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IEEE Standard 802.16: A Technical Overview of the WirelessMAN™ Air Interface for Broadband Wireless Access

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ABSTRACT

The broadband wireless access industry, which provides high-rate network connections to stationary sites, has matured to the point at which it now has a standard for second-generation wireless metropolitan area networks. IEEE Standard 802.16, with its WirelessMAN™ air interface, sets the stage for widespread and effective deployments worldwide. This article overviews the technical medium access control and physical layer features of this new standard.

INTRODUCTION AND MARKET OPPORTUNITIES

IEEE Standard 802.16-2001 [1], completed in October 2001 and published on 8 April 2002, defines the WirelessMAN™ air interface specification for wireless metropolitan area networks (MANs). The completion of this standard heralds the entry of broadband wireless access as a major new tool in the effort to link homes and businesses to core telecommunications networks worldwide.

As currently defined through IEEE Standard 802.16, a wireless MAN provides network access to buildings through exterior antennas communicating with central radio base stations (BSs). The wireless MAN offers an alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and digital subscriber line (DSL) links. Because wireless systems have the capacity to address broad geographic areas without the costly infrastructure development required in deploying cable links to individual sites, the technology may prove less expensive to deploy and may lead to more ubiquitous broadband access. Such systems have been in use for several years, but the development of the new standard marks the maturation of the industry and forms the basis of new industry success using second-generation equipment.

In this scenario, with WirelessMAN technology bringing the network to a building, users inside the building will connect to it with conventional in-building networks such as, for data, Ethernet (IEEE Standard 802.3) or wireless LANs (IEEE Standard 802.11). However, the fundamental design of the standard may eventually allow for the efficient extension of the WirelessMAN networking protocols directly to the individual user. For instance, a central BS may someday exchange medium access control (MAC) protocol data with an individual laptop computer in a home. The links from the BS to the home receiver and from the home receiver to the laptop would likely use quite different physical layers, but design of the WirelessMAN MAC could accommodate such a connection with full quality of service (QoS). With the technology expanding in this direction, it is likely that the standard will evolve to support nomadic and increasingly mobile users. For example, it could be suitable for a stationary or slow-moving vehicle.

IEEE Standard 802.16 was designed to evolve as a set of air interfaces based on a common MAC protocol but with physical layer specifications dependent on the spectrum of use and the associated regulations. The standard, as approved in 2001, addresses frequencies from 10 to 66 GHz, where extensive spectrum is currently available worldwide but at which the short wavelengths introduce significant deployment challenges. A new project, currently in the balloting stage, expects to complete an amend-

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ment denoted IEEE 802.16a [2] before the end of 2002. This document will extend the air interface support to lower frequencies in the 2–11 GHz band, including both licensed and license-exempt spectra. Compared to the higher frequencies, such spectra offer the opportunity to reach many more customers less expensively, although at generally lower data rates. This suggests that such services will be oriented toward individual homes or small to medium-sized enterprises.

The 802.16 Working Group

Development of IEEE Standard 802.16 and the included WirelessMAN™ air interface, along with associated standards and amendments, is the responsibility of IEEE Working Group 802.16 on Broadband Wireless Access (BWA) Standards (http://WirelessMAN.org). The Working Group's initial interest was the 10–66 GHz range. The 2–11 GHz amendment project that led to IEEE 802.16a was approved in March 2000. The 802.16a project primarily involves the development of new physical layer specifications, with supporting enhancements to the basic MAC. In addition, the Working Group has completed IEEE Standard 802.16.2 [3] ("Recommended Practice for Coexistence of Fixed Broadband Wireless Access Systems") to address 10–66 GHz coexistence and, through the amendment project 802.16.2a, is expanding its recommendations to include licensed bands from 2 to 11 GHz.

Historically, the 802.16 activities were initiated at an August 1998 meeting called by the National Wireless Electronics Systems Testbed (N-WEST) of the U.S. National Institute of Standards and Technology. The effort was welcomed in IEEE 802, which opened a Study Group. The 802.16 Working Group has held weeklong meetings at least bimonthly since July 1999. Over 700 individuals have attended a session. Membership, which is granted to individuals based on their attendance and participation, currently stands at 130. The work has been closely followed; for example, the IEEE 802.16 Web site received over 2.8 million file requests in 2000.

Technology Design Issues

Medium Access Control

The IEEE 802.16 MAC protocol was designed for point-to-multipoint broadband wireless access applications. It addresses the need for very high bit rates, both uplink (to the BS) and downlink (from the BS). Access and bandwidth allocation algorithms must accommodate hundreds of terminals per channel, with terminals that may be shared by multiple end users. The services required by these end users are varied in their nature and include legacy time-division multiplex (TDM) voice and data, Internet Protocol (IP) connectivity, and packetized voice over IP (VoIP). To support this variety of services, the 802.16 MAC must accommodate both continuous and bursty traffic. Additionally, these services expect to be assigned QoS in keeping with the traffic types. The 802.16 MAC provides a wide range of service types analogous to the classic asynchronous transfer mode (ATM) service categories as well as newer categories such as guaranteed frame rate (GFR).

The 802.16 MAC protocol must also support a variety of backhaul requirements, including both asynchronous transfer mode (ATM) and packet-based protocols. Convergence sublayers are used to map the transport-layer-specific traffic to a MAC that is flexible enough to efficiently carry any traffic type. Through such features as payload header suppression, packing, and fragmentation, the convergence sublayers and MAC work together to carry traffic in a form that is often more efficient than the original transport mechanism.

