Project	**IEEE 802.16 Broadband Wireless Access Working Group**	
Title	Physical Layer Proposal for the 802.16 Air Interface Specification	
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Re:	This contribution is a response to the invitation to provide a detailed proposal for a physical layer specification, based upon the acceptance of the proposal(s) presented at Session #4.	
Abstract	This contribution provides a detailed description of a physical layer that incorporates many aspects of existing standards in order to leverage existing technology, with modifications to ensure reliable operation in the targeted 10-60 GHz frequency band. In addition, it was designed with a high degree of flexibility in order to optimize system deployments with respect to cell planning, cost considerations, radio capabilities, offered services, and capacity requirements.	
Purpose	To provide a detailed description of a proposed physical layer specification.	
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Physical Layer Proposal for the 802.16 Air Interface Specification

Table of Contents

Scope

This section describes the physical layer components that meet the functional requirements of the Broadband Wireless Access (BWA) system that has been defined by this specification. Detailed electrical and signal processing specifications are presented that enable the production of interoperable equipment.

Normative References

[1] ETSI EN 300 421 V1.1.2 (1997-08), "Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for 11/112 GHz satellite services."

[2] ETSI EN 301 210 V1.1.1 (1999-03), "Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for Digital Satellite News Gathering (DSNG) and other contribution applications by satellite."

[3] ITU-T J.83 (04/97), Series J: Transmission of Television, Sound Programme and Other Multimedia Signals: Digital transmission of television signals, "Digital multi-programme systems for television, sound and data services for cable distribution."

[4] Data-Over-Cable Service Interface Specifications, "Radio Frequency Interface Specification," SP-RFIv1.1-I03-991103.

[5] ETSI EN 301 199 v1.2.1 (1999-06), "Digital Video Broadcasting (DBV); Interaction channel for Local Multi-point Distribution Systems (LMDS)."

[6] ITU-T draft Recommendation J.116, "Interaction channel for Local Multipoint Distribution services."

[7] ITU-R 9B/134-E, JRG 8A-9B, Draft New Recommendation ITU-R F.BWA, "Radio Transmission Systems for Fixed Broadband Wireless Access (BWA) Based on Cable Modem Standards (Annex B of ITU-T Rec. J.112)."

[8] John B. Anderson, *Digital Transmission Engineering*, 1999 IEEE Press, Ch.6.3.

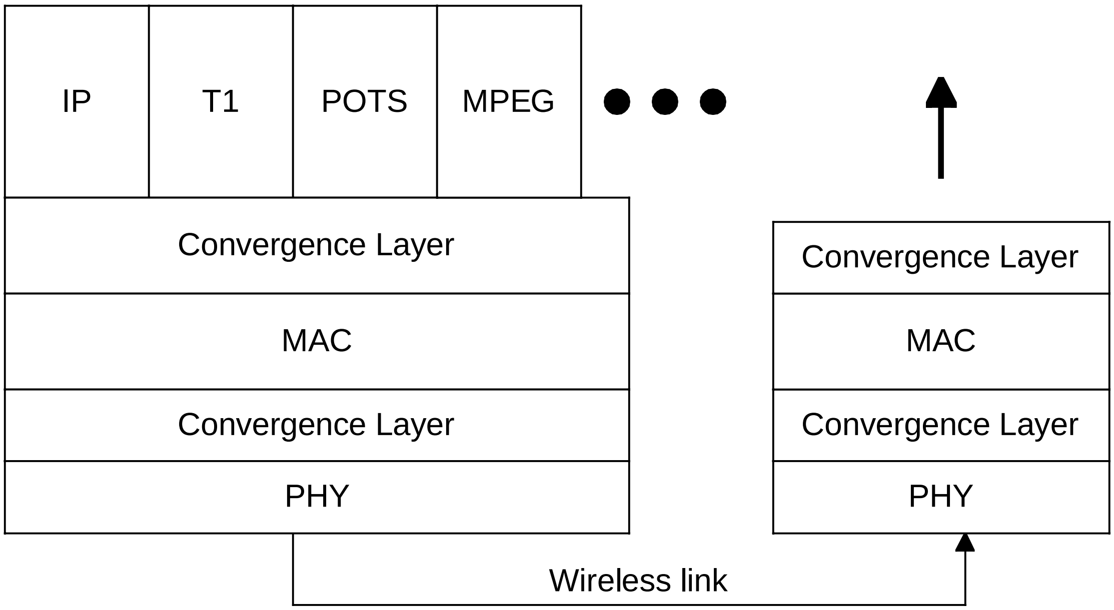
PHY Overview

Introduction

The following physical layer specification was designed to meet the functional requirements that have been defined for Broadband Wireless Access systems. It incorporates many aspects of existing standards [1]-[7] in order to leverage existing technology for demonstrated robustness of implementation, with modifications to ensure reliable operation in the targeted 10-60 GHz frequency band. In addition, this physical layer was designed with a high degree of flexibility in order to optimize system deployments with respect to cell planning, cost considerations, radio capabilities, offered services, and capacity requirements.

Reference Configuration

The physical layer is designed to support both 802.16 MAC frames and native MPEG packets in the downstream channel. However, all traffic must still pass through the MAC for scheduling of the available bandwidth for both the upstream and downstream channels. The support of native MPEG video packets has been incorporated into the physical layer, so that they do not need to be encapsulated into 802.16 MAC frames. Below is a simple reference model that is used to show the interface between the physical layer and the MAC layer, and to show how the MAC layer might interface with higher layers. The convergence layer between the MAC and higher layers is beyond the scope of this specification, but the convergence layer between the MAC and PHY is clearly defined in order to ensure a seamless interoperation between the two entities.



Multiple Access Technique

The upstream physical layer is based on the use of a combination of time division multiple access (TDMA) and demand assigned multiple access (DAMA). In particular, the upstream channel is divided into a number of "time slots". The number of slots assigned for various uses (polling, contention, guard, or reserved) is controlled by the MAC layer in the basestation and can vary in time for optimal performance. The downstream channel is based upon time division multiplexing (TDM), where the information for each subscriber station is multiplexed onto the same stream of data and is received by all subscriber stations located within the same sector.

Duplexing Technique

This physical layer has been targeted to primarily support frequency division duplexing (FDD), which provides a separate frequency assignment for the upstream and downstream channels. This approach to transmitter and receiver isolation is a proven technique that has been utilized for many other wireless systems, including cellular, PCS, and satellite communication systems. In addition, it allows for cheap modem receivers to be used in the subscriber station units that have been designed to demodulate signals with continuous transmission. For added flexibility, an optional downstream mode is given that describes a method of using the same basic physical layer architecture, defined for the FDD system, to support half-duplex FDD or time division duplex (TDD) modes of operation.

Downstream Transmission Convergence (TC) Sublayer

In order to improve demodulation robustness, facilitate common receiving hardware for both video and data, and provide an opportunity for the possible multiplexing of video and data over the physical layer, the following convergence sublayer between the MAC and PHY layer has been adopted.

The downstream bitstream is defined as a continuous series of 188-byte MPEG [ITU-T H.222.0] packets. These packets consist of a 4-byte header followed by 184 bytes of payload. The header identifies the payload as containing 802.16 MAC messages or other types of payloads, including digital video. The mixtures of the various services that are transported in the downstream are to be controlled by the basestation.

The format of the MPEG Packet carrying MAC messages is given below

P=1 byte pointer field, not present in all packets

Format of an MPEG Packet

The format of the MPEG transport stream header is defined in Section 2.4 of [ITU-T H.222.0]. The particular field values that distinguish the 802.16 MAC message stream are defined in the following table, where the field names are from the ITU specification. The MPEG header consists of 4 bytes that begin the 188-byte MPEG packet. The format of the header for use on an 802.16 PID is restricted to that shown in the table. The header format conforms to the MPEG standard, but its use is restricted in this specification to NOT ALLOW inclusion of an adaptation_field in the MPEG packets.

Field	**Length (bits)**	**Description**
sync_byte	8	0x47 or 0xB8; MPEG Packet sync byte
transport_error_indicator	1	Indicates an error has occurred in the reception of the packet. This bit is reset to zero by the sender, and set to one whenever an error occurs in the transmission of the packet.
payload_unit_start_indicator (PUSI)	1	A value of one indicates the presence of a pointer_field as the first byte of the payload (fifth byte of the packet).
transport_priority (frame_start_indicator)	1	This bit is set to 1 to indicate the beginning of a downstream frame, when framing is used.
PID	13	802.16 well-known packet ID (TBD)
transport_scrambling_control	2	Reserved, set to '00'
adaptation_field_control	2	'01'; use of the adaptation_field is NOT ALLOWED on the 802.16 PID
continuity_counter	4	cyclic counter within this PID

MPEG Header Format for 802.16 MAC packets

The payload portion of the MPEG packet will carry the 802.16 MAC frames. The first byte of the MPEG payload will be a 'pointer_field' if the PUSI is set. A stuff_byte pattern having a value (0xFF) must be used within the MPEG payload to fill any gaps between the 802.16 MAC frames. This value is chosen as an unused value for the first byte of the 802.16 MAC frame, which is designed to NEVER have this value. The pointer_field is present as the fifth byte of the MPEG packet (first byte following the MPEG header) whenever the PUSI is set to one in the MPEG header. The interpretation of the pointer_field is as follows:

The pointer_field contains the number of bytes in the packet that immediately follow the pointer_field that the subscriber station decoder must skip past before looking for the beginning of an 802.16 MAC frame. A pointer field MUST be present if it is possible to begin an 802.16 MAC frame in the packet, and MUST point to either:

1. the beginning of the first MAC frame to start in the packet or
2. to any stuff_byte preceding the MAC frame.

MAC frames may begin anywhere within an MPEG packet, MAC frames may span MPEG packets, and several MAC frames may exist within an MPEG packet. The following figures show the format of the MPEG packets that carry 802.16 MAC frames. In all cases, the PUSI flag indicates the presence of the pointer_field as the first byte of the MPEG payload. The following figure shows a MAC frame that is positioned immediately after the pointer_field byte. In this case, pointer_field is zero, and the 802.16 decoder will begin searching for a valid MAC header byte at the byte immediately following the pointer_field.

Header (PUSI=1)	P =0	MAC frame (up to 183 bytes)	stuff_byte (0 or more)

P=1 byte pointer field

Packet Format Where a MAC Frame Immediately Follows the pointer_field

The next figure shows the more general case where a MAC Frame is preceded by the tail of a previous MAC Frame and a sequence of stuffing bytes. In this case, the pointer_field still identifies the first byte after the tail of Frame #1 (a stuff_byte) as the position where the decoder should begin searching for a legal MAC header byte. This format allows the multiplexing operation in the basestation to immediately insert a MAC frame that is available for transmission if that frame arrives after the MPEG header and pointer_field has been transmitted.

In order to facilitate multiplexing of the MPEG packet stream carrying 802.16 data with other MPEG-encoded data, the basestation SHOULD NOT transmit MPEG packets with the 802.16 PID which contain only stuff_bytes in the payload area. MPEG null packets SHOULD be transmitted instead. Note that there are timing relationships implicit in the 802.16 MAC sublayer which must also be preserved by any MPEG multiplexing operation.

Header (PUSI=1)	P =M	Tail of MAC frame #1 (M bytes)	stuff_byte (0 or more)	Start of MAC Frame 2

P=1 byte pointer field

Packet Format with MAC Frame Preceded by Stuffing Bytes

The next figure shows that multiple MAC frames may be contained within the MPEG packet. The MAC frames may be concatenated one after the other or be separated by an optional sequence of stuffing bytes.

Header (PUSI=1)	P =0	MAC Frame 1	MAC Frame 2	stuff_byte (0 or more)	Start of MAC Frame 3

P=1 byte pointer field

Packet Format Showing Multiple MAC Frames in a Single Packet

The next figure shows the case where a MAC frame spans multiple MPEG packets. In this case, the pointer_field of the succeeding frame points to the byte following the last byte of the tail of the first frame.

<table>
<tr><td>Header (PUSI=1)</td><td>P =0</td><td>stuff_byte (0 or more)</td><td colspan="2">Start of MAC Frame 1 (up to 183 bytes)</td></tr>
<tr><td>Header (PUSI=0)</td><td>P =0</td><td colspan="3">Continuation of MAC frame 1 (184 bytes)</td></tr>
<tr><td>Header (PUSI=1)</td><td>P =M</td><td>Tail of MAC frame 1 (M bytes)</td><td>stuff_byte (0 or more)</td><td>Start of MAC Frame 2</td></tr>
</table>

P=1 byte pointer field

Packet Format Where a MAC Frame Spans Multiple Packets

Downstream Framing

The frame_start_indicator bit identified in the MPEG header allows for the upstream and downstream channel to follow a "virtual" framing structure. This may be desirable and simplifies bandwidth allocation for some applications that require constant bit rate services (*i.e.*, T1/E1, POTS, video conferencing, etc.). The relationship between the downstream frames and the upstream frames should be left up to the MAC layer. Note that the use of framing can be used to simplify certain functions, but puts no restrictions on how the time slots within the frame are used.

Upstream Transmission Convergence (TC) Sublayer

The upstream transmission directly transports MAC layer packets over-the-air, so there is no convergence layer needed.

Upstream Framing

Since the upstream channel is TDMA based, the channel can be modeled as a continuous sequence of "time slots", the smallest of which is called a mini-slot, with the following restrictions:

- The MAC layer specification shall define the actual time slot sizes and use of the time slots within the channel.
- The upstream channel can be either viewed as a continuous stream of contiguous time slots, or it can be viewed as being divided into a number of "virtual" frames, each of which consists of an integer number of time slots. The latter configuration allows for a more flexible method for calculating symbol rates, allocating bandwidth (especially for fixed rate applications), and performing transmit timing

synchronization. The "virtual" frame time should be programmable in steps of 125 usec (typically in the range of 2-6 msec) to match T1/E1 rate requirements, and the frame boundaries can be determined from the downstream frame start indicator or other MAC management messages. The term "virtual" when referring to the frame is simply to suggest that having a framing structure puts no inherent limitations on how the time slots within the frame can be used.

- The subscriber station transmitter must be able to support the programmable "burst" configurations described later, which places limits on the size of different types of bursts.

