Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**802.16.3 PHY Ottawa Proposal**
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Source(s)	Ron McCallister and John Liebetreu Intersil Corporation 8515 East Anderson Drive Scottsdale, AZ 85255 Voice: 480-607-4831 Fax: 480-607-4806 mailto:rmccalli@intersil.com
Re:	This proposal is in response to the *Invitation to Contribute PHY Proposals: Session #11*, of Task Group 3 of the IEEE 802.16 Working Group on Broadband Wireless Access, as issued in document IEEE 802.16.3-00/24, dated 2000-12-02.
Abstract	This proposed PHY addresses the criteria in the Evaluation Table of the cited Call for Contributions with a flexibly scalable structure based on existing wireless standards, which can efficiently respond to the 802.16.3 Functional Requirements Document and support cost-effective implementations over alternative PHY structures.
Purpose	This proposal is submitted for consideration by Task Group 3 of the IEEE 802.16 Working Group on Broadband Wireless Access, as the 2-11 GHz Licensed Band PHY solution.
Notice	
Release	
Patent Policy and Procedures	

802.16.3 PHY Ottawa Proposal

Ron McCallister and John Liebetreu
Intersil Corporation

PHY Architectural Concept

Selecting a PHY standard for 802.16.3 links poses a substantial technical challenge. The Raleigh propagation channel is associated with severe link pathologies, and the urgent need by service providers demands adoption of a standard in less time than permits a completely thorough PHY selection methodology. A prudent approach would be to determine a previously developed open standard serving links very similar to those of 802.16.3's metropolitan area networks (MANs), and to consider a set of modifications to that standard based on specific distinctions between the two problems. In this spirit, we acknowledge the contribution of RunCOM in proposing the DVB-T and DVB-RCT standards as addressing a problem most similar to our own. However, there are numerous significant distinctions between the challenges of these two applications, video broadcast and interactive services as opposed to the set of services defined by the 802.1.6.3 Functional Requirement Document (FRD). We should adhere to the broader elements of these well-developed standards, while carefully modifying them where necessary to reflect these distinctions.

In this spirit, our proposed PHY will reflect the overall OFDM structure of the DVB-T and DVB-RCT, but will deviate from those standards where required to address key critical distinctions: 1) in the range of link variability; 2) in the types of data traffic; and, 3) in link quality-of-service (QoS) requirements.

DVB-T and DVB-RCT provide video broadcast and interactive service. The impact of occasional frequency-selective fading on either of these traffic types is negligible. Video broadcast readily accommodate link outages by simple “freeze framing,” exploiting human visual perception to mitigate the actual data loss. The return channel easily accommodates simple repeat-requests to assure receipt of a user request, without concerns over bandwidth efficiency or latency. Services defined in the 802.16.3 FRD are not afforded these simple compensations for link outage, and so our proposed PHY must explicitly address the need for more reliable service in Rayleigh fading than the DVB standards.

Television services are also far more uniform in their technical specifications, with uniform channel bandwidth and frequency band assignments, and far less critically dependent on maximizing bandwidth-efficiency than the services supported by 802.16.3. In every one of the many varied applications envisioned by our FRD, service providers face severe competitive pressure from alternatives to wireless access, and cannot afford to suffer the loss of revenue associated with using a single inflexible solution designed to satisfy some worst-case scenario. The PHY we select must reflect this reality by supporting a very wide range of channel bandwidths, link ranges (cell sizes), and frequency bands. These considerations immediately translate into the need to accommodate a wide range of propagation losses, delay spreads, Doppler rates, and levels of phase noise and amplifier nonlinearity; as always, this exceptional degree of flexibility must be achieved with negligible impact on PHY implementation complexity.

The PHY described in this proposal successfully addresses each of these considerations, offering a remarkably flexible response to the diverse demands of a PHY for 802.16.3 applications and is readily configurable to achieve the maximum system capacity under ***all*** conditions defined within the scope of the 802.16.3 FRD. Figure 1 depicts the top-level flow of system requirements into the small set of design parameters applied as input to the PHY modem ASIC to assure maximum link capacity, subject to any constraint on both data quality (bit error-rate) and data latency.

