (the “CD” of Ethernet) is not. An Ethernet node continues to sense the medium during transmission and is thereby able to detect collisions. IEEE 802.11 devices are half-duplex and, therefore, cannot listen while transmitting. In fact, given the fact that IEEE Std 802.11 uses the same frequency for UL and DL, it would be a significant challenge to design an IEEE 802.11 device that could accurately sense the medium for collisions during transmission.

In lieu of collision detection, IEEE 802.11’s collision avoidance process uses a physical carrier sense and a virtual carrier sense mechanism are used to avoid potential collisions. The physical carrier sense mechanism listens for the presence of any other transmissions on the channel before attempting a transmission of its own. The virtual carrier sense mechanism utilizes the explicit indication from another transmitter that essentially reserves the channel for a specific amount of time.

Since CSMA/CA is a fully distributed scheme with no central coordinator, collisions are still possible. The absence of collision detection makes it essential to use an acknowledgment scheme to ensure successful reception. IEEE Std 802.11 uses immediate MAC acknowledgments to confirm that an IEEE 802.11 frame has reached its destination. This is essentially a stop-and-wait ARQ scheme with synchronous acknowledgment, where the transmitter waits for the acknowledgment before attempting the next transmission or repeating the previous one. In the IEEE 802.11 MAC, the immediate acknowledgment is mandatory for all unicast frames⁷. Note that, in IEEE Std 802.11, the word *frame* is used in both the MAC sense (as a single MAC PDU, carrying data, management, or control content) and in the PHY sense (as a unit of PHY transmission) because each PHY frame carries one MAC frame. In contrast, IEEE Std 802.16 uses *frame* only as a PHY transmission unit; an IEEE 802.16 frame may carry one or more MAC PDUs or partial MAC PDUs. Although IEEE Std 802.11 supports fragmentation, it is optional and seldom implemented by IEEE 802.11 devices. The optional fragmentation is not dynamic and uses a fixed, configurable fragment size.

The duplexing method used in IEEE Std 802.11 is TDD, which is half-duplex by definition. However, in IEEE Std 802.11, no centralized coordinator allocates time slots; instead, transmission decisions are taken independently at each transmitter. The IEEE 802.11 AP, which is analogous to the IEEE 802.16 BS, has no special rules for accessing the media. The AP has to contend for the media just like any other IEEE 802.11 client communicating with it.

MAC overhead

The IEEE 802.11 MAC requires a minimum of 24 bytes of MAC header information per frame. Note that an IEEE 802.11 MAC frame can carry only one higher layer SDU; i.e., multiple higher layer SDUs such as IP packets cannot be packed into a single MAC frame. For example, each 40 byte TCP acknowledgment would require at least 42 bytes of MAC overhead (24 bytes of MAC header + 4 bytes of CRC + 14 bytes of acknowledgment) in addition to the per-frame PHY overhead. The PHY rates must be considered in this

⁷ IEEE Std 802.11e™-2005 includes an option to omit immediate acknowledgments in favor of delayed acknowledgments.

MAC discussion because the IEEE 802.11 acknowledgment is typically sent at one of the more robust PHY rates. A large frame sent at a lower rate can occupy the channel for a significant amount of time.

The transmission rate to be used is also chosen independently by the transmitters. The standard does not specify an algorithm to choose the transmission rate, and vendors implement their own rate-selection algorithm. However, an IEEE 802.11 AP can restrict the number of transmission rates that can be used in the network.

The IEEE 802.11 MAC supports two alternative channel access modes, the distributed coordination function (DCF) and the optional point coordination function (PCF). The DCF is the fully distributed scheme discussed in the previous paragraphs. PCF offers some centralized polling, although it is not scalable and the polling does not take the frame size or transmission rate into account. For these reasons, PCF is not widely supported and is rarely used.

MAC summary

The CSMA/CA protocol with DCF works reasonably well in a WLAN environment. However, it is not without problems in some situations. The following is a partial list of concerns in CSMA/CA WLAN:

- **Nondeterminism:** CSMA/CA is nondeterministic, and the stop-and-wait ARQ can make successful reception significantly unpredictable if frames need to be resent often. The situation can become drastically worse as the network load increases. Deterministic behavior is required for many QoS-sensitive applications.
- **Hidden nodes:** Two CSMA devices that cannot hear each other may simultaneously initiate transmission. A collision will result. Retransmission will take time and waste future transmission opportunities. This problem is somewhat addressed by the RTS/CTS-based reservation protocol, but its effectiveness declines with a large number of hidden nodes.
- **Near-far problem:** The near-far problem refers to a scenario in which devices closer to an IEEE 802.11 AP can overpower devices farther away, thus unfairly affecting the performance of those devices.

- **Slowest node:** Since transmission decisions are taken independently, one or more nodes choosing to transmit at the lowest rate will, by using a less efficient communication scheme, occupy a disproportionate fraction of airtime. This adversely affects other devices that can communicate at a higher rate.
- **Capture effect:** The capture effect is a fundamental problem in any CSMA protocol, including wired networks such as Ethernet. Since the CSMA devices make independent decisions on transmissions and backoff, the device that successfully completes a transmission resets its contention window and starts afresh for the next contention. This provides an unfair advantage to the device with a successful transmission when multiple devices are contending for access.
- **Overhead:** In general, the IEEE 802.11 MAC has high overhead, especially for smaller frames such as voice or TCP acknowledgments.