Coding, Interleaving, Scrambling & Modulation

The downstream physical layer is based on the transport of MPEG frames over-the-air in order to leverage existing technology that supports broadcast video services. However, as described previously, the information content within the MPEG frame is designed to also support the transmission of IEEE 802.16 MAC packets, which are described in the MAC layer specification. In addition, several physical layer optional modes are described that provide flexible configurations to support different types of bearer services, deployment scenarios, and cellular layouts. Modes and mechanisms explicitly indicated as "optional" within the present document need not be implemented in the equipment to comply with the present document. Nevertheless, when an "optional" mode or mechanism is implemented, it shall comply with the specification as given in the present document. An interoperable subscriber station will be required to implement, at a minimum, the basic physical layer structure that is described here as **Mode A**. In this mode, following the encapsulation of the MAC packets into the MPEG frame, based on the transmission convergence layer specified above, the data is randomized and encoded using a (204,188) Reed-Solomon code over GF(256). Following the block encoder, the data goes through a convolutional interleaver with a depth of I=12. Following the interleaver, the data must either pass through an inner, constraint length K=7, convolutional code with a rate of _, 2/3, _, 5/6, or 7/8, or pass through a differential encoder (*i.e*., bypassing the convolutional encoder). In order to ensure interoperability in different system configurations, a subscriber station must support both data paths. Code bits are then mapped to a QPSK or 16-QAM signal constellation with symbol mapping as described here. Finally, symbols are Nyquist filtered using a square-root raised cosine filter with a roll-off factor of either 0.15 or 0.35.

Mode B, an optional mode, adds additional flexibility to several of the parameters defined in **Mode A**. In particular, **Mode B** specifies the support of a variable length convolutional interleaver with depth I=1,3,6, or 12, a programmable roll-off factor from 0.15 to 0.35, the use of 64-QAM modulation with differential encoding, or the use of $\pi/4$-DQPSK modulation.

In **Mode C**, an optional mode, following the encapsulation of the MAC packets into the MPEG frame, the data is randomized using the same mechanism as in **Mode A**. The randomized bitstream is placed in a 32 x 47 array of information bits. Each row is encoded by (54,47) shortened Hamming code and each column by (39,32) shortened Hamming code. The resulting 54x39 coded array is block interleaved either by writing consecutive bits in rows and reading them out in columns, or by writing consecutive bits in columns and reading them out in rows. Coded bits are Gray mapped to a QPSK, 16QAM or 64QAM (optional) signal constellation. Finally, symbols are Nyquist filtered using a square-root raised cosine with roll-of that is programmable from 0.15 to 0.35.

Mode D, an optional mode, supports 8-PSK and 16-QAM modulation using a pragmatic trellis coding scheme as specified in [2].

Finally, **Mode E**, an optional mode, describes a method to support half-duplex FDD or TDD transmission using the same basic physical layer structure as defined in **Mode A**.

The upstream physical layer is based on the transmission of bursts, with several parameters that are programmable by the MAC. Each burst is designed to carry IEEE 802.16 MAC messages of variable lengths.

The based mode of operation, designated as **Mode A**, first encodes the incoming MAC messages using a Reed-Solomon encoder based on GF(256), and then randomizes the complete outgoing burst. The length of the codeword and the error correction capability of the code are programmable by the MAC messages coming from the basestation via a burst configuration message. Each burst also contains a variable length preamble and a variable length guard space at the end of the burst. The preamble and coded bits are mapped to QPSK or 16-QAM constellations. Nyquist pulse shaping using a square-root raised cosine filter is also employed with a roll-off factor of 0.25.

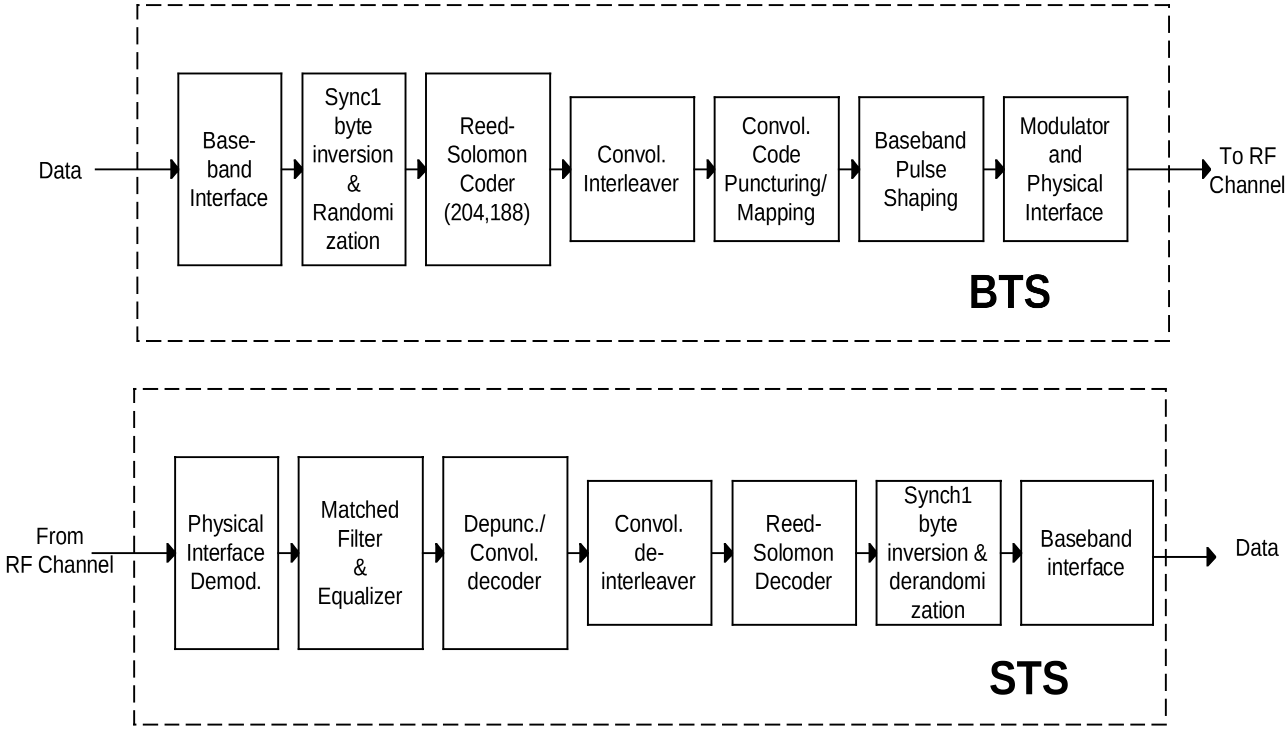
For added flexibility, an optional **Mode B** is defined to support all the functionality of **Mode A** with a programmable roll-off factor of 0.15-0.35.

In addition, an optional **Mode C** is described that replaces the Reed-Solomon code with a variable length product code. This mode supports Gray coded 4,16 and optionally 64QAM and a programmable roll-off factor between 0.15-0.35.

Downstream Physical Media Dependent (PMD) Sublayer

Mode A: Basic Mode of Operation

The encoding and decoding functions for the downstream physical layer are summarized in the following block diagram.



Conceptual Block diagram of the 802.16 Downstream Physical layer

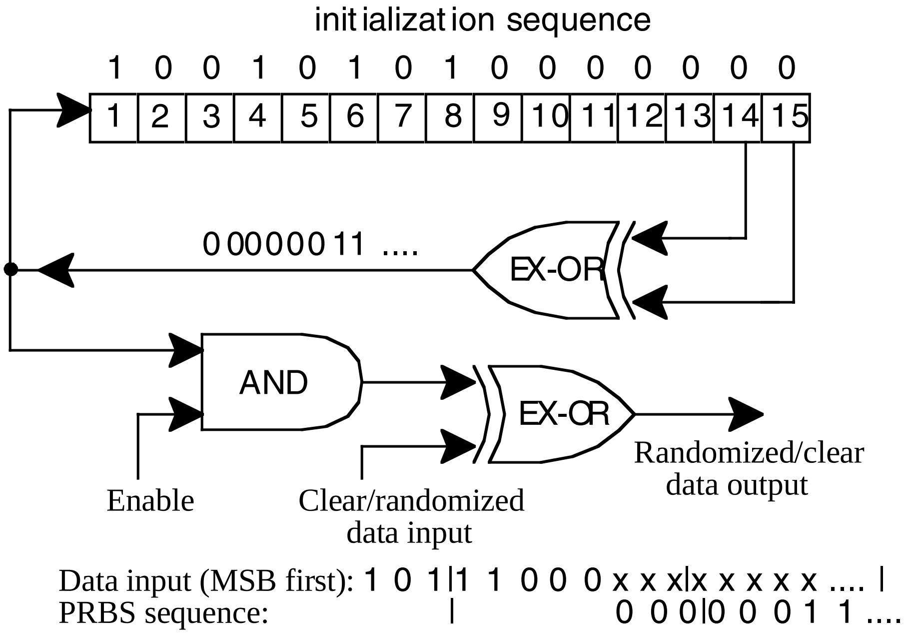
Baseband interfacing

This unit shall perform the transmission convergence sublayer function by adapting the data structure coming from the MAC layer to the format of the proposed physical layer transport stream based on the MPEG packet structure.

Sync 1 inversion and randomization

This unit shall invert the Sync 1 byte according to the MPEG framing structure, and randomizes the data stream for spectrum shaping purposes. Randomization shall be employed to minimize the possibility of transmission of an unmodulated carrier and to ensure adequate numbers of bit transitions to support clock recovery.

The stream of uncoded downstream packets, excluding sync bytes, shall be randomized by modulo-2 addition of the data with the output of the pseudo random binary stream (PBRS) generator, as illustrated in the following diagram.



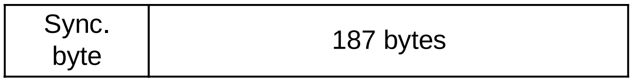
Randomizer logic diagram.

The PBRS shall be initialized at each inverted sync byte by the sequence 100101010000000 in the manner depicted in the figure. The sync byte (hex 47) shall be inverted (hex B8) every eight packets, starting at the beginning of the frame.

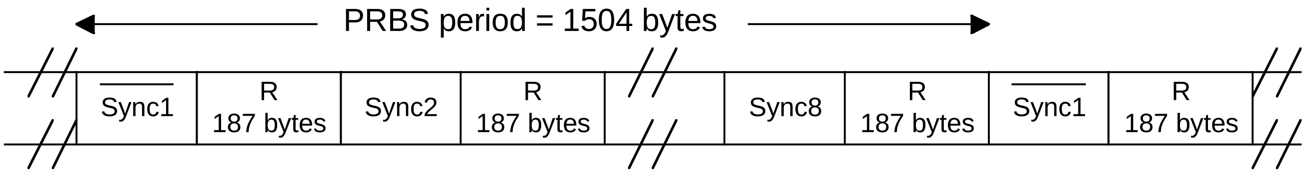
The generator polynomial for the PRBS shall be:

$$1 + X^{14} + X^{15}$$

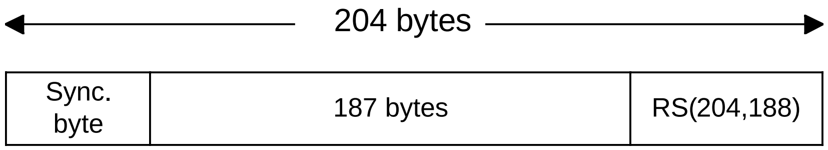
Following initialization, the first PRBS generator output bit shall be added to the first bit following the inverted sync bit. Over subsequent sync bytes, the PBRS generator shall continue to step its internal shift register state but the PBRS output addition to the sync byte bits shall be disabled. Thus, the period of the PRBS sequence shall be 1504 bytes. The following diagram illustrates the framing structure of the MPEG transport stream.



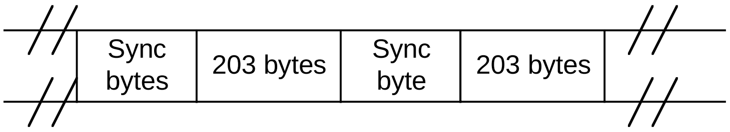
(a) MPEG Transport Stream MUX Packet



(b) Randomized transport packets: Sync bytes and Raondomized Sequence R



(c) Reed-Solomon RS(204,188,t=8) error protected packet



(d) Interleaved Frames maintaining sync. byte periodicity

$\overline{\text{Sync1}}$ = not randomized complemented sync byte

Sync n = not randomized sync byte, n=2...8

Framing structure based on MPEG transport stream.

Reed-Solomon coding

Following the energy dispersal randomization process, systematic shortened Reed-Solomon encoding shall be performed on each randomized MPEG transport packet, with T = 8. This means that 8 erroneous bytes per transport packet can be corrected. This process adds 16 parity bytes to the MPEG transport packet to give a codeword (204,188). RS coding shall also be applied to the packet sync byte, either non-inverted (i.e. 47hex) or inverted (i.e. B8hex).

The Reed-Solomon code shall have the following generator polynomials:

Code Generator Polynomial: $g(x) = (x+\mu^0)(x+\mu^1)(x+\mu^2) \ldots (x+\mu^{15})$, where μ= 02hex

Field Generator Polynomial: $p(x) = x^8 + x^4 + x^3 + x^2 + 1$

The shortened Reed-Solomon code shall be implemented by appending 51 bytes, all set to zero, before the information bytes at the input of a (255,239) encoder; after the coding procedure these bytes are discarded.