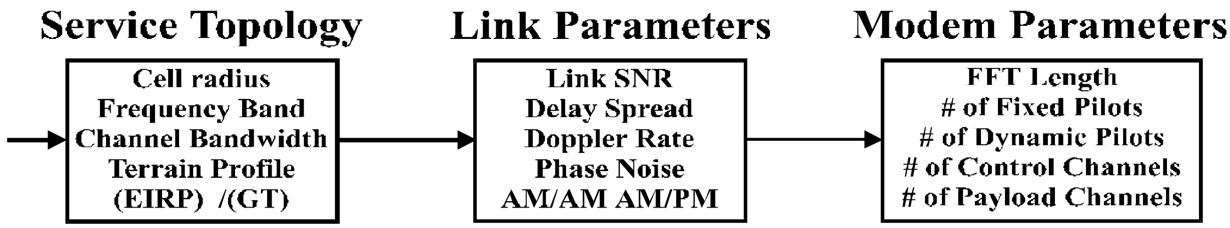

Figure 1. OFDM Design Methodology and Specification Flow

System Overview

The proposed PHYsical model uses bi-directional orthogonal frequency-division-multiplexing (OFDM), with scalable symbol rates to accommodate available bandwidth. This approach is based on OFDM PHY layers used by DVB-T and DVB-RCT standards, and to a lesser extent those of the ETSI HIPERLAN2 and IEEE 802.11a standards. The specific design parameters (e.g. number of sub-channels, pilot channel spacing, guard-time duration, etc.) will be more programmable than these previous standards, reflecting the much higher degree of variability associated with BWA/MAN links, which address a broader range of frequency bands, channel types/dynamics and link distances. Optional features are also proposed (e.g. transmit-diversity, and iterative decoding). In addition, this proposed PHY standard recommends incorporation of transmitter-diversity into the 802.16.3 standard. This technology advance has recently been embraced by multiple existing wireless standards. The proposed transmit-diversity scheme is identical to that already adopted as part of several 3G open standards (WCDMA 3GPP FDD mode, WCDMA 3GPP TDD mode, CDMA2000 and EDGE.)

The proposed PHY is MAC-agnostic, which will facilitate the transition between currently available and rapidly emerging MACs optimized for broadband fixed wireless applications. Moreover, this PHY supports both TDD and FDD duplexing schemes.

Reference Model

The proposed PHY layer supports all required functions described in the 802.16.3 Functional Requirements Document (FRD). The interfaces between the proposed PHY and other layers and sub-layers of the ISO stack are depicted in figure 2.

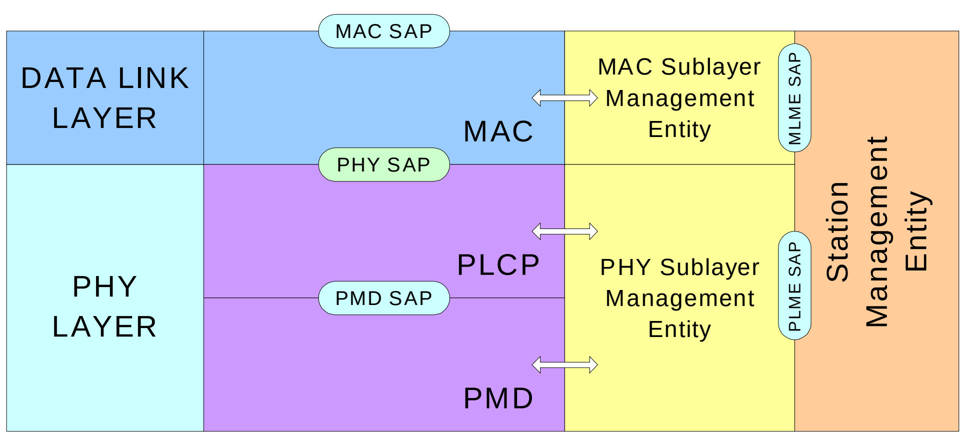

Figure 2. Reference Model of PHY and Interfaces to other ISO Layers

PHY System Architecture

The PHY system architecture is depicted in figure 3. The individual functional blocks of this system architecture are described in detail in subsequent sections of this proposal.