IEEE 802.11 PHY

IEEE Std 802.11 has standardized several PHY modes, including the following:

- Frequency-hopping spread spectrum (FHSS), up to 2 Mbit/s
- Direct sequence spread spectrum, up to 11 Mbit/s, in IEEE Std 802.11b™
- OFDM, up to 54 Mbit/s, in IEEE Std 802.11a™ and IEEE Std 802.11g™

The quoted data rates are raw PHY rates. For instance, the maximum IEEE 802.11a PHY rate is 54 Mbit/s, but the highest actual UDP throughput with maximum packet size is only about 30 Mbit/s due to the MAC and PHY overheads.

The OFDM PHY of IEEE Std 802.11a and IEEE Std 802.11g is based on a 64-FFT. The channel size is approximately 20 MHz. The maximum delay spread is about 800 ns, which is sufficient for a LAN with reasonable multipath.

IEEE 802.11 extensions

The IEEE 802.11 Working Group has recently developed and is currently developing many amendment projects, including the following:

- **IEEE Std 802.11e:** IEEE Std 802.11e-2005 defines MAC extensions to CSMA/CA in order to improve QoS. Some MAC efficiency improvements are also included. The QoS extensions improve both DCF and PCF by defining a new hybrid coordination function (HCF), which includes enhanced distributed channel access (EDCA) and the HCF coordinated channel access (HCCA) functions. Both EDCA and HCCA schemes are backward compatible with IEEE 802.11 DCF and frame formats. HCCA offers some centralized scheduled functions. Some of the efficiency improvements include the option of not having immediate acknowledgments and allowing block (i.e., delayed) acknowledgments. IEEE Std 802.11e works for any of the underlying PHY modes.
- **IEEE P802.11n:** The primary objective of the amendment project IEEE P802.11n is to improve the throughput of IEEE Std 802.11 beyond 100 Mbit/s, using techniques such as SDMA and MIMO. Both PHY and MAC enhancements are under consideration. This project is expected to make use of most of the IEEE 802.11e features and to define additional efficiency mechanisms. The project is expected to achieve most of the throughput improvements by doubling the channel size. Completion of the standard is expected in 2007.
- **IEEE P802.11p:** The objective of the amendment project IEEE P802.11p is to support communication between vehicles, and from vehicles to the roadside, while operating at speeds up to 200 km/h for communication ranges up to 1000 m. This is specifically targeted for the 5 GHz bands and in all forms of surface transportation. Both MAC and PHY enhancements are being considered, including a smaller channel size of 10 MHz.
- **IEEE P802.11s:** The amendment project IEEE P802.11s is working on defining a mesh MAC extension to IEEE Std 802.11. The objective is to use the existing IEEE 802.11 addressing format (especially the four-address format) to fully define a multihop network with autoconfiguration capabilities.

Using IEEE Std 802.11 as a MAN

Although IEEE Std 802.11 and its extensions were designed to operate in a LAN environment, many IEEE 802.11 systems, sometimes with modifications, are being operated in long-range outdoor MAN environments. To extend the range, most of these systems make use of high-gain directional antennas to support clients communicating with a (standard or modified) IEEE 802.11 AP. This situation massively exacerbates the hidden node problem, forcing every terminal to be hidden from every other. MAC customization becomes particularly important. Many proprietary and nonstandard extensions to IEEE Std 802.11 have been applied, including the following:

- **IEEE 802.16-like MAC over IEEE 802.11 PHY:** Some IEEE 802.11 chipsets allow an implementor to use the IEEE 802.11 PHY, but bypass the IEEE 802.11 MAC. Some vendors have used such an approach to implement a TDMA scheme. However, the PHY overhead and some of the MAC overhead cannot be eliminated using this approach. Similarly, the limitations of the IEEE 802.11 PHYs, such as the limited ability to address the delay spread typical of long-range outdoor environments, cannot be eliminated either.
- **Modified IEEE 802.11 MAC:** Some of the proprietary modifications include modification of basic IEEE 802.11 timing or channel access parameters, the turning off of acknowledgments, and modification of the acknowledgment timeout. The IEEE 802.11 standard requires that the immediate acknowledgment be received within a specific time. This time is sufficient to deal with smaller propagation delays in a LAN. However, long-range communication such as a MAC requires longer propagation delays.
- **FDD:** Some systems use an FDD-like approach, with communications in opposite directions using different IEEE 802.11 channels.

Quantitative comparison of IEEE Std 802.11 and IEEE Std 802.16

In general, the IEEE 802.11 and IEEE 802.16 technologies are complementary, as one is targeted for LANs and the other for MANs. However, we need to summarize the differences between the two standards in

order to stress the differences in the target markets, which is reflected in the design choices made. Table 16-1 shows some of these differences.