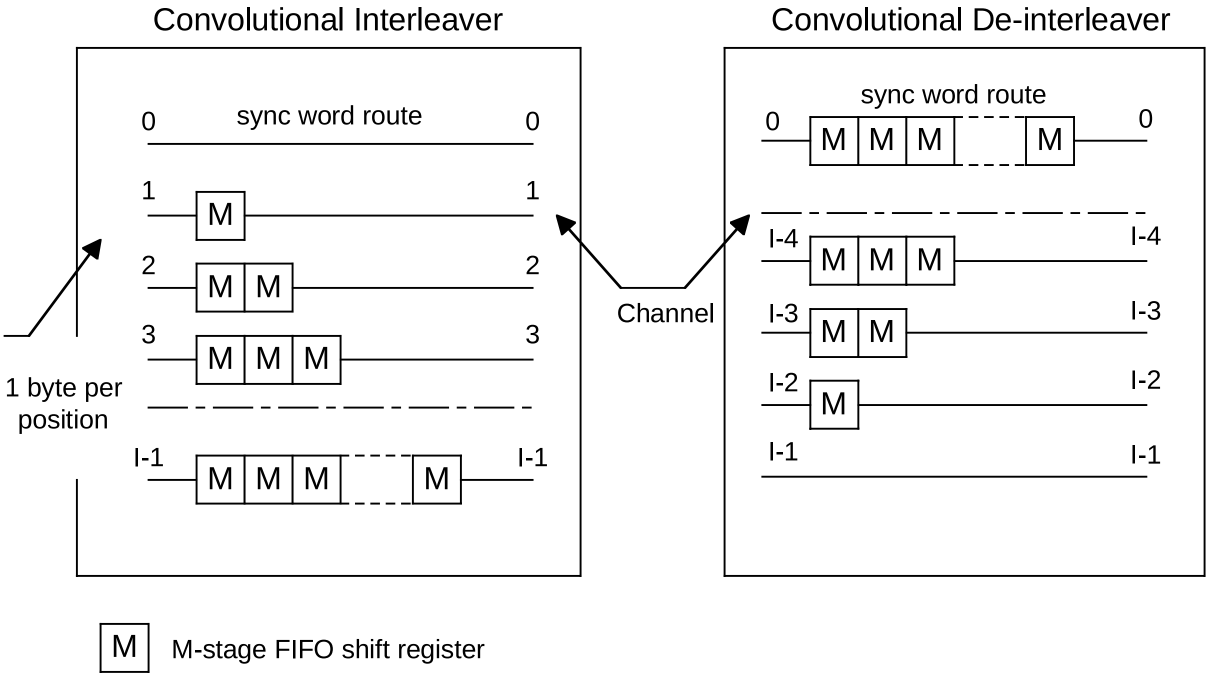
Convolutional interleaving

The convolutional interleaving process shall be based on the Forney approach, with a depth of I=12. The interleaved frame shall be composed of overlapping error protected packets and shall be delimited by MPEG sync bytes (preserving the periodicity of 204 bytes).

The interleaver is composed of I branches, cyclically connected to the input byte-stream by the input switch. Each branch shall be a First In First Out (FIFO) shift register, with depth (M) cells (where M = N/I, N = 204 = error protected frame length, I =12 = maximum interleaving depth, j = branch index). The cells of the FIFO shall contain 1 byte, and the input and output switches shall be synchronized, as shown in the diagram below.

For synchronization purposes, the sync bytes and the inverted sync bytes shall be always routed into the branch "0" of the interleaver (corresponding to a null delay).

The deinterleaver is similar, in principle, to the interleaver, but the branch indexes are reversed (i.e. j = 0 corresponds to the largest delay). The de-interleaver synchronization is achieved by routing the first recognized sync byte into the "0" branch.



Conceptual diagram of the convolutional interleaver and de-interleaver.

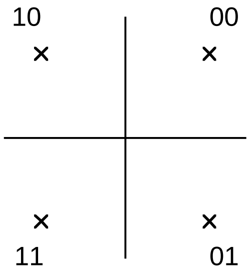
Convolutional Coding with QPSK Modulation

When convolutional encoding is employed, the convolutional code shall be chosen from the following table of code rates, which are obtained by puncturing a rate 1/2 constraint length K = 7 code having the following generator vectors g, and puncturing patterns P (0 denotes punctured (deleted) bit).

Table 1: Convolutional Code Puncture Patterns

Original code			**Code rates**									
			1/2		2/3		3/4		5/6		7/8	
K	G_1	G_2	P	d_{free}	P	d_{free}	P	d_{free}	P	d_{free}	P	d_{free}
7	171_{oct}	133_{oct}	X=1 Y=1 I=X_1 Q=Y_1	10	X=10 Y=11 I=$X_1Y_2Y_3$ Q=$Y_1X_3Y_4$	6	X=101 Y=110 I=X_1Y_2 Q=Y_1X_3	5	X=10101 Y=11010 I=$X_1Y_2Y_4$ Q=$Y_1X_3X_5$	4	X=1000101 Y=1111010 I=$X_1Y_2Y_4Y_6$ Q=$Y_1Y_3X_5X_7$	3
NOTE: 1=transmitted bit 0 = non transmitted bit												

The QPSK symbols will use gray-coded direct mapping of (I,Q) from bit pairs out of the convolutional encoder as follows:



Differential encoding with QPSK or 16-QAM Modulation

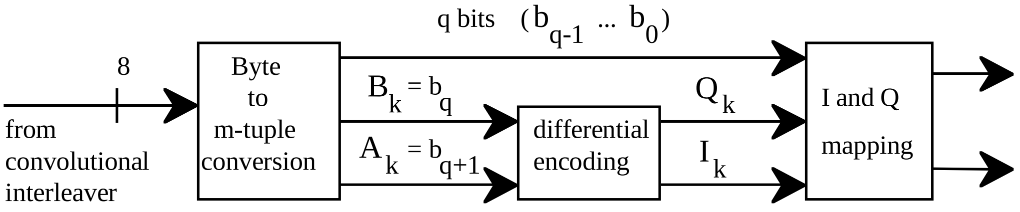
In this mode, the inner convolutional code is disabled, and the mapping of bits to symbols shall use the following differential encoder and mapper as defined in [3, ITU-T J.83 Annex A]. The two most significant bits (MSBs) of each symbol shall be differentially coded in order to obtain a π/2 rotation-invariant QAM constellation. The differential encoding of the two MSBs shall be given by the following Boolean expression:

$$I_k = \overline{(A_k \quad B_k)}.(A_k \quad I_{k-1}) + (A_k \quad B_k).(A_k \quad Q_{k-1})$$

$$Q_k = \overline{(A_k \quad B_k)}.(B_k \quad Q_{k-1}) + (A_k \quad B_k).(B_k \quad I_{k-1})$$

> Note: For the above Boolean expression " " denotes the EXOR function, "+" denotes the logical OR function, "." denotes the logical AND function and the overstrike denotes inversion.

The following figure gives an example of implementation of byte to symbol conversion.



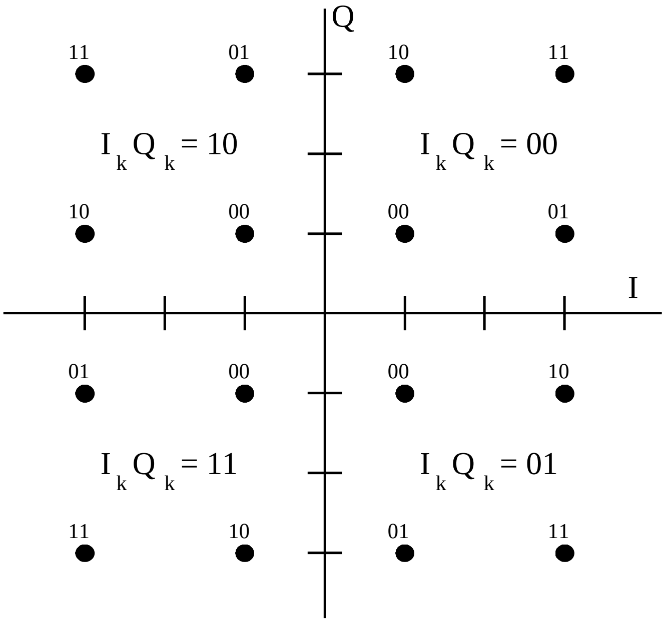
q=1 for QPSK, q=2 for 16-QAM

Example implementation of the byte to m-tuple conversion
and the differential encoding of the two MSBs.

For QPSK, the output of the differential encoder shall map directly to the QPSK signal constellation based on the Quadrant to MSB mapping shown in the following table. The mapping of bits to symbols for 16-QAM is given by the following diagrams.

Conversion of constellation of quadrant 1 to other quadrants of the
constellation diagrams given in the following diagrams.

Quadrant	**MSBs**	**LSBs rotation**
1	00	0
2	10	+ _/2
3	11	+ _
4	01	+ 3_/2



16 QAM Constellation diagram

Baseband Pulse Shaping

Prior to modulation, the I and Q signals shall be filtered by square-root raised cosine filters. The excess bandwidth factor α shall be either 0.15 or 0.35. The square-root raised cosine filter is defined by the following transfer function H:

$$\begin{array}{lll} & H(f)=1 & for|f|< f_N(1-\alpha) \\ H(f)= & \frac{1}{2}+\frac{1}{2}\sin\frac{\pi}{2f_N}\;\frac{f_N-|f|}{\alpha}\;\begin{matrix}?\\?\end{matrix}^{1/2} & for\ f_N(1-\alpha)\le|f|\le f_N(1+\alpha) \\ & H(f)=0 & for|f|> f_N(1+\alpha) \end{array}$$

where $f_N = \frac{1}{2T_s} = \frac{R_s}{2}$ is the Nyquist frequency. Since *H(f)=0* is impossible to realize in practice, the actual response in the range $|f|>f_N(1+\alpha)$ should be *H(f) < 50 dBc* measured with respect to the passband.

Summary of Mode A Downstream Physical Layer Parameters

Randomization	$1 + X^{14} + X^{15}$ Initialization: 100101010000000
Reed-Solomon Coding	(204,188) with T=8 byte errors corrected
Interleaving	Convolutional with depth I=12.
Convolutional coding	Selectable: rate _, 2/3, _, 5/6, 7/8, or 1 (disabled)
Modulation	QPSK or 16-QAM (16-QAM supported only when convolutional coding is disabled)
Differential encoding	enabled/disabled (only enabled when convolutional coding is not employed)
Spectral shaping	α=0.15 or 0.35
Spectral inversion	inverted or non-inverted
Achievable symbol rates	1-45 Mbaud

Downstream Physical Layer Optional Modes

The following optional modes of operation allow vendors to add additional flexibility to the downstream receivers. It is mandatory that an 802.16 standards compliant subscriber station support the basic physical layer given by Mode A, while the following options need not be implemented in order to be standards compliant. If the following options are implemented, they shall be implemented as described here. This approach to the downstream physical layer allows for rapid time to market for this standard, using existing and mature technology, while providing a migration path for more advanced coding and modulation schemes supporting different services, higher capacity links, and/or cheaper equipment cost following the market demands.

Mode B: Enhanced Flexibility Mode

The modifications contained with this optional mode include various enhancements to improve the flexibility of the physical layer with respect to the interleaver, modulation, or spectral shaping filters. It is not necessary for a subscriber station to implement all of the following options, so it is expected that some negotiation of capability sets may need to be done for subscribers implementing options in this mode.

Variable length interleaver

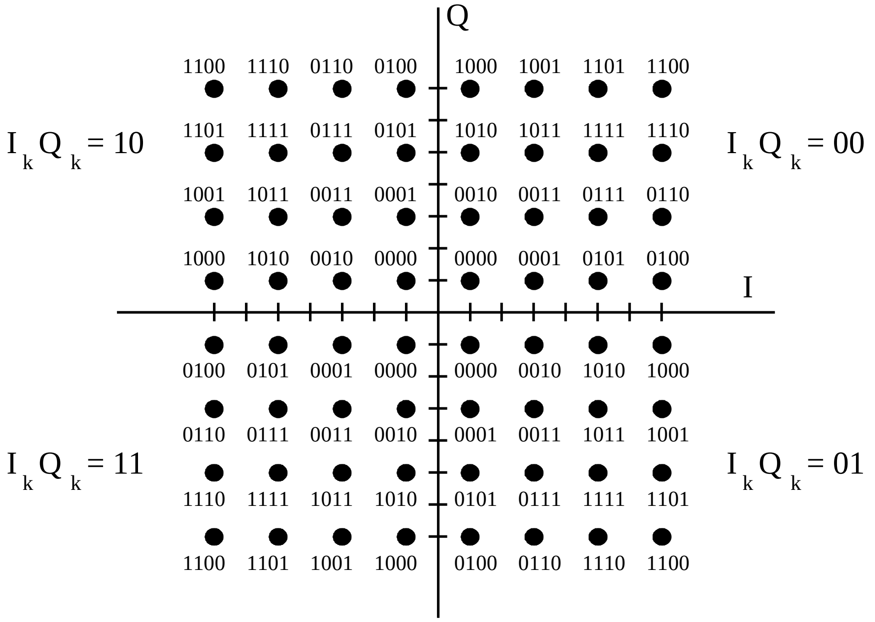
In order to support latency sensitive applications, it may be desirable to reduce the delays incurred by the interleaver block. In this case, the convolutional interleaver shall have a programmable depth with I=1, 3, 6, or 12. The interleaved frame shall be composed of overlapping error-protected packets and shall be delimited by MPEG sync bytes (preserving the periodicity of 204 bytes). Each branch shall be a First In First Out (FIFO) shift register, with depth (M) cells (where $M = N/I_{max}$, $N = 204$ = error protected frame length, $I_{max} = 12$ = maximum interleaving depth, j = branch index).

Programmable roll-off factor

In order to provide greater flexibility in system level design by trading off spectral efficiency with power efficiency, a variable roll-off parameter should be supported, with α ranging from 0.15 to 0.35.

Support for 64-QAM with differential encoding

This mode uses the same differential encoding structure described for the basic mode of operation with the inner convolutional code disabled, with q=4 in the differential encoder, and the following mapping of bits to symbols:



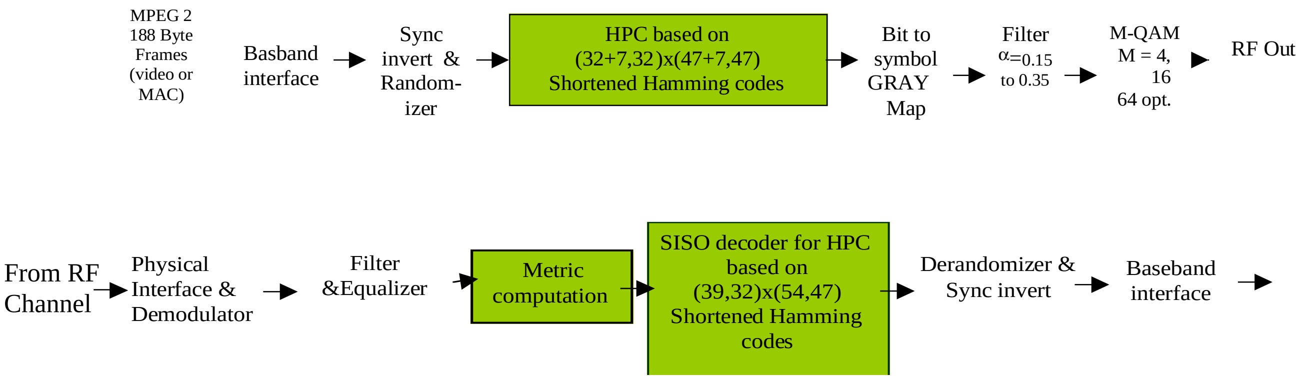
64 QAM Constellation Diagram

Support for π/4-DQPSK Modulation

π/4-DQPSK modulation shall be supported as described in [**TBD**].