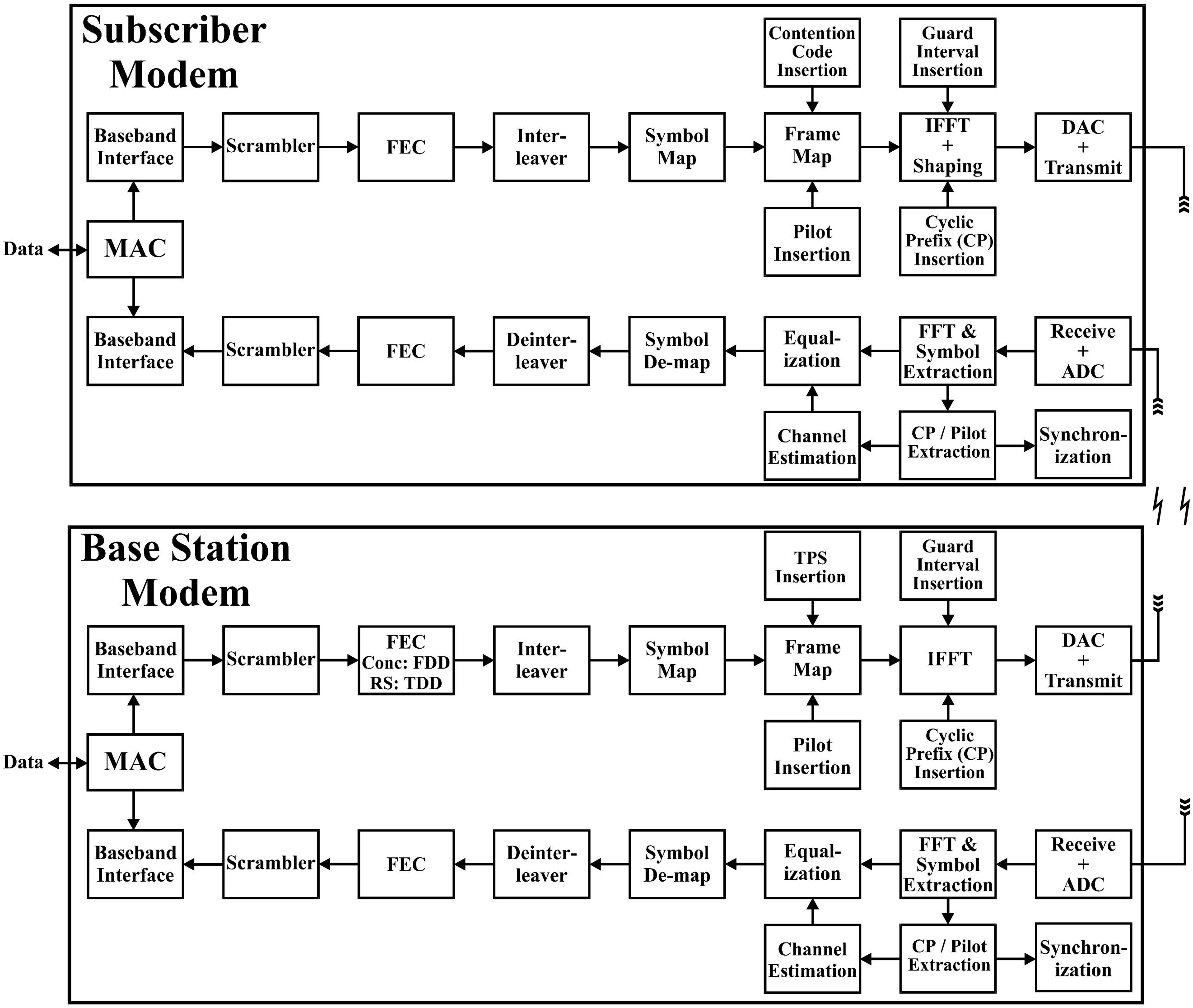

Figure 3. PHY System Architecture

Key features of the proposed PHY are summarized below:

Forward Link:

- Modulation: OFDM, based on variable length FFT, with cyclic prefix
- FEC: Concatenated Reed-Solomon and K=7 trellis code with puncturing, per DVB-T
- Scrambling + intra-frame interleaving and bit interleaving
- BPSK, QPSK, 16QAM and 64QAM
- Burst: supports TDD, FDD, FDMA, TDMA
- 2-way transmit-diversity

Return Link:

- Modulation: OFDM, with cyclic prefix
- FEC: K=7 trellis code with tail-biting and puncturing
- Scrambling + intra-frame interleaving
- BPSK, QPSK, 16QAM and 64QAM
- Burst: supports TDD, FDD, FDMA, TDMA
- *Optional*: Iterative decoding, per 802.16.1

Channel Coding and Modulation

Purpose: support adaptive modulation and coding depending on link SNR.

Randomization and packetizing

Purpose: precondition and package forward link traffic.

In order to assure adequate transitions, downstream traffic stream will be randomized using the DVB-S pseudo-random binary sequence with generator polynomial $p(x)=1+x^{14}+x^{15}$, according to the DVB-S standard specification EN300 421 [2]. The scrambled forward traffic stream will then be partitioned into fixed length packets, using the MPEG2 transport protocol; the total length of the MPEG2 transport multiplex (MUX) packet is 188 bytes, which includes a 1-byte sync-word (47hex); the processing order at the transmitting side will always start from the MSB of the sync-word byte ("01 000 111").

Outer Coding and Interleaving

Purpose: enhance link quality using powerful forward error-correction coding (FEC).

Each MPEG2 transport packet is encoded using a Reed-Solomon RS(204,188, t=8) shortened code; following this encoding, byte-wise convolutional interleaving, with depth I=12 will be applied. Both the RS code and the interleaving are defined in the DVB-S standard specification EN300 421 [2].

Inner Coding

Purpose: enhance link quality using powerful forward error-correction coding (FEC).