Table 16-1: Comparison of IEEE Std 802.11 and IEEE Std 802.16

Feature	IEEE Std 802.11	IEEE Std 802.16
Medium access	CSMA/CA Some TDMA-like functions in IEEE Std 802.11e	TDM/TDMA OFDMA (optional)
Channel size	~22 MHz (IEEE Std 802.11b) 20 MHz (IEEE Std 802.11a and IEEE Std 802.11g) 10 MHz (IEEE Std 802.11j TM)	1.25–28 MHz
Maximum PHY data rate	54 Mbit/s	72 Mbit/s (10 MHz channel)
Maximum (bit/s)/Hz	~2.7	~5
Delay spread tolerance	Up to 800 ns	Up to 10 μ s
Minimum MAC overhead	28 bytes (header + CRC)	6 bytes
QoS	Limited QoS support (up to eight priorities per system) in IEEE Std 802.11e	Per-connection QoS

Although IEEE Std 802.11e supports a form of QoS, with eight priorities (or classes), the addition of QoS to IEEE Std 802.11 is an afterthought. On the other hand, the IEEE 802.16 MAC is a QoS-centric MAC that has been designed with QoS as an integral part of the MAC functions. Moreover, the IEEE 802.16 MAC is much more efficient than IEEE Std 802.11 for outdoor applications, with packing, ARQ, dynamic fragmentation, and smaller header overhead. The problems associated with the IEEE 802.11 CSMA/CA protocol, such as hidden nodes, capture effect, and the near-far problem, are eliminated by the use of a centrally scheduled IEEE 802.16 MAC with TDM/TDMA (and optionally OFDMA).

Ultimately, IEEE Std 802.11 and IEEE Std 802.16 are two parts of a team that can form the basis of a flexible network with an extensive range of applicability.

IEEE 802.20 WORKING GROUP

The IEEE 802.20 Working Group, chartered to develop a standard for mobile broadband access supporting vehicular speeds, first met formally in March 2003. The goal is to support operation in licensed bands below 3.5 GHz allocated to the mobile service. The main performance targets given in the IEEE P802.20 PAR are shown in Table 16-2.

Table 16-2: IEEE 802.20 performance targets

Characteristic	Target value
Mobility	Vehicular mobility classes up to 250 km/h (as defined in ITU-R M.1034-1)
Sustained spectral efficiency	>1 (bit/s)/Hz per cell
Peak user data rate	> 1 Mbit/s in paired 1.25 MHz channel
Peak aggregate data rate per cell in the DL	>4 Mbit/s in 1.25 MHz channel
Peak aggregate data rate per cell in the UL	> 800 kbit/s 1.25 MHz channel
Airlink MAC round-trip time	< 10 ms
Duplex	FDD, TDD
Channel bandwidth	1.25 MHz, 5 MHz

At the moment, very little can be said about the technology itself, and whether it meets the targets, as the group has addressed mostly the technology selection process and system requirements rather than developing draft specifications. The working group first considered proposals for draft text in

November 2005, but the process is in its early stages. It is too soon to speculate on the content of the future standard.

IEEE 802.22 WORKING GROUP

The IEEE P802.22 PAR on wireless regional area networks (WRANs) was approved in September 2004. The PAR covers "Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications of fixed point-to-multipoint wireless regional area networks operating in the VHF/UHF TV broadcast bands between 54 MHz and 862 MHz." This range of operation is based on U.S. frequency allocations and implies 6 MHz channelization. For other scenarios, the broader frequency range of 41 MHz to 910 MHz may be considered a target, with 6 MHz, 7 MHz, or 8 MHz channelization. However, the PAR specially addresses U.S. rules promulgated by the FCC.

The aim of the project is to develop a fixed broadband access standard for use in licensed but unused broadcast television spectra. Such a network is envisioned to have a long range, yet prevent interference with incumbent licensed services within the same spectrum. A primary objective is to provide rural, low-population markets with performance levels similar to those of broadband access technologies servicing urban and suburban areas. The WRAN must support QoS, enabling simultaneous support for data, voice, and audio/video applications, and must be available 99.9% of the time.

The target markets to be addressed by such a system are residential, small office/home office (SOHO), small business, multitenant dwellings, and campuses. IEEE P802.22 is intended to provide these customers with capabilities similar to those provided by digital subscriber line (ADSL) and cable modems, but more economically in sparsely populated rural settings. The system is expected to have a typical range of 33 km, with a maximum range of 100 km. The minimum peak throughput at cell edge is required to be 1.5 Mbit/s per subscriber in the DL and 384 kbit/s per user in the UL. To achieve this, the PAR proposes a spectral efficiency goal of 5 (bit/s)/Hz.

Use of the VHF/UHF TV broadcast frequency range is possible in near-LOS and NLOS situations. In the rural settings targeted, operation may include

partial or complete blockage by foliage, contributing to multipath and attenuation of the signal. We may expect that macrodiversity, repeaters, and other techniques will be combined with the natural propagation characteristics of the frequency band to solve the issues of range, multipath, and blockage.

The problems faced by systems operating in this spectrum are compounded by the fact that they are operating in an license-exempt mode in spectrum that technically is licensed to other uses. These other uses are not limited to broadcast TV services that would be relatively easy to map and avoid. They also include FCC Part 74 devices, such as licensed wireless microphones, wireless intercoms, etc. Regulations require that license-exempt users detect these licensed users and avoid interfering with them by moving to a different frequency. This may, however, be very challenging because some of the licensed users are transient and low power in nature.

To better ensure the proper avoidance of incumbents, designers envision that subscriber devices (and repeaters) will be in a master-slave relationship with the BS, with the BS providing centralized power and spectrum management and centralized scheduling control. They also imagine distributed sensing of the RF environment by the subscriber devices for the purpose of detecting incumbents, with the sensing also controlled by the BS.