Mode C: Advanced coding and modulation mode using Binary Product Codes

The encoding and decoding functions for the downstream physical layer in this advanced coding and modulation mode are summarized in the following block diagram. Following the encapsulation of the MAC packets into the MPEG frame, the data is randomized using the same mechanism as in the basic mode. The randomized bitstream is placed in a 32 x 47 array of information bits. Each row is encoded by (54,47) shortened Hamming code and each column by (39,32) shortened Hamming code. The resulting 54x39 coded array is block interleaved either by writing consecutive bits in rows and reading them out in columns, or by writing consecutive bits in columns and reading them out in rows. Coded bits are Gray mapped to a QPSK, 16QAM or 64QAM (optional) signal constellation. Finally, symbols are Nyquist filtered using a square-root raised cosine with a roll-off factor that is programmable from 0.15 to 0.35. This form of encoding enables the possible use of a soft-in\soft-out iterative decoding scheme.



Conceptual Block diagram of Mode C Downstream Physical layer

Main features of this advance mode:

- Sync Invert and randomization: As defined for basic physical layer architecture above
- Error Control Code (ECC): HPC(m=6,S1=25,S2=10) = (2106, 1504, 16)
- Interleaving: Block interleaver 54 bits or 39 bits (selectable)
- Modulation: QPSK, 16QAM and optionally 64QAM
- Bit to symbol map: Gray-coded for all modulation formats
- Spectral shaping: α=0.15-0.35 programmable
- Symbol rates: configurable up to 45 Mbaud

Convention and notations

(n, k, d) is a linear block code of length n dimension k and minimum Hamming distance d. The ratio k/n is the code rate. In many cases we shall drop the last parameter and we shall refer to (n, k) block code.

$(n_1, k_1, d_1) \times (n_2, k_2, d_2)$ is a general representation of a block code with length $n=n_1n_2$ dimension $k= k_1k_2$ and minimum distance $d=d_1d_2$. The code constructed in this way is called a "product code" (or 2-D array code), and (n_i, k_i) for i=1,2 are called the components codes. The codewords of the product code can be described by an n_1 times n_2 rectangular array, where the columns are a codewords of code (n_1, k_1) and the rows are codewords of (n_2, k_2).

Product code for MPEG packet structure

The general product code based on shortened binary Hamming codes as component codes is given by

$(2^m - S1, 2m - m - 1 - S1, 4) \times (2^m - S2, 2^m - m - 1 - S2, 4)$.

This code will be referred in the sequel as a Hamming Product Code **HPC(m, S1,S2).**

An MPEG package contains 188 bytes of 8 bits each. Thus, a product code which contains exactly these 188x8=1504 bits is realized with the following parameters:

m = 6, S1 = 25, S2 = 10.

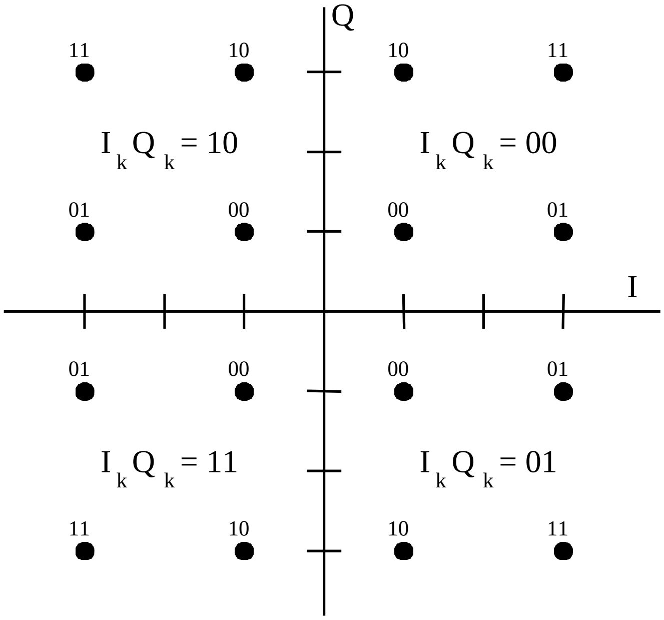
This implies (39, 32) and (54, 47) shortened Hamming components codes which constitute the binary product code (39x54, 32x47, 4x4) = (2106, 1504, 16) with code rate 0.714.

The shortened Hamming code (64-S, 57 - S) with shortening parameter S shall be implemented by appending S bits, all set to zero, before the information bits at the input of (64,57) extended Hamming encoder. This encoder shall be implemented by appending a parity check column the generator matrix of the Hamming code (63,57) generated by the primitive polynomial of degree 6:

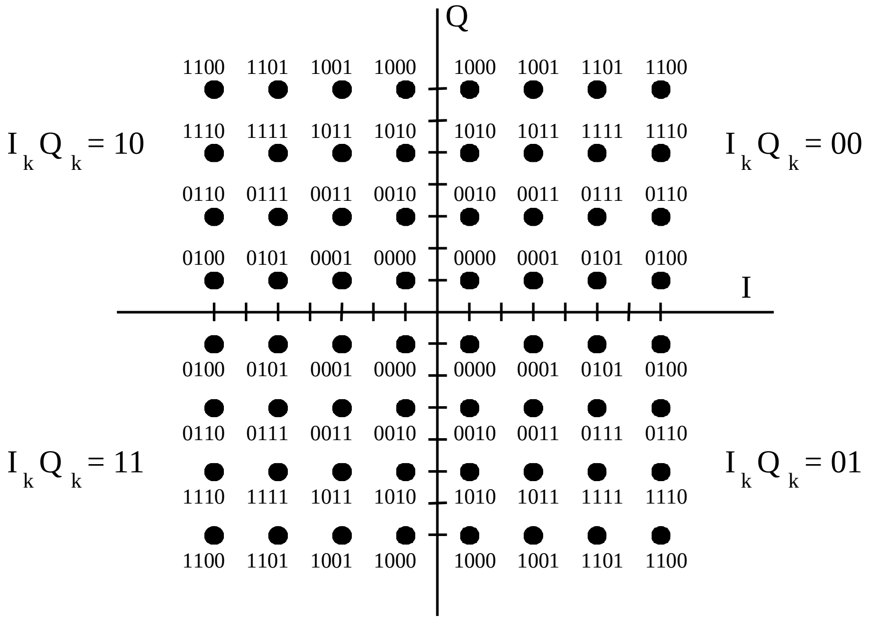
$g(x) = X^{6} + X^{1} + 1$

The block interleaving shall have two selections. Either 64 - 25 = 39 or 64 - 10 = 54 bits.

The Gray code mapping for QPSK shall follow the mapping as described in the Mode A specification above. The following diagrams illustrate the Gray code mapping of bits to symbols for 16-QAM and 64-QAM when using the mode:



16-QAM constellation with Gray code mapping



64-QAM constellation with Gray code mapping.

The downstream demodulator may perform soft-in\soft-out iterative decoding as follows:

Following the physical interface, demodulation and filtering as in **Mode A,** the symbols enter the metric computation unit. This unit compute "soft decisions" metrics for each received symbol. The product-code decoder makes use of these metrics. A reduced performance low cost CPE can perform simple (i.e., non-iterative) soft decoding, while high performance CPE can make SISO iterative decoding to improve the BER versus E_b/N_0 . The soft decoder should operate in SISO mode with BER in the order of 10E-2 and should provide an output BER corresponds to 10E-9. It is expected that (see [8]) simple soft decision decoding adds roughly 3dB to conventional hard decision coding gain and SISO Iterative decoding gains additional 3dB over soft decoding.

Mode D: Advanced coding and modulation mode using "pragmatic" trellis codes

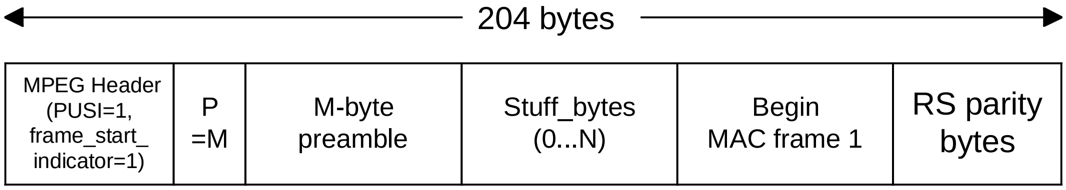
The use of "pragmatic" trellis coding, as described in [2], can be supported as an option with 8-PSK or 16-QAM modulation and a roll-off factor of α=0.25. This method of inner coding uses the same constraint length K=7 convolutional code defined above for the basic physical layer configuration. Mapping of bits to symbols shall be as described [2].

Mode E: Advanced duplexing mode supporting Half-Duplex FDD and/or TDD

Supporting H-FDD and TDD may be a desirable option in some cases. In order to leverage the components of the proposed FDD based system, the following configurations are recommended to support an H-FDD or TDD system. A compliant subscriber station should be able to support both of the following configuration options.

Configuration 1: FDD and H-FDD stations sharing the same downstream channel

1. The DS channel should be divided into equal length frames, which contain an integer number of MPEG packets. Note that any required guard time needs to be accounted for in the US and DS framing, which can be controlled by the MAC layer.
2. The downstream physical layer is identical to the FDD physical layer with the following additional changes:
   a. The same 188-byte MPEG packet format is used for the transmission of H-FDD/TDD packets, including the 4-byte MPEG header, pointer byte, and 802.16 MAC frames.
   b. The following diagram illustrates the format of the first MPEG packet in an H-FDD or TDD frame:

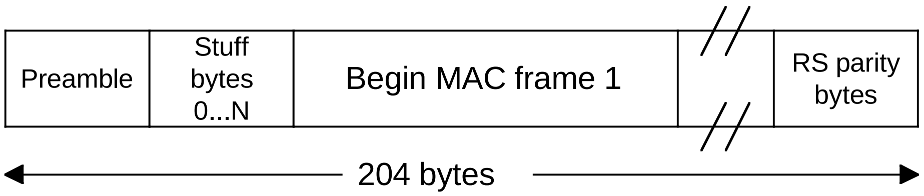


P=1 byte pointer field

   c. The use of the MPEG header for identifying an H-FDD/TDD MPEG packet is to allow for equipment that is operating in the FDD only mode to ignore the preamble. This method allows for both FDD and H-FDD units to operate in the same downstream channel. Since H-FDD equipment will not be able to read the header information until after synchronization and training, it is expected that equipment operating in H-FDD mode will look for the preamble for timing/phase/equalizer training, buffer the incoming packet (including the MPEG header and pointer bytes), and use the estimates to decode the whole packet contents.
   d. Note that, this mode of operation does not allow the continuation of a MAC packet in this frame.
   e. The randomizer shall continue to run during the preamble (as it does for the synch. byte) in order to maintain randomizer synchronization, but the output of the randomizer shall be disabled during the transmission of the preamble.
3. The convolutional interleaver shall be disabled (*i.e.*, I=1).
4. Inner convolutional coding shall be disabled.
5. The length of the preamble and the preamble value is **TBD**.

Configuration 2: H-FDD only or TDD only stations on the same downstream channel

1. The DS channel should be divided into equal length frames, which contain and integer number of MPEG packets. Note that any required guard time needs to be accounted for in the US and DS framing, which can be controlled by the MAC layer.
2. The downstream physical layer is identical to the FDD physical layer with the following differences in the first MPEG packet in the frame:
   a. The synch. byte shall be replaced by a variable length preamble that can be used to derive framing and equalizer coefficients. The following diagram illustrates the format of this first MPEG packet:



   b. The randomizer shall continue to run during the preamble (as it does for the synch. byte) in order to maintain randomizer synchronization, but the output of the randomizer shall be disabled for the preamble.

   c. Following the preamble, a MAC packet shall begin. If no MAC packets are available, then stuff_bytes shall be added. Therefore, no MPEG Header bytes are included in this first MPEG packet.
   d. The preamble and following payload (equaling 188 bytes) shall be encoded using the (204,188) Reed-Solomon code.
3. The subsequent MPEG packets shall use the synch. byte and Header bytes as defined for the basic physical layer described previously.
4. The convolutional interleaver shall be disabled (*i.e.*, I=1).
5. Inner convolutional coding shall be disabled.
6. The length of the preamble and the preamble value is **TBD**.

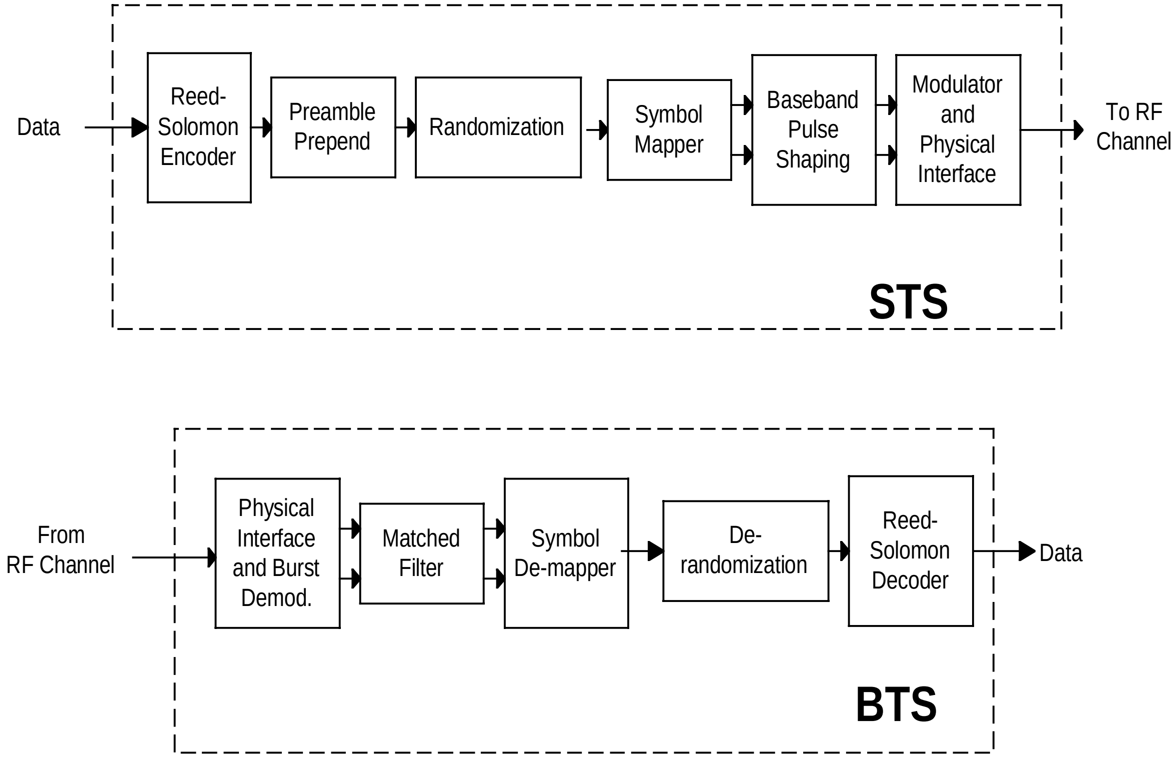
Summary of Downstream Physical Layer Optional Modes

Mode B: Enhanced flexibility mode	Defines the support of a variable length interleaver, a programmable roll-off factor, 64-QAM modulation with differential encoding, or π/4-DQPSK modulation.
Mode C: Advanced coding and modulation mode using Binary Product Codes	Replaces convolutional interleaver, Reed-Solomon encoder, and inner convolutional code with a Binary Product Code. Supports 4, 16, and optionally 64QAM Gray coded constellations.
Mode D: Advanced coding and modulation mode using "pragmatic" trellis codes	Use same inner convolutional code as basic physical layer with 8-PSK and 16-QAM constellations and different input to inner code and mapping of bits to symbols.
Mode E: Advanced duplexing mode supporting Half-Duplex FDD and/or TDD	Removes interleaving and inner convolutional coding, and modifies convergence layer to support a preamble for burst detection.