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

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

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.

Along with the fundamental task of allocating bandwidth and transporting data, the MAC includes a privacy sublayer that provides authentication of network access and connection establishment to avoid theft of service, and it provides key exchange and encryption for data privacy.

To accommodate the more demanding physical environment and different service requirements of the frequencies between 2 and 11 GHz, the 802.16a project is upgrading the MAC to provide automatic repeat request (ARQ) and support for mesh, rather than only point-to-multipoint, network architectures.

The Physical Layer

10–66 GHz — In the design of the PHY specification for 10–66 GHz, line-of-sight propagation was deemed a practical necessity. With this condition assumed, single-carrier modulation was easily selected; the air interface is designated "WirelessMAN-SC." Many fundamental design challenges remained, however. Because of the point-to-multipoint architecture, the BS basically transmits a TDM signal, with individual subscriber stations allocated time slots serially. Access in the uplink direction is by time-division multiple access (TDMA). Following extensive discussions regarding duplexing, a

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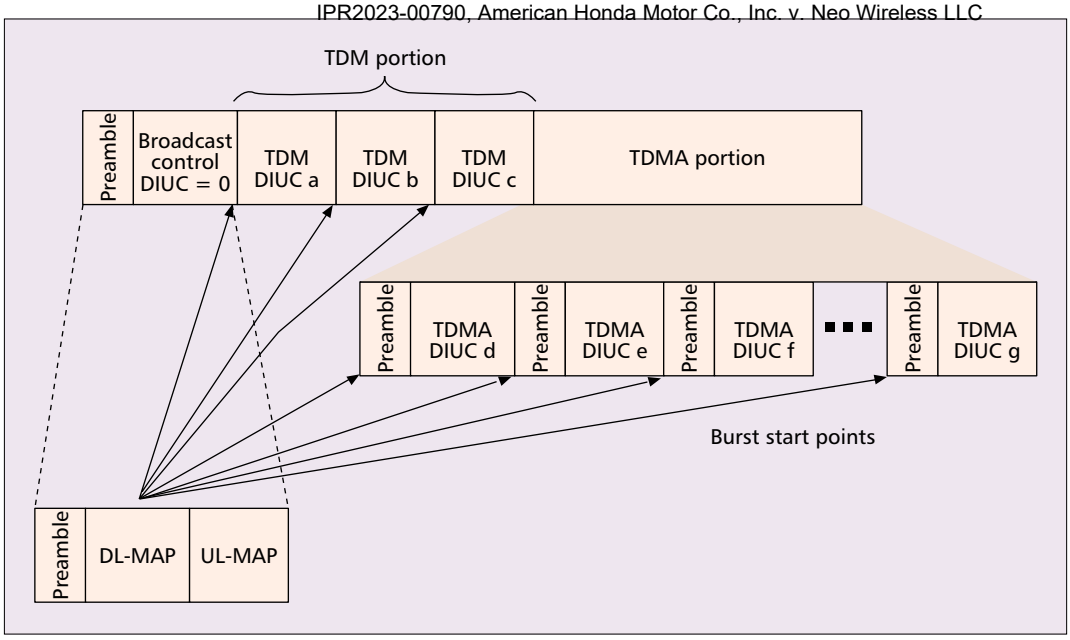
The PHY specification defined for 10–66 GHz uses burst single-carrier modulation with adaptive burst profiling in which transmission parameters, including the modulation and codling schemes, my be adjusted individually to each subscriber station on a frame-by-frame basis. Both TDD and burst FDD variants are defined.



■ **Figure 1.** *The downlink subframe structure.*

burst design was selected that allows both time-division duplexing (TDD), in which the uplink and downlink share a channel but do not transmit simultaneously, and frequency-division duplexing (FDD), in which the uplink and downlink operate on separate channels, sometimes simultaneously. This burst design allows both TDD and FDD to be handled in a similar fashion. Support for half-duplex FDD subscriber stations, which may be less expensive since they do not simultaneously transmit and receive, was added at the expense of some slight complexity. Both TDD and FDD alternatives support adaptive burst profiles in which modulation and coding options may be dynamically assigned on a burst-by-burst basis.

2–11 GHz — The 2–11 GHz bands, both licensed and license-exempt, are addressed in IEEE Project 802.16a. The standard is in ballot but is not yet complete. The draft currently specifies that compliant systems implement one of three air interface specifications, each of which provides for interoperability. Design of the 2–11 GHz physical layer is driven by the need for non-line-of-sight (NLOS) operation. Because residential applications are expected, rooftops may be too low for a clear sight line to a BS antenna, possibly due to obstruction by trees. Therefore, significant multipath propagation must be expected. Furthermore, outdoor-mounted antennas are expensive due to both hardware and installation costs.

The three 2–11 GHz air interface specifications in 802.16a Draft 3 are:

- WirelessMAN-SC2: This uses a single-carrier modulation format.
- WirelessMAN-OFDM: This uses orthogonal frequency-division multiplexing with a 256-point transform. Access is by TDMA. This air interface is mandatory for license-exempt bands.
- WirelessMAN-OFDMA: This uses orthogonal frequency-division multiple access with a 2048-point transform. In this system, multiple access is provided by addressing a subset of the multiple carriers to individual receivers.

Because of the propagation requirements, the use of advanced antenna systems is supported.

It is premature to speculate on further specifics of the 802.16a amendment prior to its completion. While the draft seems to have reached a level of maturity, the contents could change significantly in balloting. Modes could even be deleted or added.