In terms of services supported, the clear intent of the IEEE P802.22 functional requirements document (see [B46]) is to support variable-length IP-based services with some level of QoS.

There is currently some interest in using a version of IEEE Std 802.16, modified to provide the intended detection and avoidance of incumbents, in order to meet the needs of the IEEE P802.22 PAR.

ETSI BRAN

Within the European Telecommunications Standards Institute (ETSI), the Broadband Radio Access Networks (BRAN) Technical Committee has been active since 1997. Its three primary activities include ETSI BRAN HiperLAN/2 (a WLAN standard that is, in effect, defunct) and two broadband wireless access standards: ETSI BRAN HiperACCESS and ETSI BRAN HiperMAN.

The IEEE 802.16 Working Group has had an active liaison relationship with ETSI BRAN since 1999; for example, the two groups have exchanged over 60 documents and reports. The initial collaboration strove for harmonization between the WirelessMAN-SC and ETSI BRAN HiperACCESS projects, in which ETSI was the first mover. Although this effort made some progress, it ultimately failed. Later, the attention turned to the lower frequency work, in which IEEE Std 802.16 went first. In this case, the harmonization results were remarkably successful. ETSI BRAN HiperMAN, as discussed below, is compatible with the WirelessMAN-OFDM and WirelessMAN-OFDMA modes in IEEE Std 802.16.

ETSI BRAN HiperACCESS

ETSI BRAN HiperACCESS defines PMP broadband wireless for use in the frequency bands between 11 GHz and 66 GHz. In this respect, it attempts to fill the same niche as IEEE 802.16 WirelessMAN-SC.

The ETSI BRAN HiperACCESS standard was developed by many of the same participants involved in creating WirelessMAN-SC. Some parties, however, participated in only one. The result was less harmonization than would ultimately have been desirable. Both standards assume LOS operation and specify a single-carrier PHY. Many other similarities exist also. However, the two also have significant differences and are not compatible.

ETSI BRAN HiperACCESS shares the following features with IEEE 802.16 WirelessMAN-SC:

- Single-carrier modulation, with QPSK, 16-QAM, and 64-QAM
- Similar FEC
- Same basic request/grant scheme
- Same CoSs and QoS concepts
- Same basic ranging, power control, and PHY maintenance
- Similar UL and DL MAP structure
- Similar frame structure, including support for TDD, FDD, and H-FDD
- Similar RCT specification

ETSI BRAN HiperACCESS differs from IEEE 802.16 WirelessMAN-SC in the following ways:

- Fixed-length packet ATM cell transport only
- No packing
- No fragmentation
- Far fewer options of FEC combinations (a few options are defined, tailored for the size of an ATM cell)
- No incremental BW requests
- No piggybacked BW requests

The result was a standard that is simpler to implement than WirelessMAN-SC, but considerably less efficient (even for ATM cells) and not forward looking to IP as the preferred network protocol.

ETSI BRAN HiperMAN

When ETSI BRAN initiated the HiperMAN activity to consider fixed broadband wireless access below 11 GHz, the amendment project IEEE P802.16a was well on its way to adding the new PHY specifications WirelessMAN-OFDM, WirelessMAN-OFDMA, and WirelessMAN-SCa, all operating under the IEEE 802.16 MAC, first defined in IEEE Std 802.16-2001. Thanks to active cooperation between the IEEE 802.16 Working Group and the ETSI BRAN HiperMAN activity, a unified solution was obtained.

One key player in this success was Mariana Goldhamer, who served as the IEEE 802.16 Working Group's liaison official to ETSI BRAN while also chairing the ETSI BRAN HiperMAN activity and later serving as vice chair of the ETSI BRAN Technical Committee. Another key player was Nico van Waes, the technical editor of the IEEE 802.16a and ETSI BRAN HiperMAN drafts as well as the area coordinator (ETSI terminology for chair) of ETSI BRAN HiperMAN during that period.

Rather than adapting the MAC from ETSI BRAN HiperACCESS, the ETSI BRAN HiperMAN group came to the conclusion that it would instead adopt the IEEE 802.16 MAC. However, it sought a single PHY solution, rather than three of them. It came to choose WirelessMAN-OFDM, eventually supporting a standard that was a subset of WirelessMAN-OFDM. The ETSI project was

not passive in the collaboration; it contributed ideas and comments to IEEE Std 802.16 during the refinement of that standard. Notably, ETSI moved first to specify UL subchannelization; this was not added into WirelessMAN-OFDM until IEEE Std 802.16-2004 [B20].

More recently, in 2005, the scope of the ETSI BRAN HyperMAN project was extended to include nomadic wireless access. At this stage, ETSI BRAN HyperMAN moved to extend its support of IEEE Std 802.16 and incorporated not only WirelessMAN-OFDM but also WirelessMAN-OFDMA.

As discussed in Chapter 15, ETSI is very active in the development of conformance test specifications for IEEE Std 802.16, particularly through its agreement with the WiMAX Forum. ETSI conformance test documents have referenced IEEE Std 802.16 as their source standards. IEEE Std 802.16 has already moved to accept the notion of making normative reference to ETSI conformance test documentation.