Upstream Physical Media Dependent (PMD) Sublayer

Mode A: Basic Mode of Operation

The upstream physical layer coding and modulation is summarized in the block diagram shown below.



Conceptual Block diagram of the 802.16 Upstream Physical Layer

Reed-Solomon coding

Reed-Solomon coding shall be applied to each randomized MAC packet. The code shall be a shortened, systematic Reed-Solomon code generated from GF(256) with codeword lengths (N) variable from 18-255 bytes, and error correction capability able to correct from T=0-10 byte errors. The specified code generator polynomials are given by

Code Generator Polynomial: $g(x) = (x+\mu^0)(x+\mu^1)(x+\mu^2) \ldots (x+\mu^{2T-1})$, where $\mu = 02\text{hex}$

Field Generator Polynomial: $p(x) = x^8 + x^4 + x^3 + x^2 + 1$

The specified code has a block length of 255 bytes, and shall be configured as a RS(255,255-2T, T) code with information bytes preceded by (255-N) zero symbols.

Preamble

The preamble should be programmable in length from 0-1024 bits and have a value that is also programmable.

Randomization for spectrum shaping

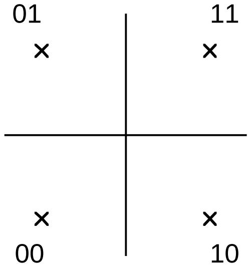
The upstream modulator must implement a scrambler using the polynomial $x^{15}+x^{14}+1$with a 15-bit programmable seed. At the beginning of each burst, the register is cleared and the seed value is loaded. The seed value must be used to calculate the scrambler bit, which is combined in an XOR with the first bit of data of each burst (which is the MSB of the first symbol following the last symbol of the preamble).

Modulation

The modulation used on the upstream channel should be programmable with the following options. Both QPSK and 16-QAM must be supported with the following mappings of bits to symbols.

QPSK Symbol Mapping

The following mapping of bits to symbols shall be support for QPSK modulation:

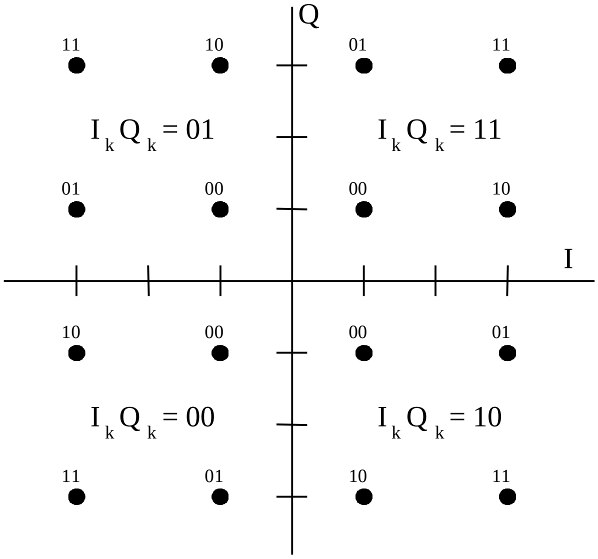


If differential encoding is employed, the encoder shall accept bits A and B in sequence and generate phase changes as follows:

A	B	Phase Change
0	0	none
0	1	+90 degrees
1	1	180 degrees
1	0	-90 degrees

Differentially encoded 16-QAM

If differential encoding is desired for 16-QAM, then the following signal constellation should be supported (I1 Q1 I0 Q0 represent the bits identifying the 16-QAM symbol).

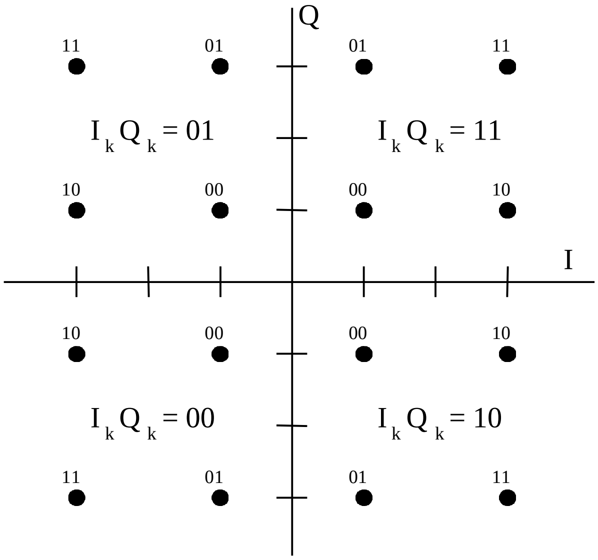


Differentially encoded 16-QAM Constellation diagram

Current Input Bits I1 Q1	Quadrant Phase change	MSBs of Previously Transmitted Symbol	MSBs for Currently Transmitted Symbol
00	0°	11	11
00	0°	01	01
00	0°	00	00
00	0°	10	10
01	90°	11	01
01	90°	01	00
01	90°	00	10
01	90°	10	11
11	180°	11	00
11	180°	01	10
11	180°	00	11
11	180°	10	01
10	270°	11	10
10	270°	01	11
10	270°	00	01
10	270°	10	00

Gray-coded 16-QAM

If differential encoding is not desired, then the following signal constellation shall be supported:



Gray-coded 16-QAM Constellation diagram

Baseband Pulse Shaping

Prior to modulation, the I and Q signals shall be filtered by square-root raised cosine filters. The excess roll-off factor α shall be 0.25. The square-root raised cosine filter is defined by the following transfer function H:

$$H(f)=1 \qquad for|f|< f_N(1-\alpha)$$

$$H(f)= \frac{1}{2}+\frac{1}{2}\sin\frac{\pi}{2f_N}\;\frac{f_N-|f|}{\alpha}\;\begin{matrix}?\\?\end{matrix}^{1/2} \qquad for\ f_N(1-\alpha)\le|f|\le f_N(1+\alpha)$$

$$H(f)=0 \qquad for|f|> f_N(1+\alpha)$$

where $f_N=\frac{1}{2T_s}=\frac{R_s}{2}$ is the Nyquist frequency. Since *H(f)=0* is impossible to realize in practice, the actual response in the range $|f|>f_N(1+\alpha)$ should be *H(f) < 50 dBc* measured with respect to the passband.

Summary of Mode A Upstream Physical Layer Parameters

Reed-Solomon Coding	Codeword lengths: 18-255 bytes T=0-10
Randomization	$x^{15}+x^{14}+1$ Initialization seed: 15-bit programmable
Preamble	Programmable length: 0-1024 bits Programmable value
Modulation	QPSK or 16-QAM
Differential encoding	Selectable on/off
Spectral shaping	α=0.25

Achievable symbol rates	up to 40 Mbaud
Frame time (when enabled)	Programmable in steps of 125 usec

Upstream Physical Layer Optional Modes

Mode B: Enhanced Flexibility Mode

The modifications contained with this optional mode include various enhancements to improve the flexibility of the physical layer with respect to the modulation or spectral shaping filters. It is not necessary for a subscriber station to implement all of the following options, so it is expected that some negotiation of capability sets may need to be done for subscribers implementing options in this mode.

Programmable roll-off factor

In order to provide greater flexibility in system level design by trading off spectral efficiency with power efficiency, a variable roll-off parameter should be supported, with α ranging from 0.15 to 0.35.

Support for $\pi/4$-DQPSK Modulation

$\pi/4$-DQPSK modulation shall be supported as described in [**TBD**].

Mode C: Advanced coding and modulation mode using Binary Product Codes

In the upstream, the parameters of the product code shall be configurable yielding a family of product codes denoted Hamming Product Codes, HPC. This family of codes shall be used in the upstream to protect frame formats from 18 bytes up to 399 bytes and have code rates between 0.44 – 0.8. For very short frame of length less than 32 bytes, a very high rate Parity Product Code (PPC) based on parity check codes is suggested. Both HPC and PPC have remarkable efficient SISO iterative decoders (*i.e.*,"Turbo decoders").

In this mode, most of the transmission formats of the baseline upstream physical layer, such as randomization, preamble prepend, Gray bit-to-symbol mapping, and pulse shaping are maintained. However, in order to give better protection against errors, two schemes for using a variable length block product code are described. For information packets between 18 to 255 bytes, HPC(m, S1, S2) are suggested (see Appendix A for a detailed list of available configurations). For short packets between 8 bytes and 32 bytes and a relatively very high rate, a block product code based on $(k_1+1,k_1) \times (k_2+1, k_2)$ parity product codes, denoted PPC(k_1, k_2), are suggested. Unlike Reed-Solomon codes based on GF(256) which are limited to codewords of length up to 255, HPC codes can support up to 399 bytes.

Main features:

- Randomizer: As in **Mode A**.
- ECC: Variable information length between 18 - 399bytes, variable rate 0.44 to 0.8 based on HPC(m,S1,S2) m = 5 or 6, S1, S2 configurable between 0 to 32.
- Short burst mode: Variable length between 8 to 32 bytes based on PPC(k_1, k_2).
- Interleaving: Bit block-interleaver, configurable 2^m - S1 or 2^m - S2
- Modulation: Gray coded QPSK, 16QAM and optionally 64QAM
- Bit to symbol map: Gray-coded for all modulation formats
- Spectral shaping: $\alpha = 0.15 - 0.35$ programmable through MAC messaging.
- Symbol rates: Configurable up to 40 Mbaud

The generator polynomial for the shortened Hamming component codes shall be based on the following primitive binary polynomial.

m=5 $g(x) = X^5 + X^2 + 1$

or m=6 $g(x) = X^6 + X + 1$

The HPC encoder and interleaver consist of a rectangular array of 2^m x 2^m bits. The block encoder for HPC(m, S1, S2) accepts S1 bits of zeros followed by $k_1 = 2^m - m - 1 - S1$ bits of data. Those k_1 bits are written in columns of the array where last bit is regarded as the MSB. A sequence of m parity check bits are computed based on g(x) followed by an overall parity check bit. This procedure is repeated column by column until the first $k_2 = 2^m - m - 1 - S2$ columns of the encoder array. When this process, called column encoding, is finished a line encoding process starts by appending S2 bits of zero followed by a sequence of m parity check bits for the first row followed by overall parity check bit. This process is repeated until all n_1 lines are encoded. The coded bits are read from the array row-by-row and Gray mapped to symbols in the constellation map.

Applications of product codes to variable length and relatively short IP packages can be realized with the aid of parity check product codes (PPC). Consider two examples of short package: 8 bytes**,** 32 bytes. Information bits are arranged in a bit rectangle, and encoded as a parity check block codes**:** **PPC(9,8)**^{2} and **PPC(17,16)**^{2} respectively.

Summary of Upstream Physical Layer Optional Modes

Mode B: Enhanced Flexibility Mode	Adds support of a variable roll-off factor for spectral shaping with α=0.15-0.35.
Mode C: Advanced coding and modulation mode using Binary Product Codes	Replaces Reed-Solomon encoder with a Binary Product Code.

Upstream channel description

The following parameters and their ranges can be used to configure the necessary upstream channel. It is expected that these parameters be sent in MAC messages from the basestation.

Parameter description	**Parameter needed from MAC**	**Meaning**
Mini-slot size	0-255 (M)	Number of bytes per mini-slot, which is the smallest unit of time slot size
Framing mode	0 or 1	enabled/disabled
Frame time	0-255 (N)	Frame time is Nx125 usec N=0 indicates framing is disabled
Mini-slots per frame	0-65,535 (P)	Number of mini-slots per frame
Symbols per mini-slot	0-1024 (Q)	Integer number of symbols per mini-slot period (independent of modulation used for transmission)
Upstream symbol rate (when framing is enabled)	--	Rs=PxQ/(Nx125 usec)
Roll-off factor*	Ro	Ro=15-35 (for α=0.15-0.35)
Spectrum inversion	0= inverted, 1=non-inverted	
Scrambler tap coefficients	16 bits	Each tap is either on (1) or off (0)
Upstream center frequency	0-60 GHz	in KHz

* = optional feature

Burst profiles

The upstream transmitter should be able to save multiple burst profiles, each of which contain the following information:

Parameter description	**Parameter needed from MAC**
Modulation	2=QPSK, 4=16-QAM
Preamble length	0-1023 bits
Preamble pattern	0-1023 bits
RS information bytes	16-255 bytes
Error correction of codeword	0-10 bytes
Last codeword length	1=fixed; 2=shortened (**optional**)
Guard time	0-255 symbols
Scrambler seed	15 bits
Differential encoding	on/off
Maximum burst size	0-255 mini-slots
Scrambler	on/off

Radio Sub-system Control

Synchronization Technique (Frame and Slot)

In order to satisfy timing requirements for telephony or other CBR applications (T1/E1), the downstream demodulator should provide an output reference clock that is derived from the downstream symbol clock. This reference can then be used by the subscriber station to provide timing for rate critical interfaces when the downstream clock is locked to an accurate reference at the basestation. A time-stamp based method could be used if the desired clock accuracy is sufficient for the services provided, but it should at least be an option to choose to derive subscriber station timing from the downstream symbol clock or an internal oscillator with time stamps coming from the MAC layer at the basestation.