Physical Layer Details

The PHY specification defined for 10–66 GHz uses burst single-carrier modulation with adaptive burst profiling in which transmission parameters, including the modulation and coding schemes, may be adjusted individually to each subscriber station (SS) on a frame-by-frame basis. Both TDD and burst FDD variants are defined. Channel bandwidths of 20 or 25 MHz (typical U.S. allocation) or 28 MHz (typical European allocation) are specified, along with Nyquist square-root raised-cosine pulse shaping with a rolloff factor of 0.25. Randomization is performed for spectral shaping and to ensure bit transitions for clock recovery.

The forward error correction (FEC) used is Reed-Solomon GF(256), with variable block size and error correction capabilities. This is paired with an inner block convolutional code to robustly transmit critical data, such as frame control and initial accesses. The FEC options are paired with quadrature phase shift keying (QPSK), 16-state quadrature amplitude modulation (16-QAM), and 64-state QAM (64-QAM) to form burst profiles of varying robustness and efficiency. If the last FEC block is not filled, that block may be shortened. Shortening in both the uplink

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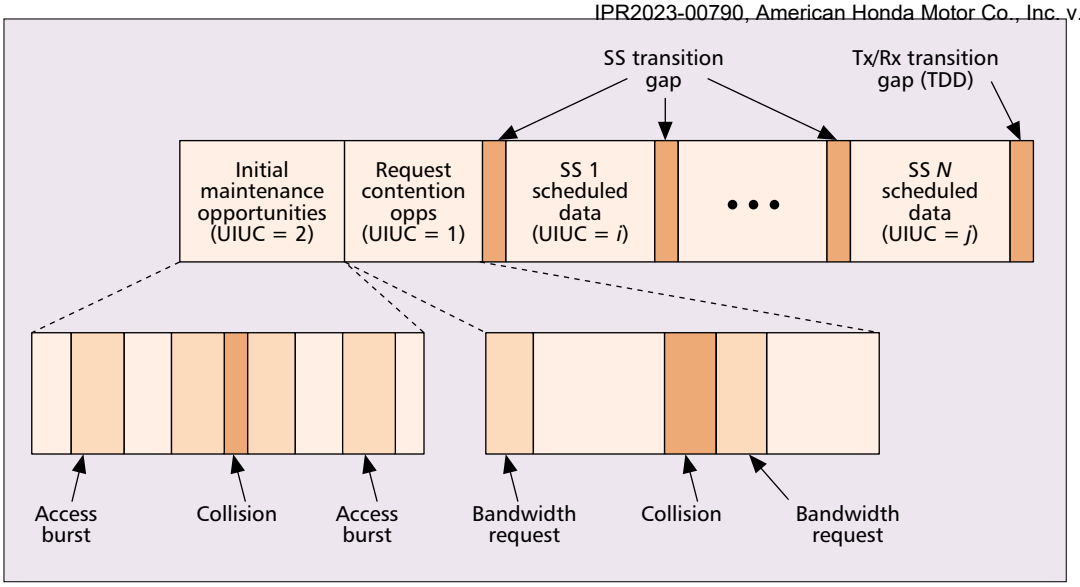


■ **Figure 2.** *The uplink subframe structure.*

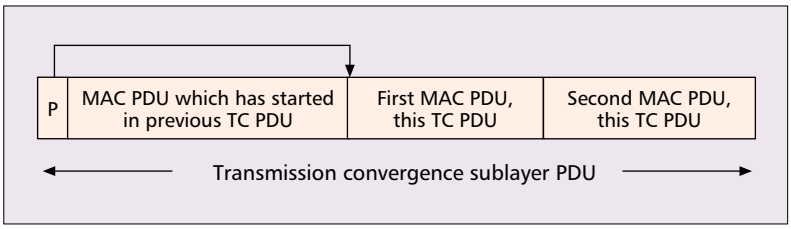
and downlink is controlled by the BS and is implicitly communicated in the uplink map (UL-MAP) and downlink map (DL-MAP).

The system uses a frame of 0.5, 1, or 2 ms. This frame is divided into physical slots for the purpose of bandwidth allocation and identification of PHY transitions. A physical slot is defined to be 4 QAM symbols. In the TDD variant of the PHY, the uplink subframe follows the downlink subframe on the same carrier frequency. In the FDD variant, the uplink and downlink subframes are coincident in time but are carried on separate frequencies. The downlink subframe is shown in Fig. 1.

The downlink subframe starts with a frame control section that contains the DL-MAP for the current downlink frame as well as the UL-MAP for a specified time in the future. The downlink map specifies when physical layer transitions (modulation and FEC changes) occur within the downlink subframe. The downlink subframe typically contains a TDM portion immediately following the frame control section. Downlink data are transmitted to each SS using a negotiated burst profile. The data are transmitted in order of decreasing robustness to allow SSs to receive their data before being presented with a burst profile that could cause them to lose synchronization with the downlink.

In FDD systems, the TDM portion may be followed by a TDMA segment that includes an extra preamble at the start of each new burst profile. This feature allows better support of half-duplex SSs. In an efficiently scheduled FDD system with many half-duplex SSs, some may need to transmit earlier in the frame than they receive. Due to their half-duplex nature, these SSs lose synchronization with the downlink. The TDMA preamble allows them to regain synchronization.