OTHER REGIONAL STANDARDS ACTIVITIES

Beyond its active relationship with ETSI, the IEEE 802.16 Working Group has developed and maintained relationships with some other regional organizations that are interested in broadband wireless access standardization.

Korean Telecommunication Technology Association (TTA) and WiBro

The Korean TTA approached the IEEE 802.16 Working Group in January 2004 with information concerning its effort to develop a parallel standard in the PG05 project, later renamed PG302. Unlike the ETSI BRAN interest, which was on fixed access, the TTA focus was on mobile access. Also, in contrast to ETSI BRAN HyperMAN's interest in WirelessMAN-OFDM, it was clear that the TTA focus was on WirelessMAN-OFDMA. Early in the process, it appeared that the TTA was headed toward a standard similar to, but different from, the WirelessMAN-OFDMA that was eventually approved in IEEE Std 802.16e. However, a number of letters and reports were exchanged, and meetings were held to coordinate activity. Eventually, the two projects began to see significant alignment.

In July 2004, the Korean Ministry of Information and Communication announced that service in the 2.3 GHz spectrum, which had been set aside for portable Internet service, "must comply with IEEE 802.16-2004 and IEEE 802.16e/Draft3 or later versions." The Korean regulations also stipulate some additional specifications, including use of the WirelessMAN-OFDMA mode with a 1024-FFT. The Korean government named this service *WiBro*, for wireless broadband. It is important to understand that WiBro is a service, not a technology. The regulations required that the technology be WirelessMAN-OFDMA.

In retrospect, the IEEE 802.16 Working Group's decision to support multiple modes turns out to have been well justified. The working group, in trying to develop a single standard for worldwide use, had a major challenge because the world includes many diverse interests. In this case, the Europeans leaned toward an OFDM solution and the Koreans toward OFDMA. The multimode decision included in IEEE Std 802.16a formed a basis to satisfy both.

China Communications Standards Association (CCSA)

The CCSA has been pursuing broadband wireless access standards through Working Group 3 of its Technical Committee 5. CCSA has been communicating actively with the IEEE 802.16 Working Group since IEEE Std 802.16's Session #31, which was held in Shenzhen, China, in May 2004. Since then, the organizations have remained in contact through letters, reports, and liaison exchanges. In November 2005, CCSA reported a number of standards projects in fixed access related to IEEE Std 802.16, including test specifications. Work regarding mobile broadband wireless access was at an earlier stage.

INTERNATIONAL TELECOMMUNICATIONS UNION (ITU)

Historically, some of the IEEE 802 standards have been entered into the more formal arena of "international" standardization through IEEE 802's engagement with Joint Technical Committee 1 (JTC1), the committee on information technology standards administered by two private Geneva-based organizations, the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). Although the original

collaborations covered only wired networks, the partnership was extended to wireless networks also by the adoption of IEEE Std 802.11 as ISO/IEC 8802-1 in 1999.

In spite of the successful relationship between IEEE 802 and ISO/IEC JTC1, the IEEE 802.16 Working Group has never shown an interest in following that precedent. The working group has always recognized the value of engaging with the formal international process in Geneva. However, instead of ISO/IEC, IEEE Std 802.16 looks to partner with the ITU, particularly the ITU Radiocommunications Sector (ITU-R). This is partly because IEEE Std 802.16 is the only IEEE 802 standard expected to operate significantly in licensed spectra, the administration of which is significantly dependent on the ITU. It is also because the ITU has always been a focal point of the telecommunications industry. IEEE Std 802.16 is a convergent technology, drawing significantly from the data communications community, but targeting applications that have historically been supported by the telecommunications establishment. Many of the potential customers for IEEE 802.16 systems have a natural home in ITU. The IEEE 802.16 community naturally seeks to engage that community and encourage its participation.

From the beginning, IEEE Std 802.16 has looked to engage with ITU. The original IEEE 802.16 PAR, submitted in March 1999, in answering the question "Is this standard planned for adoption by another international organization?" responded "Yes," referencing ITU. Since then, IEEE 802.16 PARs have done so consistently.

Central to building the IEEE 802.16 Working Group's relationship with ITU-R was Dr. José Costa, who has served since Session #1 in 1999 as the working group's ITU-R liaison official. Dr. Costa originally helped to connect the working group with ITU-R's Joint Rapporteurs Group 8A/9B, on Wireless Access Systems, where Dr. Costa served as one of two principle rapporteurs.

The relationship strengthened significantly in October 2003, when ITU-R named IEEE as a Sector Member, under the same membership classification as ISO. Shortly before, the ITU-R's Strategy and Policy Unit had published its seminal document *The Birth of Broadband* [B28], which made numerous references to the role of IEEE Std 802.16, particularly regarding the expansion of Internet access in rural and developing areas. ITU, perhaps as a

consequence, invited the IEEE 802.16 Working Group chair to speak at its major conference, ITU Telecom World, in Geneva during October 2003. During that meeting, the working group chair, with the assistance of ITU-R Counsellor Fabio Leite, met with staff and various study group officials, discussing opportunities to develop the relationship and, in particular, on drafting new ITU-R recommendations based on the IEEE 802.16 standard and its amendments, which were seen to be valuable because of ITU-R's "global approach and visibility." Following those discussions, the working group began to pursue contacts with several ITU study groups, including some in ITU's Telecommunications Bureau (related to network access and cable modem technology).