In order to provide a time slot reference for the upstream channel, the upstream and downstream channels can be divided into equal and fixed length frames. The beginning of the downstream frame can be identified by the frame start indicator bit in the downstream MPEG Header. The beginning of the upstream frame could simply be a fixed offset from the downstream frame start message, programmed via a MAC message. Accurate upstream time slot synchronization should be supported through a ranging calibration procedure defined by the MAC layer to ensure that upstream transmissions by multiple users do not interfere with each other. Therefore, the physical layer needs to support accurate timing estimates at the basestation, and the flexibility to finely modify the timing at the subscriber station according to the transmitter characteristics specified in table below.

Frequency Control

Frequency control is also a critical component of the physical layer. Due to the large carrier frequencies proposed for Broadband Wireless Access systems, frequency errors will exist in the radio units, and will vary with age and temperature. In order to allow for cost effective radio units at the subscriber station, the upstream and downstream RF sources should reference each other. Note that the initial ranging process described above for timing adjustment should also be applicable for initial frequency and power calibration. After the initial frequency has been calibrated, it is expected that periodic measurements of the frequency offset value at the basestation will be made by the physical layer and sent to the subscriber station via a MAC message, enabling low cost frequency references to be used in the radio units.

Power Control

As with frequency control, a power control algorithm should be supported for the upstream channel with both an initial calibration and periodic adjustment procedure. The basestation should be able to provide accurate power measurements of the received burst signal. This value can then be compared against a reference level, and the resulting error can be fed back to the subscriber station in a calibration message coming from the MAC layer. The power control algorithm should be designed to support dynamic power fluctuations at rates of at least 5 dB/second with depths at least 20 dB. Static power attenuation due to distance loss should be compensated for up to 20 dB (for example, this could correspond to the difference between a 1 km and a 10 km distance assuming free space path loss).

Physical Layer Transmitter Characteristics

Basestation transmitter	
Tx power level/accuracy	Tx power shall not exceed +14 dBW/MHz
Max. Tx phase noise	TBD at a later date
Tx symbol Timing accuracy	Peak-to-peak symbol jitter, referenced to the previous symbol zero crossing, of the transmitted waveform, MUST be less than 0.02 of the nominal symbol duration over a 2-sec. period. The peak-to-peak cumulative phase error, referenced to the first symbol time and with any fixed symbol frequency offset factored out, MUST be less than 0.04 of the nominal symbol duration over a 0.1 sec period.
Tx RF frequency/accuracy	10-60 GHz/ +- 5 ppm (including aging and temperature variations)
Spectral Mask (OOB)	TBD by Coexistence group
Spectral mask (in-band)	TBD at a later date
Filter distortion	
Group delay variation	TBD at a later date
Amplitude ripple	TBD at a later date
Adjacent channel interference	TBD by coexistence
Co-channel interference	TBD by coexistence
Spurious	TBD by coexistence
Subscriber Station transmitter	
Tx power level and range	Tx power not to exceed +30 dBW/MHz with a range > 30 dB.
Tx power level adjustment steps and accuracy	The subscriber station shall adjust its Tx power level, based on feedback from the basestation via MAC messaging, in steps of 0.5 dB +/- 0.25 dB in a monotonic fashion.
Max. Tx phase noise	TBD at a later date.
Tx symbol timing jitter	Peak-to-peak symbol jitter, referenced to the previous symbol zero-crossing, of the transmitted waveform, MUST

	be less than 0.02 of the nominal symbol duration over a 2-sec. period. The peak-to-peak cumulative phase error, referenced to the first symbol time and with any fixed symbol frequency offset factored out, MUST be less than 0.04 of the nominal symbol duration over a 0.1 sec period.
Tx burst timing accuracy	Must implement corrections to burst timing with an accuracy of +/- _ of a symbol and a resolution of +/- _ of a symbol.
Tx RF frequency/accuracy	10-60 GHz/ +- 10 ppm
Tx frequency range	TBD at a later date.
Spectral Mask (OOB)	TBD by Coexistence group.
Spectral mask (in-band)	TBD at a later date.
Filter distortion	
Group delay variation	TBD at a later date.
Amplitude ripple	TBD at a later date.
Adjacent channel interference	TBD by Coexistence group.
Co-channel interference	TBD by Coexistence group.
Spurious	TBD by Coexistence group.

Appendix A: *Frame formats for binary product codes based on shortened Hamming codes in the upstream channel*

The following is a list of information frame formats for binary product codes when using Mode C for the upstream channel.

144=12*12 (18 bytes) R=0.444
160=10*16 (20 bytes) R=0.485
168=12*14 (21 bytes) R=0.467
176=11*16 (22 bytes) R=0.500
192=12*16 (24 bytes) R=0.485
208=13*16 (26 bytes) R=0.498
216=12*18 (27 bytes) R=0.500
224=14*16 (28 bytes) R=0.509
240=15*16 (30 bytes) R=0.519
256=16*16 (32 bytes) R=0.529
272=16*17 (34 bytes) R=0.538
280=14*20 (35 bytes) R=0.538
288=16*18 (36 bytes) R=0.545
304=16*19 (38 bytes) R=0.553
320=16*20 (40 bytes) R=0.559
336=16*21 (42 bytes) R=0.566
352=16*22 (44 bytes) R=0.571
360=18*20 (45 bytes) R=0.577
368=16*23 (46 bytes) R=0.577
384=16*24 (48 bytes) R=0.582
400=20*20 (50 bytes) R=0.592
408=17*24 (51 bytes) R=0.591
432=18*24 (54 bytes) R=0.600
440=20*22 (55 bytes) R=0.604

456=19*24 (57 bytes) R=0.608
480=20*24 (60 bytes) R=0.615
504=21*24 (63 bytes) R=0.622
520=20*26 (65 bytes) R=0.625
528=22*24 (66 bytes) R=0.629
552=23*24 (69 bytes) R=0.634
560=20*28 (70 bytes) R=0.615
576=24*24 (72 bytes) R=0.640
600=24*25 (75 bytes) R=0.645
616=22*28 (77 bytes) R=0.629
624=24*26 (78 bytes) R=0.650
648=24*27 (81 bytes) R=0.635
672=24*28 (84 bytes) R=0.640
696=24*29 (87 bytes) R=0.644
704=22*32 (88 bytes) R=0.645
720=24*30 (90 bytes) R=0.649
728=26*28 (91 bytes) R=0.650
736=23*32 (92 bytes) R=0.651
744=24*31 (93 bytes) R=0.653
768=24*32 (96 bytes) R=0.656
784=28*28 (98 bytes) R=0.640
792=24*33 (99 bytes) R=0.660
800=25*32 (100 bytes) R=0.662
816=24*34 (102 bytes) R=0.663
832=26*32 (104 bytes) R=0.667
840=28*30 (105 bytes) R=0.649
864=27*32 (108 bytes) R=0.652
888=24*37 (111 bytes) R=0.673
896=28*32 (112 bytes) R=0.656
928=29*32 (116 bytes) R=0.661
936=26*36 (117 bytes) R=0.680
952=28*34 (119 bytes) R=0.663
960=30*32 (120 bytes) R=0.665
992=31*32 (124 bytes) R=0.669
1008=28*36 (126 bytes) R=0.670
1024=32*32 (128 bytes) R=0.673
1040=26*40 (130 bytes) R=0.691
1056=32*33 (132 bytes) R=0.677
1064=28*38 (133 bytes) R=0.676
1080=30*36 (135 bytes) R=0.679
1088=32*34 (136 bytes) R=0.680
1120=32*35 (140 bytes) R=0.684
1152=32*36 (144 bytes) R=0.687
1160=29*40 (145 bytes) R=0.686
1176=28*42 (147 bytes) R=0.686
1184=32*37 (148 bytes) R=0.690
1200=30*40 (150 bytes) R=0.690
1216=32*38 (152 bytes) R=0.693
1224=34*36 (153 bytes) R=0.694
1240=31*40 (155 bytes) R=0.694
1248=32*39 (156 bytes) R=0.696
1280=32*40 (160 bytes) R=0.698
1296=36*36 (162 bytes) R=0.701
1312=32*41 (164 bytes) R=0.701
1320=33*40 (165 bytes) R=0.702
1344=32*42 (168 bytes) R=0.703
1360=34*40 (170 bytes) R=0.706
1368=36*38 (171 bytes) R=0.707
1376=32*43 (172 bytes) R=0.706
1400=35*40 (175 bytes) R=0.709

1408=32*44 (176 bytes) R=0.708
1440=36*40 (180 bytes) R=0.713
1472=32*46 (184 bytes) R=0.712
1480=37*40 (185 bytes) R=0.716
1496=34*44 (187 bytes) R=0.715
1504=32*47 (188 bytes) R=0.714
1512=36*42 (189 bytes) R=0.718
1520=38*40 (190 bytes) R=0.719
1536=32*48 (192 bytes) R=0.716
1560=39*40 (195 bytes) R=0.722
1568=32*49 (196 bytes) R=0.718
1584=36*44 (198 bytes) R=0.722
1600=40*40 (200 bytes) R=0.724
1632=34*48 (204 bytes) R=0.724
1640=40*41 (205 bytes) R=0.727
1656=36*46 (207 bytes) R=0.727
1672=38*44 (209 bytes) R=0.729
1680=40*42 (210 bytes) R=0.729
1720=40*43 (215 bytes) R=0.732
1728=36*48 (216 bytes) R=0.731
1760=40*44 (220 bytes) R=0.734
1768=34*52 (221 bytes) R=0.731
1776=37*48 (222 bytes) R=0.734
1800=40*45 (225 bytes) R=0.736
1824=38*48 (228 bytes) R=0.737
1840=40*46 (230 bytes) R=0.739
1848=42*44 (231 bytes) R=0.739
1872=39*48 (234 bytes) R=0.740
1880=40*47 (235 bytes) R=0.741
1920=40*48 (240 bytes) R=0.743
1936=44*44 (242 bytes) R=0.744
1944=36*54 (243 bytes) R=0.741
1960=40*49 (245 bytes) R=0.745
1968=41*48 (246 bytes) R=0.745
1976=38*52 (247 bytes) R=0.744
2000=40*50 (250 bytes) R=0.747
2016=42*48 (252 bytes) R=0.748
2024=44*46 (253 bytes) R=0.749
2040=40*51 (255 bytes) R=0.748

Evaluation Table

<table>
<tr><th>#</th><th>Criterion</th><th>Discussion</th></tr>
<tr><td>1</td><td>Meets system requirements</td><td>This physical layer meets the Functional Requirements by having a general structure that allows any MAC layer to reside above it. It has components which allow accurate synchronization of clocks at the subscriber station to support T1/E1 services and accurate determination of burst timing. See Annex A for a point-by-point treatment of each of the Functional Requirements.</td></tr>
<tr><td>2</td><td>Spectrum efficiency</td><td>Following are some configuration examples:
Downstream: assuming α=0.25 and a payload of 183 bytes.
<table>
<tr><th>Modulation</th><th>Inner Code Rate</th><th>bps/Hz</th></tr>
<tr><td>QPSK</td><td>0.5</td><td>0.717647</td></tr>
<tr><td></td><td>0.666666667</td><td>0.956863</td></tr>
<tr><td></td><td>0.75</td><td>1.076471</td></tr>
<tr><td></td><td>0.833333333</td><td>1.196078</td></tr>
<tr><td></td><td>0.875</td><td>1.255882</td></tr>
<tr><td></td><td>1</td><td>1.435294</td></tr>
<tr><td>HPC (rate=0.714)*</td><td>1</td><td>1.1424</td></tr>
<tr><td>8-PSK*</td><td>0.666666667</td><td>1.435294</td></tr>
<tr><td>*</td><td>0.833333333</td><td>1.794118</td></tr>
<tr><td>*</td><td>0.888888889</td><td>1.913725</td></tr>
<tr><td>16-QAM</td><td>1</td><td>2.870588</td></tr>
<tr><td>*</td><td>0.75</td><td>2.152941</td></tr>
<tr><td>*</td><td>0.875</td><td>2.511765</td></tr>
<tr><td>HPC (rate=0.714)*</td><td>1</td><td>2.2848</td></tr>
<tr><td>64-QAM*</td><td>1</td><td>4.305882</td></tr>
<tr><td>HPC (rate=0.714)*</td><td>1</td><td>3.4272</td></tr>
</table>
*=optional configuration
Upstream: Depends on a number of variables that are configured by the basestation, including preamble length, code rate (R), and guard time. As an example: 4 byte preamble, 1 byte guard time, roll-off of 0.25, and QPSK modulation.
bps/Hz=1.247 (RS(63,53) code with differential encoding)
bps/Hz=1.249 (PPC with 32 byte word)</td></tr>
<tr><td>3</td><td>Simplicity of implementation</td><td>This physical layer uses elements from several existing standards, many components of which exist in silicon form today.</td></tr>
<tr><td>4</td><td>CPE cost optimization</td><td>Leveraging existing technology results in lower cost chip sets due to maturity of technology and increased volume of sales.</td></tr>
<tr><td>5</td><td>Spectrum resource flexibility</td><td>This proposal contains several flexible parameters including symbol rates, roll-off factors, modulation, and coding, so that efficient spectrum resource and power planning can be done based on services required and deployment scenarios.</td></tr>
<tr><td>6</td><td>System diversity flexibility</td><td>The proposed physical layer is MAC independent, except for certain programmable variables that need to be defined by the MAC, so it is</td></tr>
</table>

		amenable to any future services that may reside above the MAC.
7	**Protocol interfacing complexity**	The proposed physical layer is MAC independent with simple mapping of MAC packets to physical layer frames.
8	**Implications on other network interfaces**	The proposed physical layer is MAC independent, except for certain programmable variables that need to be defined by the MAC, so it is amenable to any network interfaces that may reside above the MAC.
9	**Reference system gain**	Assumptions: BER=10^(-10), 40 MHz DS channel, 10 MHz US channel, DS assumes a 0 dBW transmitter, 0 dB NF LNA, noise floor = -174 dBm + 10log(BW). See Annex B for results.
10	**Robustness to interference**	QPSK modulation is very robust against interference. Coding is flexible and can be changed to accommodate channel conditions.
11	**Robustness to channel impairments**	QPSK modulation is very robust against interference. Coding is flexible and can be changed to accommodate channel conditions.