Due to the dynamics of bandwidth demand for the variety of services that may be active, the mixture and duration of burst profiles and the presence or absence of a TDMA portion vary dynamically from frame to frame. Since the recipient SS is implicitly indicated in the MAC headers rather than in the DL-MAP, SSs listen to all portions of the downlink subframe they are capable of receiving. For full-duplex SSs, this means receiving all burst profiles of equal or greater robustness than they have negotiated with the BS.



■ **Figure 3.** *TC PDU format.*

A typical uplink subframe for the 10–66 GHz PHY is shown in Fig. 2. Unlike the downlink, the UL-MAP grants bandwidth to specific SSs. The SSs transmit in their assigned allocation using the burst profile specified by the Uplink Interval Usage Code (UIUC) in the UL-MAP entry granting them bandwidth. The uplink subframe may also contain contention-based allocations for initial system access and broadcast or multicast bandwidth requests. The access opportunities for initial system access are sized to allow extra guard time for SSs that have not resolved the transmit time advance necessary to offset the round-trip delay to the BS.

Between the PHY and MAC is a transmission convergence (TC) sublayer. This layer performs the transformation of variable length MAC protocol data units (PDUs) into the fixed length FEC blocks (plus possibly a shortened block at the end) of each burst. The TC layer has a PDU sized to fit in the FEC block currently being filled. It starts with a pointer indicating where the next MAC PDU header starts within the FEC block. This is shown in Fig. 3.

The TC PDU format allows resynchronization to the next MAC PDU in the event that the previous FEC block had irrecoverable errors.

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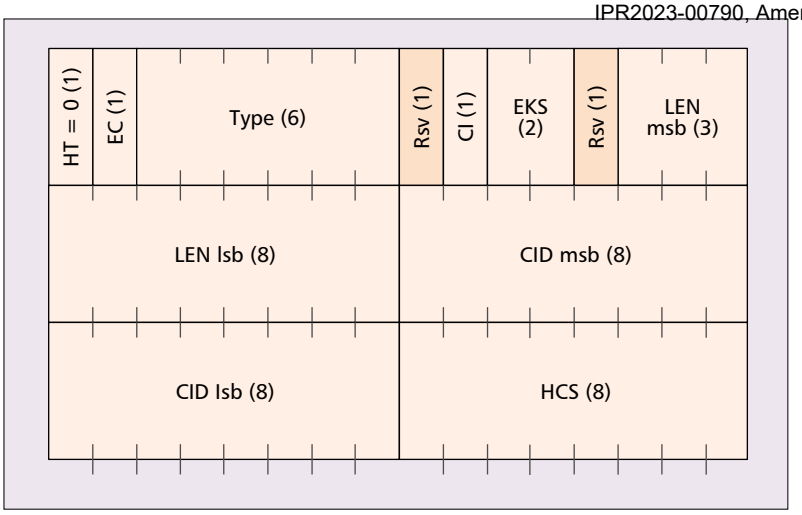

■ **Figure 4.** *Format of generic header for MAC PDU.*

Without the TC layer, a receiving SS or BS would potentially lose the entire remainder of a burst when an irrecoverable bit error occurred.

Medium Access Control Details

The MAC includes service-specific convergence sublayers that interface to higher layers, above the core MAC common part sublayer that carries out the key MAC functions. Below the common part sublayer is the privacy sublayer.

Service-Specific Convergence Sublayers

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

Common Part Sublayer

Introduction and General Architecture — In general, the 802.16 MAC is designed to support a point-to-multipoint architecture with a central BS handling multiple independent sectors simultaneously. On the downlink, data to SSs are multiplexed in TDM fashion. The uplink is shared between SSs in TDMA fashion.

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

Each SS has a standard 48-bit MAC address, but this serves mainly as an equipment identifier, since the primary addresses used during operation are the CIDs. Upon entering the network, the SS is assigned three management connections in each direction. These three connections reflect the three different QoS requirements used by different management levels. The first of these is the basic connection, which is used for the transfer of short, time-critical MAC and radio link control (RLC) messages. The primary management connection is used to transfer longer, more delay-tolerant messages such as those used for authentication and connection setup. The secondary management connection is used for the transfer of standards-based management messages such as Dynamic Host Configuration Protocol (DHCP), Trivial File Transfer Protocol (TFTP), and Simple Network Management Protocol (SNMP). In addition to these management connections, SSs are allocated transport connections for the contracted services. Transport connections are unidirectional to facilitate different uplink and downlink QoS and traffic parameters; they are typically assigned to services in pairs.

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

MAC PDU Formats — The MAC PDU is the data unit exchanged between the MAC layers of the BS and its SSs. A MAC PDU consists of a fixed-length MAC header, a variable-length payload, and an optional cyclic redundancy check (CRC). Two header formats, distinguished by the HT field, are defined: the generic header (Fig. 4) and the bandwidth request header.

Except for bandwidth request MAC PDUs, which contain no payload, MAC PDUs contain either MAC management messages or convergence sublayer data.

Three types of MAC subheader may be present. The grant management subheader is used by an SS to convey bandwidth management needs to its BS. The fragmentation subheader contains information that indicates the presence and orientation in the payload of any fragments of SDUs. The packing subheader is used to indicate the packing of multiple SDUs into a single PDU. The grant management and fragmentation subheaders may be inserted in MAC PDUs immediately following the generic header if so indicated by the Type field. The packing subheader may be inserted before each MAC SDU if so indicated by the Type field. More details are provided below.