In November 2003, the IEEE 802.16 Working Group followed up these discussions with a letter to ITU-R indicating its support for the idea of developing ITU-R recommendations referring to IEEE Std 802.16. This work was slightly delayed by the termination of Joint Rapporteurs Group 8A/9B. However, with the assistance of Dr. Costa (who had assumed the chairmanship of Working Party 8A), the work progressed. IEEE, using its ITU-R membership, contributed a series of documents to Working Party 9B, coordinated with ETSI, on the development of a recommendation on "radio interface standards for broadband wireless access (BWA) systems in the fixed service operating below 66 GHz," pointing to IEEE Std 802.16 and the compatible ETSI BRAN HiperMAN standard. After many discussions and coordination actions, Study Group 9 approved this recommendation in December 2005. The ITU-R recommendation awaits a formal written consultation of the member administration in mid-2006.

In March 2005, the IEEE contributed a parallel proposal to ITU-R Working Party 8A, proposing a preliminary draft new recommendation on "radio interface standards for broadband wireless access systems in the mobile service operating below 6 GHz." The proposal would point to IEEE Std 802.16, including the IEEE 802.16e mobility amendment. The proposal has not progressed rapidly in Working Party 8A, mainly because supporters of a number of alternative technologies have become vocal. It is far from certain where this will lead.

Appendix A IEEE 802.16 headers, subheaders, and management messages

The list of IEEE 802.16 MAC headers, subheaders, and MAC management messages is provided here for quick reference. Table A-1 shows the list of MAC headers, subheaders, and special payloads.

Table A-1: MAC headers, subheaders and special payloads

Description	Size in bytes
Generic MAC header	6
BW request header	6
Fragmentation subheader (FSH)	1
FSH (ARQ)	2
FSH (Extended)	2
Grant management subheader (GMSH)	2
Packing subheader (PSH)	2
PSH (ARQ)	3
PSH (Extended)	3
Mesh subheader (MSH)	2
Fast-feedback allocation subheader (FFSH)	1

Table A-2 lists the management messages and the type of connections that may be used to send them.

Table A-2: Management messages

Type	Name	Description	Connection
0	UCD	UL channel descriptor	Fragmentable Broadcast
1	DCD	DL channel descriptor	Fragmentable Broadcast
2	DL-MAP	Downlink access definition	Broadcast
3	UL-MAP	Uplink access definition	Broadcast
4	RNG-REQ	Ranging request	Initial Ranging or Basic
5	RNG-RSP	Ranging response	Initial Ranging or Basic
6	REG-REQ	Registration request	Primary Management
7	REG-RSP	Registration response	Primary Management
8		Reserved	
9	PKM-REQ	Privacy key management request	Primary Management
10	PKM-RSP	Privacy key management response	Primary Management
11	DSA-REQ	Dynamic service addition request	Primary Management
12	DSA-RSP	Dynamic service addition response	Primary Management
13	DSA-ACK	Dynamic service addition acknowledgment	Primary Management
14	DSC-REQ	Dynamic service change request	Primary Management

Table A-2: Management messages (Continued)

Type	Name	Description	Connection
15	DSC-RSP	Dynamic service change response	Primary Management
16	DSC-ACK	Dynamic service change acknowledgment	Primary Management
17	DSD-REQ	Dynamic service deletion request	Primary Management
18	DSD-RSP	Dynamic service deletion response	Primary Management
19		Reserved	
20		Reserved	
21	MCA-REQ	Multicast assignment request	Primary Management
22	MCA-RSP	Multicast assignment response	Primary Management
23	DBPC-REQ	DL burst profile change request	Basic
24	DBPC-RSP	DL burst profile change response	Basic
25	RES-CMD	Reset command	Basic
26	SBC-REQ	SS basic capability request	Basic
27	SBC-RSP	SS basic capability response	Basic
28	CLK-CMP	SS network clock comparison	Broadcast
29	DREG-CMD	De/Re-register Command	Basic
30	DSX-RVD	DSx received message	Primary Management

Table A-2: Management messages (Continued)

Type	Name	Description	Connection
31	TFTP-CPLT	Config file TFTP complete message	Primary Management
32	TFTP-RSP	Config file TFTP complete response	Primary Management
33	ARQ-Feedback	Stand-alone ARQ Feedback	Basic
34	ARQ-Discard	ARQ Discard	Basic
35	ARQ-Reset	ARQ Reset	Basic
36	REP-REQ	Channel measurement report request	Basic
37	REP-RSP	Channel measurement report response	Basic
38	FPC	Fast power control	Broadcast
39	MSH-NCFG	Mesh network configuration	Broadcast
40	MSH-NENT	Mesh network entry	Basic
41	MSH-DSCH	Mesh distributed schedule	Broadcast
42	MSH-CSCH	Mesh centralized schedule	Broadcast
43	MSH-CSCF	Mesh centralized schedule configuration	Broadcast
44	AAS-FBCK-REQ	AAS feedback request	Basic
45	AAS-FBCK-RSP	AAS feedback response	Basic
46	AAS_Beam_Select	AAS beam select	Basic
47	AAS_BEAM_REQ	AAS beam request	Basic
48	AAS_BEAM_RSP	AAS beam response	Basic
49	DREG-REQ SS	SS deregistration message	Basic
50-255		Reserved	