Annex A: Functional Requirements Table

Item #	Page #	Line #	Requirement	Compliance	How this PHY complies
1	1	18	The forthcoming air interface standard MUST comply with the system requirements.	MUST	See following.
2	2	26	The 802.16.1 air interface interoperability standard SHALL be part of a family of standards for local and metropolitan area networks.	SHALL	NA
3	4	37	support more than one paying customer	SHOULD	TDM downstream and TDMA upstream
4	6	25	802.16.1 systems SHALL be multiple-cell frequency reuse systems.	SHALL	Flexible modulation, coding, and roll-off factors allow for optimal cell planning.
5	7	10	The base station radio SHOULD be P-MP	SHOULD	NA
6	8	23	The air interface MUST NOT preclude repeaters or reflectors to bypass obstructions and extend cell coverage.	MUST NOT	Flexible modulation, coding, and roll-off factors as well as selection of Tx characteristics allows vendors to interface with various radio requirements.
7	8	44	The standard (e.g., MAC/PHY protocols) SHALL describe common access protocol(s) and common modulation technique(s).	SHALL	PHY can support any MAC PDU format, and uses well-known and mature technologies for the physical layer.
8	9	6	Since all data traffic in a single cell of an 802.16.1 network MUST go through the base station, that station	MUST SHALL	TDM downstream and TDMA upstream supports this architecture.

			SHALL serve as a radio resource supervisor.		
9	9	17	802.16.1 protocols MUST provide the means to multiplex traffic from multiple subscriber stations nodes in the downstream direction, and provide for a means to resolve contention and allocate bandwidth in the upstream direction.	MUST	TDM downstream and TDMA upstream supports this architecture.
10	9	28	Services that an 802.16.1 system at least SHOULD support	SHOULD	NA
11	9	29	(some services MUST be supported).	MUST	NA
12	10	11	The MAC and PHY protocols may not have explicit support for each and every bearer service, since they SHOULD be handled as data streams in a generic fashion.	SHOULD	PHY supports transport of native MPEG packets as well as generic MAC PDUs.
13	10	16	Efficiently transport digital audio/video streams to subscribers	SHOULD	PHY supports direct broadcast of MPEG video streams.
14	10	17	This form of digital transport MAY bypass the MAC protocol layer.	MAY	PHY supports direct broadcast of MPEG video streams, but multiplexing of traffic still needs to be controlled by scheduler in the basestation.
15	10	22	Support telephony "pipes" to subscribers for legacy equipment and PSTN…including SDH and PDH	SHOULD	PHY includes simple method to reference subscriber station clocks with SDH clocks at basestation. DS and US can be controlled by MAC to provide service guarantees for telephony.
16	10	24	802.16.1 protocols MAY transport any layer in the nationally- and internationally-defined digital telephony service hierarchies	MAY	PHY includes simple method to reference subscriber station clocks with SDH clocks at basestation and can carry and MAC PDU that is defined by MAC for telephony services.
17	10	39	802.16.1 systems and protocols MUST support the QoS requirements of these services: ▪ Narrowband/Voice Frequency Telephony - POTS (supporting FAX services), Centrex, ISDN BRI 35 ▪ NxDSO Trunking - Fractional DS1/E1 to PBXs and/or data equipment, ISDN PRI 36 ▪ Full DS1/E1 - transparent mapping including all framing information ▪ Voice Over IP, Voice Over Frame Relay, Voice and	MUST	Timing requirements can easily be met by PHY. Coding, modulation, roll-off factors, and interleaving depth can be configured to support any types of service.

			Telephony over ATM (VTOA), and similar services as defined in Section.		
18	11	23	The amount of delay between a user speaking and another user hearing the speech MUST be kept below a certain level to support two-way conversation.	MUST	A variable interleaver has been defined to support low latency for small DS symbol rates. Modem operations result in negligible delays proven by working systems using this technology.
19	11	43	BWA protocols MUST support efficient transport of encoded voice data in terms of bandwidth, reliability and delay.	MUST	PHY can meet strict telephony timing requirements, and allows for MAC to control voice data encapsulation in MAC PDUs.
20	12	11	MUST meet the transport requirements of such telephony signaling, whether TDM- or message-oriented.	MUST	NA…signaling left up to the MAC.
21	12	18	Efficient transport of ATM cell relay service and preserve its QoS features	SHOULD	PHY can support any MAC PDU format.
22	12	27	Provide a means to utilize ATM addresses such as ITU-T E.164	SHOULD	Left up to MAC.
23	12	32	Directly transport variable length IP datagrams efficiently	MUST	Left up to MAC.
24	12	34	Both IP version 4 and 6 MUST be supported.	MUST	Left up to MAC.
25	12	35	Use TCP/IP header compression over the air	SHOULD	Left up to MAC.
26	12	37	The 802.16.1 IP service MUST provide support for real-time and non-real-time services.	MUST	Left up to MAC.
27	12	38	It SHOULD be possible to support the emerging IP Quality of Service (QoS) efforts	SHOULD	Left up to MAC.
28	13	2	The 802.16.1 protocols MAY support bridged LAN services,	MAY	Left up to MAC.
29	13	34	The 802.16.1 protocols SHOULD NOT preclude the transport of the following services: ▪ **Back-haul service** ▪ **Virtual point-to-point connections** ▪ **Frame Relay Service**	SHOULD NOT	Left up to MAC.
30	15	23	The MAC protocol MUST define interfaces and procedures to provide guaranteed service to the upper layers.	MUST	PHY has flexibility in coding, modulation, interleaving, and timing regeneration that can be configured to support various QoS requirements.
31	15	27	The MAC protocol MUST	MUST	NA

			efficiently resolve contention and bandwidth allocation.		
32	15	38	Further details, and finalization of the protocol reference model, SHALL be worked out by the 802.16.1 MAC and PHY task groups while developing the air interface interoperability standard.	SHALL	NA
33	15	12	The 802.16.1 protocols SHOULD allow for different "scales" of capacity and performance for 802.16.1 system instances.	SHOULD	Flexible coding, modulation, and roll-off factors proposed for basic PHY configuration as well as optional PHY configurations allow for various spectral/power efficiency trade-offs and capacity/cost considerations.
34	16	25	802.16.1 protocols SHALL be optimized to provide the peak capacity from 2 to 155 Mbps to a subscriber station sufficiently close to the base station.	SHALL	PHY can be configured to support a large range of data rates.
35	16	27	802.16.1 MAC protocol SHOULD allow the upper range of delivered bandwidth to scale beyond 155 Mbps. 2	SHOULD	PHY can be configured to support a large range of data rates.
36	16	28	802.16.1 protocols SHALL NOT preclude the ability of an 802.16.1 system to deliver less than 2 Mbps peak per-user capacity.	SHALL NOT	PHY can be configured to support a large range of data rates.
37	16	33	802.16.1 protocols SHOULD allow for flexibility between delivered upstream and downstream bandwidth and CoS/QoS.	SHOULD	Flexible coding, modulation, interleaving delays, and symbol rates allows PHY to support various QoS requirements.
38	17	3	An 802.16.1 system SHOULD be available to transport all services at better than their required maximum error rates (see section 5.5) 99.99from about 99.9 to 99.999% of the time.	SHOULD	Flexible coding and modulation allows system to be configured to support any desired reliability. Use of mature technologies also helps to guarantee MTBF based on historical data.
39	17	8	The 802.16.1 specifications SHALL not preclude the ability of the radio link to be engineered for different link availabilities, based on the preference of the system operator.	SHALL NOT	Flexible coding, modulation, and roll-off factors provides freedom in radio link planning.
40	17	28	802.16.1 MAC and PHY protocols MUST accommodate rain fall, perhaps consuming more radio bandwidth and/or requiring smaller radio propagation distance (radius) to meet the availability requirements.	MUST	Requirements provided for power control allow PHY to reliably operate with 5 dB/sec rain fades and depths up to 30 dB.

41	17	31	Since statistical rain rates vary widely in geography, the 802.16.1 protocols MUST be flexible in consumed radio bandwidth (spectral efficiency), cell radius, and transmit power to 6 accommodate a rain allowance that varies with geography 7	MUST	PHY is very flexible in terms of coding, modulation, and roll-off factors to optimally trade-off spectral and power efficiency for different deployed locations.
42	17	36	MAC and PHY protocols SHOULD specify functions and procedures to adjust power, modulation, or other parameters to accommodate rapid changes in channel characteristics due to atmospheric conditions	SHOULD	PHY describes requirements for power, frequency, and timing adjustments that can be controlled by the MAC to meet the expected time variations.
43	18	3	The error rate, after application of the appropriate error correction mechanism (e.g., FEC), delivered by the PHY layer to the MAC layer SHALL meet IEEE 802 functional requirements: The bit error rate (BER) is 10E-9.	SHALL	Flexible coding and modulation allows operator to configure the system to meet any BER requirement.
44	18	6	Each block of data delivered by the PHY to the MAC layer MUST allow for detection of errors by the MAC (e.g., by CRC) with 1, 2 or 3 errored bits (a Hamming Distance of 4)	MUST	The use of Reed-Solomon encoding provides a method for error detection as well as correction at the PHY layer, which can complement any CRC checksums done in the MAC.
45	18	36	In a telephony network, for example, the maximum acceptable end-to-end delay for the longest path is RECOMMENDED to be less than 300ms.	RECOMMENDED	Delays incurred by the PHY are much less then 300 ms, based on interleaving and modem functions. For low DS symbol rates, a programmable interleaver can provide lower latencies.
46	18	39	The budget for the 802.16.1 system transit delay and access delay MUST be derived. The MAC layer may have different requirements for each direction, upstream and downstream.	MUST	The primary delays in the PHY result from the downstream interleaver and upstream packet size requirements, which are fixed and can be calculated.
47	18	42	In the upstream direction, time MUST be budgeted for requesting bandwidth and contending among nodes.	MUST	Left up to MAC.
48	19	12	In a given 802.16.1 system instance, capacity MUST be carefully planned to ensure that subscribers’quality of service guarantees and maximum error rates are met.	MUST	Flexible coding and modulation allows operator to configure the system to meet any QoS requirement.
49	19	16	The following parameters of an	SHOULD	PHY has flexibility in coding,

			802.16.1 system SHOULD be addressed by the MAC and PHY protocols: ▪ Radio range (shaped sector radius) ▪ Width of the sector ▪ Upstream/downstream channels' data rates ▪ Allocation of prospective subscriber data rate to channels. Note: the MAC and PHY standards may allow subscribers to hop between channels ▪ Types of modulation		modulation, interleaving, and roll-off factors that can be configured to support various system architectures.
50	19	26	The MAC and PHY protocols MUST accommodate channel capacity issues and changes in channel capacity to meet contracted service levels with customers.	MUST	PHY has flexibility in coding, modulation, interleaving, and roll-off factors that can be configured to support various system architectures.
51	19	29	As subscribers are added to 802.16.1 systems, the protocols MUST accommodate them in an automated fashion.	MUST	The DS PHY can employ either automatic receiver detection or can be programmed upon installation. MAC can configure US once DS has been acquired.
52	20	8	802.16.1 protocols MUST support classes of service (CoS) with various quality of service (QoS) guarantees to support the bearer services (see section 9) that an 802.16.1 system MUST transport.	MUST	Flexible coding and modulation allows operator to configure the system to meet any QoS requirement.
53	20	10	802.16.1 protocols MUST provide the means to enforce QoS contracts and Service Level Agreements [2] (see section 7.1).	MUST	Left up to MAC.
54	20	11	802.16.1 protocol standards MUST define interfaces and procedures that accommodate the needs of the bearer services with respect to allocation of prioritization of bandwidth.	MUST	Left up to MAC.
	20	15	Table 1 provides a summary of the QoS requirements that the PHY and MAC SHALL provide.	SHALL	NA.
55	20	20	The 802.16.1 protocols MUST be capable of dedicating constant-rate, provisioned, bandwidth for bearer services such as SDH/PDH.	MUST	Left up to MAC.
56	20	28	For QoS-based, connectionless, but not circuit-based, bearer services, the 802.16.1 protocols MUST support bandwidth negotiation "on-demand" [9].	MUST	Left up to MAC.
57	22	26	802.16.1 protocols SHALL define a	SHALL	Flexible coding and

			set of parameters that preserve the intent of QoS parameters for both ATM- and IP-based services. (TBD)		modulation allows operator to configure the system to meet any QoS requirement.
58	22	30	The classes of service and QoS parameters of bearer services SHALL be translated into a common set of parameters defined by 802.16.1.	SHALL	Flexible coding and modulation allows operator to configure the system to meet any QoS requirement.
59	22	33	A network node that serves as an inter-working function (IWF) between a QoS-capable LAN or WAN and an 802.16.1 system MUST participate in signaling protocols to set up QoS parameters for connection-oriented services.	MUST	Left up to MAC.
60	22	37	The IWF MUST participate in the ATM signaling protocol that sets up the circuit.	MUST	Left up to MAC.
61	22	38	MUST utilize 802.16.1.1 interface primitives (e.g., MAC layer user interface primitives) to request QoS.	MUST	Left up to MAC.
62b	22	27	If 802.16.1 is to be a “link” in the IP network, an IWF MUST interface with 802.16.1 to negotiate resource allocation.	MUST	Left up to MAC.
	23	3	MUST be chosen and interface primitives defined that allow for bearer services’ IWFs to negotiate QoS “through” an 802.16.1 system	MUST	Left up to MAC.
63	23	7	BWA systems SHOULD include a mechanism that can support dynamically-variable-bandwidth channels and paths (such as those defined for ATM and IP environments).	SHOULD	TDM DS and TDMA US supports this architecture.
64	23	32	The 802.16.1 protocol MUST permit operators (def) to enforce service level agreements (SLAs) with subscribers by restricting access to the air link, discarding data, dynamically controlling bandwidth available to a user or other appropriate means. [3]	MUST	TDM DS and TDMA US supports this architecture.
65	23	34	The 802.16.1 protocols MUST also permit subscribers to monitor performance service levels of the 802.16.1 services being provided at the delivery point	MUST	Left up to MAC.
66	23	38	The operator MUST have means to shut down a subscriber station if necessary, remote from the subscriber station, in the face of a	MUST	Left up to MAC.

			malfunction.		
67	23	39	The operator also MUST have the means to shut down a base station remotely.	MUST	Left up to MAC.
68	23	41	The 802.16.1 protocols SHOULD support a function that automatically shuts down transmission from a subscriber station or base station in case of malfunction (e.g., power exceed limits).	SHOULD	Left up to MAC.
69	24	3	The 802.16.1 system management framework, architecture, protocols and managed object MUST allow for operators to effectively administer accounting and auditing.	MUST	Left up to MAC.
70	24	3	An operator MUST be able to account for time- and bandwidth-utilization and the various QoS parameters for each subscriber.	MUST	Left up to MAC.
71	24	8	The 802.16.1 system SHALL enforce security procedures described in this section.	SHALL	Left up to MAC.
72	24	19	This initial authentication MUST be very strong in order to prevent an 'enemy' subscriber station from entering the network or an 'enemy' base station from emulating a real base station.	MUST	Left up to MAC.
73	24	24	This level of authentication MUST be supported by the 802.16.1 MAC layer.	MUST	Left up to MAC.
74	24	34	The authentication mechanisms MUST be secure so that an “enemy” subscriber station is not able to gain access to an 802.16.1 system, or to the core network beyond.	MUST	Left up to MAC.
75	24	36	Passwords and secrets MUST NOT be passed “in the clear” through the air interface.	MUST NOT	Left up to MAC.
76	24	41	The 802.16.1 standard SHALL identify a standard set of credentials and allow for vendors to extend the defined credentials with non-standard credentials.	SHALL	Left up to MAC.
77	25	9	Subscriber authorization requests and responses MUST be transacted securely.	MUST	Left up to MAC.
78	25	18	Allow for a strong cryptographic algorithm to be employed that is internationally applicable for privacy.	SHOULD	Left up to MAC.
79	25	19	Facilities SHOULD also be defined in the protocol for the use of alternate cryptographic algorithms	SHOULD	Left up to MAC.

			that can be used in certain localities and that can replace algorithms as they are obsoleted or "legalized" for international use.		
79	24	40	802.16.1 SHOULD strive to fit into the 802 system model.	SHOULD	PHY can support any types of services defined by MAC.