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

IEEE 802.16 takes advantage of incorporating the packing and fragmentation processes with the bandwidth allocation process to maximize the flexibility, efficiency, and effectiveness of both. Fragmentation is the process in which a MAC SDU is divided into one or more MAC SDU fragments. Packing is the process in which multiple MAC SDUs are packed into a single MAC PDU payload. Both processes may be initiated by either a BS for a downlink connection or an SS for an uplink connection.

IEEE 802.16 allows simultaneous fragmentation and packing for efficient use of the bandwidth.

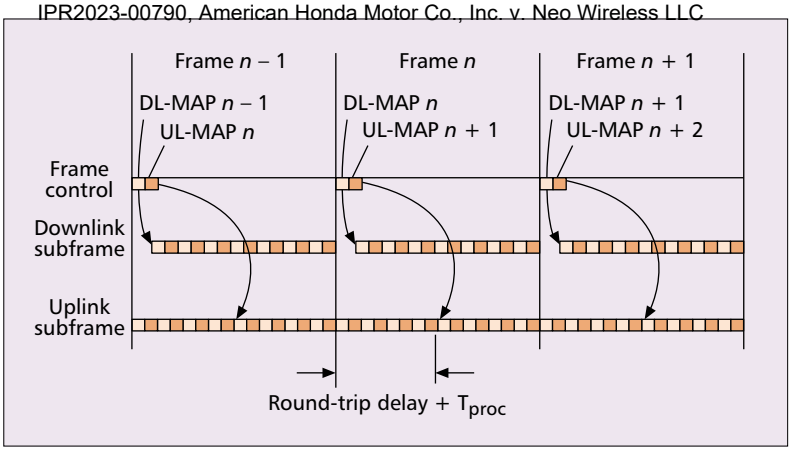
PHY Support and Frame Structure — The IEEE 802.16 MAC supports both TDD and FDD. In FDD, both continuous and burst downlinks are supported. Continuous downlinks allow for certain robustness enhancement techniques, such as interleaving. Burst downlinks (either FDD or TDD) allow the use of more advanced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

The MAC builds the downlink subframe starting with a frame control section containing the DL-MAP and UL-MAP messages. These indicate PHY transitions on the downlink as well as bandwidth allocations and burst profiles on the uplink.

The DL-MAP is always applicable to the current frame and is always at least two FEC blocks long. The first PHY transition is expressed in the first FEC block, to allow adequate processing time. In both TDD and FDD systems, the UL-MAP provides allocations starting no later than the next downlink frame. The UL-MAP can, however, allocate starting in the current frame as long as processing times and round-trip delays are observed. The minimum time between receipt and applicability of the UL-MAP for an FDD system is shown in Fig. 5.

Radio Link Control — The advanced technology of the 802.16 PHY requires equally advanced radio link control (RLC), particularly the capability of the PHY to transition from one burst profile to another. The RLC must control this capability as well as the traditional RLC functions of power control and ranging.

RLC begins with periodic BS broadcast of the burst profiles that have been chosen for the uplink and downlink. The particular burst profiles used on a channel are chosen based on a number of factors, such as rain region and equipment capabilities. Burst profiles for the downlink are each tagged with a Downlink Interval Usage Code (DIUC). Those for the uplink are each tagged with an Uplink Interval Usage Code (UIUC).



■ **Figure 5.** *Minimum FDD map relevance.*

During initial access, the SS performs initial power leveling and ranging using ranging request (RNG-REQ) messages transmitted in initial maintenance windows. The adjustments to the SS's transmit time advance, as well as power adjustments, are returned to the SS in ranging response (RNG-RSP) messages. For ongoing ranging and power adjustments, the BS may transmit unsolicited RNG-RSP messages commanding the SS to adjust its power or timing.

During initial ranging, the SS also requests to be served in the downlink via a particular burst profile by transmitting its choice of DIUC to the BS. The choice is based on received downlink signal quality measurements performed by the SS before and during initial ranging. The BS may confirm or reject the choice in the ranging response. Similarly, the BS monitors the quality of the uplink signal it receives from the SS. The BS commands the SS to use a particular uplink burst profile simply by including the appropriate burst profile UIUC with the SS's grants in UL-MAP messages.

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

In the downlink, the SS is the entity that monitors the quality of the receive signal and therefore knows when its downlink burst profile

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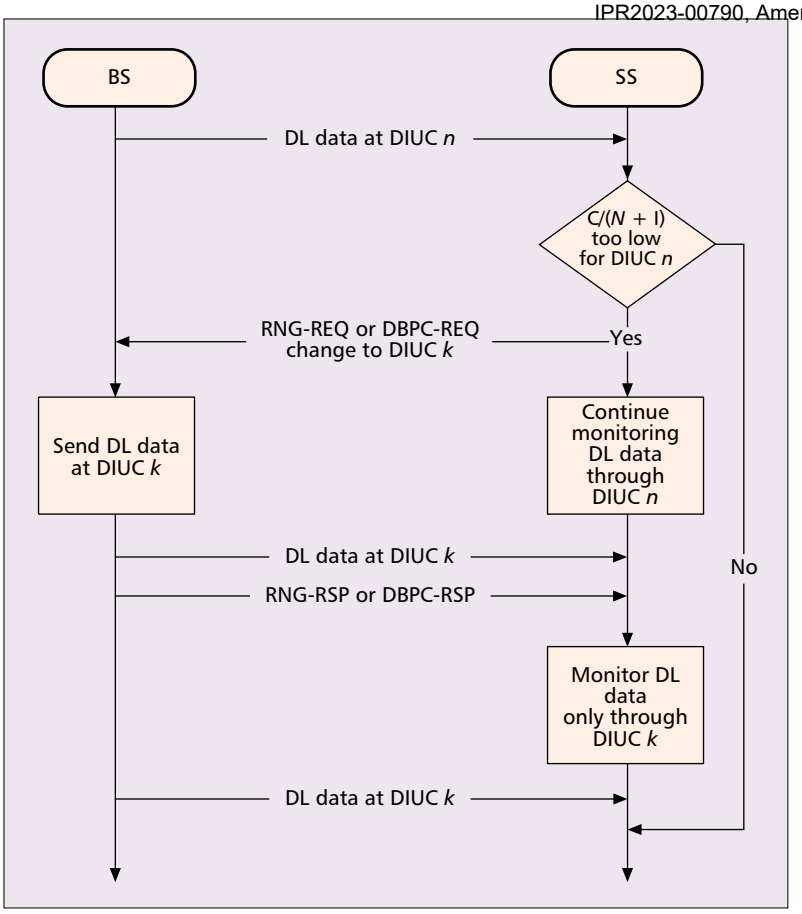