Bibliography

- [B1] Alamouti, S. M., "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas of Communication*, vol. 16, pp. 1451-1458, Oct. 1998.
- [B2] Alexiou, A., and Haardt, M., "Smart Antenna Technologies for Future Wireless Systems: Trends and Challenges," *IEEE Communications Magazine*, vol. 42, no. 9, pp. 90-97, Sept. 2004.
- [B3] Ayanoglu, E., Eng, K. Y., and Karol, M. J., "Wireless ATM: Limits, Challenges and Proposals," *IEEE Personal Communications*, Aug. 1996.
- [B4] Anderson, H. R., *Fixed Broadband Wireless System Design*, John Wiley & Sons, 2003.
- [B5] Ball, C. F., Humburg, E., Ivanov, K., and Trembl, F., "Performance analysis of IEEE 802.16 based cellular MAN with OFDM-256 in mobile scenarios," *Proceedings of IEEE Vehicular Technology Conference 2005-Spring*, vol. 3, pp. 2061-2066, May 2005.
- [B6] Bertsekas, D., and Gallager, R., *Data Networks*, Prentice Hall, 1992.
- [B7] Bing, B., *Broadband Wireless Access*, Kluwer Academic Publishers, 2000.
- [B8] C50-20010820-026, "1xEV-DV Evaluation Methodology Addendum [V6]," July 2001, (http://ftp.3gpp2.org/TSGC/Working/2001/TSG-C_0108/TSG-C-0801-Portland/WG5/C50-20010820-026%201xEV-DV-Evaluation-Methodology-Addendum-V6.doc).
- [B9] Chandran, S. R., "A Selective Repeat ARQ Scheme for Point-to-Multipoint Communications and its Throughput Analysis," *ACM SIGCOMM Conference on Communications Architecture and Protocols*, 1986.

- [B10] Cicconetti, C., Lenzini, L., Mingozzi, E., and Eklund, C., "Quality of Service Support in IEEE 802.16 Networks", *IEEE Network*, March/April 2006.
- [B11] COST Action 231, "Digital mobile radio towards future generation systems, final report," tech. rep., European Communities, EUR 18957, 1999.
- [B12] Doron, A., et al., "Problem in Interleaver and Permutation Combination in OFDMA," *IEEE C802.16maint-05/068r23*, July 2005.
- [B13] Eklund, C., Marks, R. B., Stanwood, K. L., and Wang, S., "IEEE Standard 802.16: A Technical Overview of the WirelessMAN Air Interface for Broadband Wireless Access," *IEEE Communications Magazine*, pp. 98–107, June 2002.
- [B14] ETSI TS 101 761-1 v1.2.1, Broadband Radio Access Networks (BRAN): HIPERLAN Type 2—Data Link Control (DLC) Layer—Part 1: Basic Data Transport Functions, 2000.
- [B15] ETSI TS 101 350 v6.1.0, Digital Cellular telecommunication System (Phase 2+): General Packet Radio Service (GPRS)—Overall description of the GPRS Radio Interface Stage 2, 1998.
- [B16] ETSI EN 301 958 v1.1.1, Digital Video Broadcasting (DVB); Interaction channel for Digital Terrestrial Television (RCT) incorporating Multiple Access OFDM, 2002.
- [B17] ETSI TS 121 101, Universal Mobile Telecommunications System (UMTS); Technical Specifications and Technical Reports for a UTRAN-based 3GPP system.
- [B18] Ghosh, A., Wolter, D. R., Andrews, J. G., and Chen, R., "Broadband wireless access with WiMax/802.16: Current performance benchmarks and future potential," *IEEE Communications Magazine*, vol. 43, no. 2, pp. 129–136, Feb 2005.
- [B19] Housey, R., Polk, W., Ford, W., and Solo, D., "Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile," *RFC 3280*, Apr. 2002.

- [B20] IEEE Std 802.16-2004, IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems.
- [B21] IEEE Std 802.16/Conformance01-2003, IEEE Standard for Conformance to IEEE Std 802.16—Part 1: Protocol Implementation Conformance Statement (PICS) Proforma for 10–66 GHz WirelessMAN-SC Air Interface.
- [B22] IEEE Std 802.16/Conformance02-2003, IEEE Standard for Conformance to IEEE Std 802.16—Part 2: Test Suite Structure and Test Purposes for 10–66 GHz WirelessMAN-SC Air Interface.
- [B23] IEEE Std 802.16/Conformance03-2004, IEEE Standard for Conformance to IEEE Std 802.16—Part 3: Radio Conformance Tests (RCT) for 10–66 GHz WirelessMAN-SC Air Interface.
- [B24] IEEE Std 802.16e-2005, IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems—Amendment 2—Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands.
- [B25] IEEE Std 802.16f-2005, IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems—Amendment 1—Management Information Base.
- [B26] IEEE Std 802.16.2-2004, IEEE Recommended Practice for Local and metropolitan area networks—Coexistence of Fixed Broadband Wireless Access Systems.
- [B27] Ishimaru, A., *Electromagnetic Waves, Propagation, Radiation and Scattering*, Prentice Hall, 1991.
- [B28] ITU Internet Report, "The Birth of Broadband," ITU Sales Service <<http://www.itu.int/osg/spu>>.
- [B29] ITU-T Recommendation X.200, Information technology—Open Systems Interconnection—Basic Reference Model: The basic model, 1994.
- [B30] ITU-R Recommendation M.1225, "Guidelines for valuation of radio transmission technologies for IMT-2000," 1997.