Annex B: Reference System Gain

Modulation	**Inner Code**	**Eb/No (dB)**	**C/N (dB)**	**Backoff (dB)**	**RSG (dB)**
Downstream					
QPSK	_	4.5	4.13	4	119.84
	2/3	5	5.88	4	118.10
	_	5.5	6.90	4	117.08
	5/6	6	7.85	4	116.13
	7/8	6.4	8.47	4	115.51
(differential)	1	9.3	11.9	4	112.08
HPC (block code rate = 0.714)*#	1	4.0	5.5	4	118.48
8-PSK*	2/3	6.9	9.55	5	113.43
*	5/6	8.9	12.52	5	110.46
*	8/9	9.4	13.30	5	109.68
16-QAM*	1(differential)	14.35	20.0	7	100.98
*	_	9	13.4	7	107.58
*	7/8	10.7	15.77	7	105.21
HPC (block code rate = 0.714)*#	1	7.5	12.04	7	108.94
64-QAM*	1(differential)	19.25	26.68	9	92.3
HPC (block code rate = 0.714)*#	1	12	18.32	9	100.66
Upstream	**Code rate**	**Eb/No (dB)**	**C/N (dB)**	**Backoff (dB)**	**RSG (dB)**
QPSK (differential encoding)	53/63	11	13.25	4	116.75
HPC (32 byte block)*#	0.529	9	9.23	4	120.77

PPC (32 byte block)*#	256/289	12	14.49	4	115.51

*=optional configuration

#=based on SISO iterative decoding

Note that the above numbers include an implementation loss in the downstream of 0.8 dB for QPSK (1 dB for QPSK with HPC); 1, 1.4, and 1.5 dB for 8-PSK with rates 2/3, 5/6, and 8/9, respectively; 1.5, 2.1, and 2.1 dB for 16-QAM with rates _, 7/8, and 1, respectively, and 2 dB for HPC; 2.5 dB for 64-QAM with differential encoding and 2 dB for HPC; and in the upstream of 2 dB.

Annex C: Bandwidth-On-Demand MAC / PHY Protocol Sublayer Option

Introduction

This Annex outlines an optional PHY protocol proposed for inclusion in the IEEE 802.16 Broadband Wireless Access standard. This PHY, when combined with a companion Bandwidth-On-Demand MAC Sublayer results in a universal connectivity mechanism that supports any digital communication network and user protocol. A more detailed description of the approach is described in a companion PHY contribution “802.16 PHY Contribution: Proposed PHY Amendments to Include a Bandwidth-On-Demand MAC/PHY Sublayer Option”.

The proposed PHY is based primarily on the PHY described within the main document to which this Annex is attached with only minor modifications. It is focused on supporting not only the proposed 802.16 standard, but other MAC and higher-level protocols as well. Operation of the PHY is based on tightly controlled Subscriber Station timing synchronized with the Base Station reference clock. In the case of FDD operation, it uses continuous transmission in the downstream direction and fixed-size short burst transmissions upstream. In TDD operation, downstream transmission is continuous except for the periods where the Base Station must be silent to receive upstream bursts.

The combined Bandwidth-On-Demand MAC Sublayer[1] / PHY Layer approach described results in very low transport delay, delay variation and jitter. Continuous transmission in the downstream case assures low delay operation. In the upstream case, delay and jitter are minimized compared to variable-length PDU operation. However, there is a tradeoff between the fixed burst size and bandwidth efficiency. Transport delay is directly proportional to burst size, an important consideration in setting up low speed connections.

PDU-based multiplexing techniques can be satisfactory for IP-based applications that do not require support for low-latency interactivity. However, difficult tradeoffs exist to support Asynchronous Transfer Mode (ATM) channels and Synchronous Transfer Mode (STM) bearer channels (such as Synchronous-Data-Hierarchy / Plesiochronous-Data-Hierarchy (SDH/PDH) traffic including voice). Low-delay, bandwidth-efficient support is important for these as well as highly interactive services based on IP. In addition to satisfying these needs in initial systems, the proposed approach can be extended to support directly any current or future digital transmission protocol, particularly those that must meet critical Quality of Service (QoS) objectives. This universal connectivity approach promises both high performance and non-obsolescence.

Scope

The proposed optional PHY protocol incorporates most elements of the PHY standard proposed in this document’s main sections. The protocol’s fundamental PHY structure uses Time Division Multiplex frames that

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[1] A companion MAC contribution, submitted to the 802.16 MAC group entitled “802.16 MAC Protocol: Proposed Amendments to Include a Bandwidth-On-Demand MAC/PHY Sublayer Option”, describes the proposed MAC Sublayer in more detail.

contain small fixed-length data containers called *cell slots*. These cell slots are assigned to bandwidth-on-demand information flows in a flexible and dynamic manner.

The uniqueness of the approach obtains from the assignment of each individual flow to a set of nearly uniformly spaced cell slots throughout the Time Division Multiplex frame. Such assignments are made in both the downstream and upstream directions[2]. The result is low transport delay, delay variation and jitter compared to transmitting information in conventional PDU-sized bursts. The number of cell slots per frame (and hence the assigned bandwidth) is dynamically adjustable in milliseconds so that both asynchronously clocked as well as synchronously clocked flows are efficiently supported. Bandwidth utilization efficiency of the PHY is high compared with other shared medium network approaches. Messaging overhead to achieve dynamic bandwidth allocation is low.

Because of the simplicity of implementation of the proposed PHY and its companion Bandwidth-On-Demand MAC Sublayer, it is possible to produce a first generation 802.16 Air Interface that includes dividing Broadband Wireless Access system bandwidth into partitions, one for the 802.16 standard proposed in the main document and separate partitions for SDH/PDH and ATM traffic. The SDH/PDH and ATM partitions are further divided into any number of data channels each of which can be any integer multiple of some incremental bandwidth (such as 1 Kbps).

Service Goals

Some of the primary service goals of the approach are to produce a Broadband Wireless Access Air Interface specification that:

- enables early implementation of interoperable Broadband Wireless Access systems,
- is based on an architecture that assures non-obsolescence of installed systems,
- outperforms existing and proposed wireline systems in terms of service quality and cost, and is simple to operate and maintain.

The Protocol Stack

The following figure shows the location of the proposed Bandwidth-On-Demand MAC Sublayer and PHY Layer protocols. The interface to the Bandwidth-On-Demand MAC Sublayer to the next higher (adjoining) layers is standardized and includes only send and receive data, send and receive clock (passed through from the physical layer), and a common API that forwards messages over a Common Signaling Channel. In many cases, one or more framing signals from the PHY Layer can simplify packet and cell transfer and save bandwidth. The standardized Bandwidth-On-Demand MAC Sublayer interface supports a 802.16 MAC convergence layer and similar convergence layers for SDH/PDH and ATM protocols (among others). The MAC Sublayer is divided into partitions that support the various network protocols. Such protocols can include, among others, ATM and STM. It can also support other packet-based services such as IP, Frame Relay and IPX directly although this capability is not being proposed as a part of the standard at this time. Those shown in color (shaded) in the figure are those of principal consideration of this Annex and its referenced companion documents.

Figure 1: Protocol Stack for a Bandwidth-On-Demand MAC Sublayer Physical Layer

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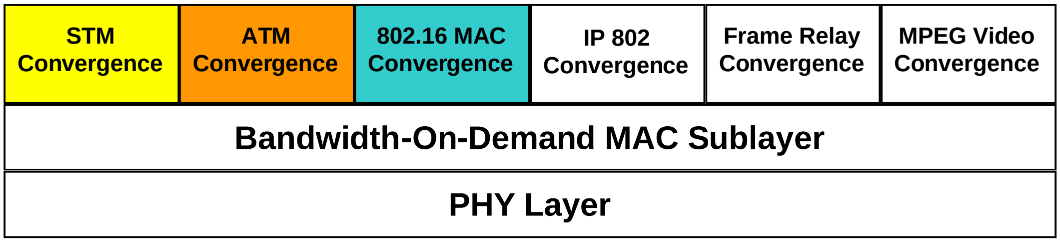
[2] Cell slots in the downstream direction are nominally 1-byte long. Cell slots in the upstream direction are as small as efficient modem design allows. The upstream cell slot size is nominally the equivalent to single stand-alone mini-slot in the 802.16 PHY.



Downstream Transmission

The Bandwidth-On-Demand MAC Sublayer maps cell slots to and from the higher layers into a Time Division Multiplex frame structure that sends information imbedded in the cell slots over the air in nearly uniformly-spaced time increments.

In the downstream direction, cell slots within Time Division Multiplex frames are always partitioned into at least three parts. These are:

- synchronization cell slots to establish the Time Division Multiplex frame boundaries,
- cell slots devoted to a Common Signaling Channel that passes messages from the Base Station to all Subscriber Stations, and
- all remaining cell slots, which are devoted to passing traffic from the Base Station to the Subscriber Stations.

The Time Division Multiplex frame period for a given system configuration is fixed in each direction of transmission. This period (i.e., the frame's length) depends on the information data rates to be supported and cell slot size. Delay, delay variation and jitter are independent of frame size (except as frame size is related to cell slot size).

Upstream Transmission

Upstream transmission is similar to downstream with three differences.

- There is no frame synchronization channel; all Subscriber Station transmissions are synchronized to the Base Station.
- There is no Common Signaling Channel devoted to each Subscriber Station. However, a Common Signaling Channel is shared among Subscriber Stations under control of the Base Station. In addition, there are contention channels for inactive Subscriber Stations to share when they require service.
- The Base Station must manage bandwidth assignments for all Subscriber Station to Base Station flows.

Frame Example

The following figure shows an example of a simple downstream Bandwidth-On-Demand MAC Sublayer frame structure. The example shows three traffic channels plus a Common Signaling Channel (labeled CSC) and a Framing channel (labeled Fr) where the framing cell slots can be distributed uniformly throughout a frame.

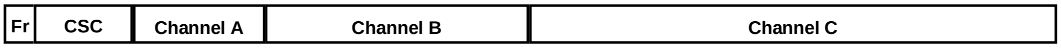


Figure 2: A simple Time Division Multiplex structure in the Element Address domain (downstream)

The frame structure exists both in a logical domain, called the Element Address domain (shown in Figure 2 and

in a physical time domain shown in Figure 3).

Figure 3: Example of Figure 2 shown in the physical (Ordinal Position Number) domain

Figure 2 shows the Element Address domain for the example. In this domain, the number of cell slots per frame assigned to a data channel determines the channel's bandwidth. A data channel is defined in the Element Address domain as a contiguous set of cell slots. (The total number of cell slots in the Element Address domain is F, the length of the Time Division Multiplex frame.) Figure 3 shows the distribution of cell slots in the physical time domain. There are also F cell slots in this domain as well.

Cell Slots and Error Correction

Considerations for physical layer transmission parameters are the same as for mini-slots defined within the main body of 802.16 PHY contribution. There must be trade-offs made between cell slot size and modem efficiency using current modem technology. Short cell slots enhance the low delay characteristics of the proposed approach. (Even so, with relatively large cell slot sizes, the delay characteristics of the approach compared with using conventional variable length PDUs is significant.)

There are a number of options for implementing error control. In the downstream case, applying the basic coding technique of the proposed 802.16 PHY of the main document or one of its optional alternatives is a good approach. However, it is not necessary to restrict the size of the encoding to the size of an MPEG packet since such packets only appear within the 802.16 MAC proposal. For example, Reed-Solomon coding might be employed over GF(256) for the entire continuous downstream transmission but using a code word size that optimally meets 802.16 requirements.

In both the downstream and upstream cases, error control is easily applied to either individual flows or aggregates of flows that must meet given QoS objectives. One advantage of the proposed PHY is that cell slot spreading is an inherent part of the system so that further interleaving is not required.

Conclusion

Using the approach proposed in this Annex results in a Broadband Wireless Access system that meets the 802.16 System Requirements more robustly and flexibly than can the baseline 802.16 system alone. The critical areas of improvement are found in supporting ATM and other fixed-length PDU applications, SDH/PDH applications and any application with critical QoS delay and jitter objectives. High bandwidth utilization efficiency, low latency, low delay variation and bounded jitter are major attributes of the approach. The ability to apply these capabilities to low speed channels such as compressed voice as well as to higher speed applications is of critical importance to the future applicability of Broadband Wireless Access networks to a broad market.