Figure 6. *Transition to a more robust burst profile.*

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

Because messages may be lost due to irrecoverable bit errors, the protocols for changing an SS's downlink burst profile must be carefully structured. The order of the burst profile change actions is different when transitioning to a more robust burst profile than when transitioning to a less robust one. The standard takes advantage of the fact that an SS is always required to listen to more robust portions of the downlink as well as the profile that was negotiated. Figure 6 shows a transition to a more robust burst profile. Figure 7 shows a transition to a less robust burst profile.

Uplink Scheduling Services — Each connection in the uplink direction is mapped to a *scheduling service*. Each scheduling service is associated with a set of rules imposed on the BS scheduler responsible for allocating the uplink capacity and the request-grant protocol between the SS and the BS. The detailed specification of the rules and the scheduling service used for a particular uplink connection is negotiated at connection setup time.

The scheduling services in IEEE 802.16 are based on those defined for cable modems in the DOCSIS standard [4].

Unsolicited grant service (UGS) is tailored for carrying services that generate fixed units of data periodically. Here the BS schedules regularly, in a preemptive manner, grants of the size negotiated at connection setup, without an explicit request from the SS. This eliminates the overhead and latency of bandwidth requests in order to meet the delay and delay jitter requirements of the underlying service. A practical limit on the delay jitter is set by the frame duration. If more stringent jitter requirements are to be met, output buffering is needed. Services that typically would be carried on a connection with UGS service include ATM constant bit rate (CBR) and E1/T1 over ATM.

When used with UGS, the grant management subheader includes the poll-me bit (see "Bandwidth Requests and Grants") as well as the slip indicator flag, which allows the SS to report that the transmission queue is backlogged due to factors such as lost grants or clock skew between the IEEE 802.16 system and the outside network. The BS, upon detecting the slip indicator flag, can allocate some additional capacity to the SS, allowing it to recover the normal queue state. Connections configured with UGS are not allowed to utilize random access opportunities for requests.

The real-time polling service is designed to meet the needs of services that are dynamic in nature, but offers periodic dedicated request opportunities to meet real-time requirements. Because the SS issues explicit requests, the protocol overhead and latency is increased, but this capacity is granted only according to the real need of the connection. The real-time polling service is well suited for connections carrying services such as VoIP or streaming video or audio.

The non-real-time polling service is almost identical to the real-time polling service except that connections may utilize random access transmit opportunities for sending bandwidth requests. Typically, services carried on these connections tolerate longer delays and are rather insensitive to delay jitter. The non-real-time polling service is suitable for Internet access with a minimum guaranteed rate and for ATM GFR connections.

A best effort service has also been defined. Neither throughput nor delay guarantees are provided. The SS sends requests for bandwidth in either random access slots or dedicated transmission opportunities. The occurrence of dedicated opportunities is subject to network load, and the SS cannot rely on their presence.

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Bandwidth Requests and Grants — The IEEE 802.16 MAC accommodates two classes of SS, differentiated by their ability to accept bandwidth grants simply for a connection or for the SS as a whole. Both classes of SS request bandwidth per connection to allow the BS uplink scheduling algorithm to properly consider QoS when allocating bandwidth. With the grant per connection (GPC) class of SS, bandwidth is granted explicitly to a connection, and the SS uses the grant only for that connection. RLC and other management protocols use bandwidth explicitly allocated to the management connections.

With the grant per SS (GPSS) class, SSs are granted bandwidth aggregated into a single grant to the SS itself. The GPSS SS needs to be more intelligent in its handling of QoS. It will typically use the bandwidth for the connection that requested it, but need not. For instance, if the QoS situation at the SS has changed since the last request, the SS has the option of sending the higher QoS data along with a request to replace this bandwidth stolen from a lower QoS connection. The SS could also use some of the bandwidth to react more quickly to changing environmental conditions by sending, for instance, a DBPC-REQ message.

The two classes of SS allow a trade-off between simplicity and efficiency. The need to explicitly grant extra bandwidth for RLC and requests, coupled with the likelihood of more than one entry per SS, makes GPC less efficient and scalable than GPSS. Additionally, the ability of the GPSS SS to react more quickly to the needs of the PHY and those of connections enhances system performance. GPSS is the only class of SS allowed with the 10–66 GHz PHY.