- [B31] Jeon, W. S., and Jeong, D., "Improved Selective Repeat ARQ Scheme for Mobile Multimedia Communications," *IEEE Communications Letters*, vol. 4, no. 2, 2000.
- [B32] Johnson, D., and Dudgeon, D., *Array Signal Processing*, Prentice Hall, 1993.
- [B33] Keshav, S., *An Engineering Approach to Computer Networking*, Addison-Wesley, 1997.
- [B34] Kwon, T., Lee, H., Choi, S., Kim, J., Cho, D.-H., Cho, S., Yun, S., Park, W.-H., and Kim, K., "Design and implementation of a simulator based on a cross-layer protocol between MAC and PHY layers in a WiBro Compatible IEEE 802.16e OFDMA system," *IEEE Communications Magazine*, pp. 136-146, Dec. 2005.
- [B35] Lee, R., Kim, J., Yu, J., and Lee, J., "Capacity analysis considering channel resource overhead for wireless mobile Internet system," *Proceedings of IEEE Vehicular Technology Conference 2005-Spring*, May 2005.
- [B36] Li, H., Lindskog, J., Malmgren, G., Miklos, G., Nilsson, F., and Rydell, G., "Automatic Repeat Request (ARQ) Mechanism in HIPERLAN/2," *The IEEE Semiannual Vehicular technology Conference - VTC2000*, Spring 2000.
- [B37] Liberti, J. C., and Rappaport, T. S., *Smart Antenna for Wireless Communications*, Prentice Hall, 1999.
- [B38] Marks, R. B., "IEEE Standard 802.16 for Global Broadband Wireless Access," *ITU Telecom World 2003*, Geneva, Oct. 12-18, 2003.
- [B39] Motorola, "Evaluation Methods for High Speed Downlink Packet Access (HSDPA)," TSG-R1 document, TSGR#14(00)0909, 2000.
- [B40] NIST 800-38C, Recommendation for Block Cipher Modes of Operation: the CCM Mode for Authentication and Confidentiality, May 2004.
- [B41] Pang, Q., Bigloo, A., Leung, V. C., and Scholefield, C., "Performance Evaluation of Retransmission Mechanisms in GPRS Networks," *IEEE WCNC'00*, Sept. 2000.
- [B42] Partridge, C., *Gigabit Networking*, Addison-Wesley, 1993.

- [B43] Rosen, E., Viswanathan, A., and Callon, R., "Multiprotocol Label Switching Architecture," *IETF RFC 3031*, Jan. 2001.
- [B44] Sandhu, S., and Paulraj, A., "Space-time block codes: a capacity perspective," *IEEE Communication Letters*, vol. 4, pp. 384-386, 2000.
- [B45] Schneier, B., *Applied Cryptography: Protocol, Algorithms and Source code in C*, 2d ed., John Wiley & Sons, 1994.
- [B46] SCTE DSS 00-05, Radio Frequency Interface Specification, v.1.1, *DOCSIS*, July 2000.
- [B47] Seybold, J. S., *Introduction to RF Propagation*, John Wiley & Sons, Inc., 2005.
- [B48] Shin, S., Kang, C., Kim, J.-C., and Oh, S.-H., "The Performance Comparison between WiBro and HSDPA," *2nd International Symposium on Wireless Communication Systems*, pp. 346-350, Sept. 2005.
- [B49] Sklar, B., "Rayleigh Fading Channels in Mobile Digital Communication Systems: Part I: Characterization," *IEEE Communications Magazine*, Sept. 1997.
- [B50] Stallings, W., *Data & Computer Communications*, Prentice Hall, 2000.
- [B51] Stallings, W., *Wireless Communications and Networks*, Prentice Hall, 2002.
- [B52] Stanwood, K., and Piggan, P., "WiMAX and Mesh Networking in the Home," *WiMAX and Mesh Networks Forum*, IEE, Savoy Place, London, June 2005.
- [B53] Stevenson, C. R., Cardeiro, C., Sofer, E., Chouinard, G., "Functional Requirements for the IEEE 802.22 WRAN Standard," *IEEE 802.22 Working Group Document*, IEEE 802.22-05/0007r45, Mar. 2006.
- [B54] Tanenbaum, A. S., *Computer Networks*, Prentice Hall, 1996.
- [B55] Van Nee, R., and Prasad, R., *OFDM for Wireless Multimedia Communications*, Artech House, 2000.

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NOTE—When phrases have been abbreviated in the text of this book, the abbreviations have generally been used when creating this index. See the Acronyms and Abbreviations list at the beginning of the book for the complete phrase for each abbreviation.

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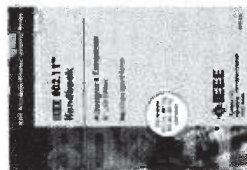
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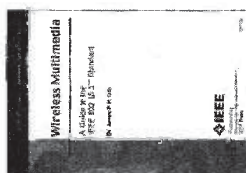


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