With both classes of grants, the IEEE 802.16 MAC uses a self-correcting protocol rather than an acknowledged protocol. This method uses less bandwidth. Furthermore, acknowledged protocols can take additional time, potentially adding delay. There are a number of reasons the bandwidth requested by an SS for a connection may not be available:

- The BS did not see the request due to irrecoverable PHY errors or collision of a contention-based reservation.
- The SS did not see the grant due to irrecoverable PHY errors.
- The BS did not have sufficient bandwidth available.
- The GPSS SS used the bandwidth for another purpose.

In the self-correcting protocol, all of these anomalies are treated the same. After a timeout appropriate for the QoS of the connection (or immediately, if the bandwidth was stolen by the SS for another purpose), the SS simply requests again. For efficiency, most bandwidth requests are incremental; that is, the SS asks for more bandwidth for a connection. However, for the self-correcting bandwidth request/grant mechanism to work correctly, the bandwidth requests must occasionally be aggregate; that is, the SS informs the BS of its total current bandwidth needs for a connection. This allows the BS to reset its perception of the SS's needs without a complicated protocol acknowledging the use of granted bandwidth.

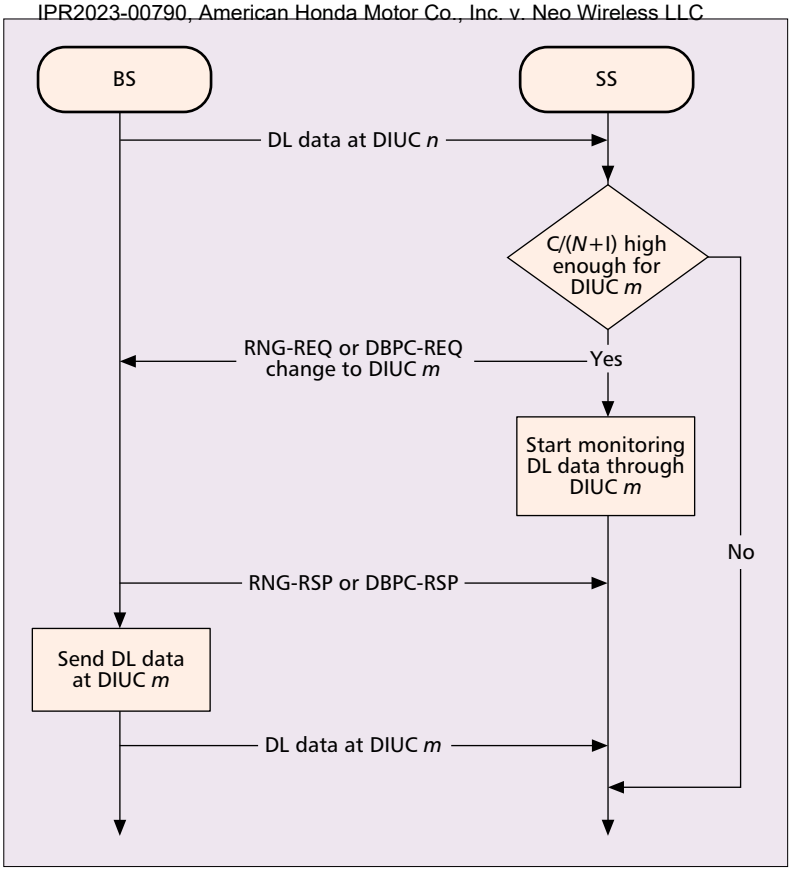

Figure 7. *Transition to a less robust burst profile.*

The SS has a plethora of ways to request bandwidth, combining the determinism of unicast polling with the responsiveness of contention-based requests and the efficiency of unsolicited bandwidth. For continuous bandwidth demand, such as with CBR T1/E1 data, the SS need not request bandwidth; the BS grants it unsolicited.

To short-circuit the normal polling cycle, any SS with a connection running UGS can use the poll-me bit in the grant management subheader to let the BS know it needs to be polled for bandwidth needs on another connection. The BS may choose to save bandwidth by polling SSs that have unsolicited grant services only when they have set the poll-me bit.

A more conventional way to request bandwidth is to send a bandwidth request MAC PDU that consists of simply the bandwidth request header and no payload. GPSS SSs can send this in any bandwidth allocation they receive. GPC terminals can send it in either a request interval or a data grant interval allocated to their basic connection. A closely related method of requesting data is to use a grant management subheader to piggyback a request for additional bandwidth for the same connection within a MAC PDU.

In addition to polling individual SSs, the BS may issue a broadcast poll by allocating a request interval to the broadcast CID. Similarly, the standard provides a protocol for forming multicast groups to give finer control to contention-based polling. Due to the nondeterministic delay that can be caused by collisions and retries, con-

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In general, service flows in IEEE 802.16 are preprovisioned, and setup of the service flows is initiated by the BS during SS initialization. However, service flows can also be dynamically established by either the BS or the SS.

tention-based requests are allowed only for certain lower QoS classes of service.

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

After deciding on which channel or channel pair to attempt communication, the SS tries to synchronize to the downlink transmission by detecting the periodic frame preambles. Once the physical layer is synchronized, the SS will look for the periodically broadcast DCD and UCD messages that enable the SS to learn the modulation and FEC schemes used on the carrier.

Initial Ranging and Negotiation of SS Capabilities — Upon learning what parameters to use for its initial ranging transmissions, the SS will look for initial ranging opportunities by scanning the UL-MAP messages present in every frame. The SS uses a truncated exponential backoff algorithm to determine which initial ranging slot it will use to send a ranging request message. The SS will send the burst using the minimum power setting and will try again with increasingly higher transmission power if it does not receive a ranging response.

Based on the arrival time of the initial ranging request and the measured power of the signal, the BS commands a timing advance and a power adjustment to the SS in the ranging response. The response also provides the SS with the basic and primary management CIDs. Once the timing advance of the SS transmissions has been correctly determined, the ranging procedure for fine-tuning the power can be performed using invited transmissions.

All transmissions up to this point are made using the most robust, and thus least efficient, burst profile. To avoid wasting capacity, the SS next reports its PHY capabilities, including the modulation and coding schemes it supports and whether, in an FDD system, it is half-duplex or full-duplex. The BS, in its response, can deny the use of any capability reported by the SS.

SS Authentication and Registration — Each SS contains both a manufacturer-issued factory-installed X.509 digital certificate and the certificate of the manufacturer. These certificates, which establish a link between the 48-bit MAC address of the SS and its public RSA key, are sent to the BS by the SS in the Authorization Request and Authentication Information messages. The network is able to verify the identity of the SS by checking the certificates and can subsequently check the level of authorization of the SS. If the SS is authorized to join the network, the BS will respond to its request with an Authorization Reply containing an Authorization Key (AK) encrypted with the SS's public key and used to secure further transactions.

Upon successful authorization, the SS will register with the network. This will establish the secondary management connection of the SS and determine capabilities related to connection setup and MAC operation. The version of IP used on the secondary management connection is also determined during registration.

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

Connection Setup — IEEE 802.16 uses the concept of service flows to define unidirectional transport of packets on either downlink or uplink. Service flows are characterized by a set of QoS parameters such as latency and jitter. To most efficiently utilize network resources such as bandwidth and memory, 802.16 adopts a two-phase activation model in which resources assigned to a particular admitted service flow may not be actually committed until the service flow is activated. Each admitted or active service flow is mapped to a MAC connection with a unique CID.

In general, service flows in IEEE 802.16 are preprovisioned, and setup of the service flows is initiated by the BS during SS initialization. However, service flows can also be dynamically established by either the BS or the SS. The SS typically initiates service flows only if there is a dynamically signaled connection, such as a switched virtual connection (SVC) from an ATM network. The establishment of service flows is performed via a three-way handshaking protocol in which the request for service flow establishment is responded to and the response acknowledged.

In addition to dynamic service establishment, IEEE 802.16 also supports dynamic service changes in which service flow parameters are renegotiated. Like dynamic service flow establishment, service flow changes also follow a similar three-way handshaking protocol.

Privacy Sublayer — IEEE 802.16's privacy protocol is based on the Privacy Key Management (PKM) protocol of the DOCSIS BPI+ specification [5] but has been enhanced to fit seamlessly into the IEEE 802.16 MAC protocol and to better accommodate stronger cryptographic methods, such as the recently approved Advanced Encryption Standard.

Security Associations — PKM is built around the concept of security associations (SAs). The SA is a set of cryptographic methods and the associated keying material; that is, it contains the information about which algorithms to apply, which key to use, and so on. Every SS establishes at least one SA during initialization. Each connection, with the exception of the basic and primary management connections, is mapped to an SA either at connection setup time or dynamically during operation.

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Cryptographic Methods — Currently, the PKM protocol uses X.509 digital certificates with RSA public key encryption for SS authentication and authorization key exchange. For traffic encryption,the Data Encryption Standard (DES) running in the cipher block chaining (CBC) mode with 56-bit keys is currently mandated. The CBC initialization vector is dependent on the frame counter and differs from frame to frame. To reduce the number of computationally intensive public key operations during normal operation, the transmission encryption keys are exchanged using 3DES with a key exchange key derived from the authorization key.

The PKM protocol messages themselves are authenticated using the Hashed Message Authentication Code (HMAC) protocol [6] with SHA-1 [7]. In addition, message authentication in vital MAC functions, such as the connection setup, is provided by the PKM protocol.

Summary and Conclusion

The WirelessMAN™ air interface specified in IEEE Standard 802.16 provides a platform for the development and deployment of standards-based metropolitan area networks providing broadband wireless access in many regulatory environments. The standard is intended to allow for multiple vendors to produce interoperable equipment. However, it also allows for extensive vendor differentiation. For instance, the standard provides the base station with a set of tools to implement efficient scheduling. However, the scheduling algorithms that determine the overall efficiency will differ from vendor to vendor and may be optimized for specific traffic patterns. Likewise, the adaptive burst profile feature allows great control to optimize the efficiency of the PHY transport. Innovative vendors will introduce clever schemes to maximize this opportunity while maintaining interoperability with compliant subscriber stations.

The publication of IEEE Standard 802.16 is a defining moment in which broadband wireless access moves to its second generation and begins its establishment as a mainstream alternative for broadband access. Through the dedicated service of many volunteers, the IEEE 802.16 Working Group succeeded in quickly designing and forging a standard based on forward-looking technology. IEEE Standard 802.16 is the foundation of the wireless metropolitan area networks of the next few decades.

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As lead PHY editors of IEEE Standard 802.16-2001, Jay Klein and Lars Lindh played key roles in the completion of the 10–66 GHz physical layer discussed here. Mr. Klein also chaired the PHY Task Group that led its development. Mr. Lindh and Ken Peirce each provided a helpful technical review of this manuscript.

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Through the dedicated service of many volunteers, the IEEE 802.16 Working Group succeeded in quickly designing and forging a standard based on forward-looking technology. IEEE Standard 802.16 is the foundation of the wireless metropolitan area networks of the next few decades.

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