The forward link will employ punctured convolutional coding to support a range of inner code rates, with the specific trellis mother code and puncturing patterns defined in the DVB-T specification EN300 744 v1.2.1.

Inner Interleaving

Purpose: enhance link quality by interleaving over constellation points and sub-carriers.

The fully encoded forward traffic stream is first bit-wise interleaved, then symbol-wise interleaved to provide maximum security against frequency-selective fading. Specific processing will be as defined in the DVB-T standard specification EN300 744 v1.2.1.

Symbol Mapping

Purpose: map the encoded information onto one of the signal constellation options.

All data sub-carriers in any single OFDM frame use either QPSK, 16QAM or 64QAM modulation; Grey mapping is used as defined in DVB-T standard specification EN300 744 v1.2.1 for non-hierarchical signaling.

Frame Adaptation

Purpose: combine data with PHY-dependent signal elements for reliable transmission.

Transmitted signals are organized into frames, each consisting of N_{FRAME} OFDM symbols. N_{SUPER} frames constitute one super-frame. Each transmitted symbol, of duration T_{SYM}, is constituted by a set of N_{SC} sub-carriers transmitted during the symbol interval, using a length N_{FFT} transform; of these sub-carriers, only N_{USC} are data-bearing. There are six modes, as depicted in table 1. In addition to the transmitted data on N_{USC}, each OFDM frame contains: pilot sub-carriers, both scattered and continuous, and CONTROL carriers. Pilots can be used for frame synchronization, frequency synchronization, time synchronization, channel estimation, transmission mode identification and phase noise estimation/extraction.

Table 1. OFDM Frame Parameters

Mode	**NFFT**	N_{usc}	N_{sc}
1	2048	1536	1729
2	1024	768	865
3	512	384	433
4	256	192	217
5	128	96	109
6	64	48	55

Pilot Sub-carriers

Purpose: Pilot sub-carriers are sent to facilitate channel parameter estimation.

Each pilot is modulated with the same pseudo-random binary sequence, defined by the generator polynomial: $g(x)=x^{11}+x^2+1$. Pilot sub-carrier locations vary according to the patterns defined by the channel assignment algorithm defined in subsequent sections of this proposal.

Control Signals

Purpose: defines modulation and coding information for channel.

The TPS is transmitted (in parallel) on $N_{CONTROL}$ sub-carriers in order to minimize the impact of frequency-selective fading; every CONTROL sub-carrier in the symbol conveys the same differentially-encoded information bit. Locations of the CONTROL sub-carriers are fixed. Over a single frame the CONTROL conveys a total of N_{FRAME} bits, including: 1 initialization bit, 16 synchronization bits, $N_{CONTROL}$ information bits, and N_{PAR} parity bits for error protection. Table 2 defines the significance of each CONTROL bit.

Table 2. Simple Channel Assignment Algorithm

Bit number	Format	Purpose
S{ 0 }		Initialization
S{ 1 } – S{ 16 }	0011010111101110/compl.	Synchronization
S{ 17 } – S{ 22 }		Length indicator
S{ 23 } – S{ 24 }		Frame number
S{ 25 } – S{ 26 }		Constellation type
S{ 27 } – S{ 29 }	8 selectable GI values	Guard interval
S{ 30 } – S{ 31 }	Four XMIT modes	Transmission mode
S{ 32 } – S{N_{FRAME}-N_{PAR}}		Reserved for future use
S{N_{FRAME}-N_{PAR}}–S{N_{FRAME}-1}		Error protection

The initialization bit provides the reference for the differentially-encoded data. The first and third CONTROL block in each super-frame use 0011010111101110; the second and fourth CONTROL block in each super-frame use its complement: 1100101000010001. The first six bits of the CONTROL information is used to indicate the CONTROL message length (i.e. number of used bits), currently TBD. The constellation type defines QPSK, 16QAM, 64QAM or TBD. Code rates are selectable from: ½, 2/3, ¾, 5/6, 7/8, or TBD. There are eight TBD selectable guard intervals. There are six transmission modes (FFT lengths). The CONTROL uses a shortened BCH code [BCH(67, 53, t=2)], derived from the systematic BCH(127, 113, t=2) code with generator polynomial

$$h(x) = x^{14}+x^{9}+x^{8}+x^{6}+x^{5}+x^{4}+x^{2}+x+1$$

Number of Reed-Solomon Packets per OFDM Super-frame

Table 3. Number of Reed-Solomon Packets per OFDM Super-frame

NUSC	NSYM / frame	NBITS/FRAME(1)	NSUPER	NBITS/SF	NBYTES/SF	NRSP/SF	code rate	NRSP/SF
1536	51	78336	4	313344	39168	192	1/2	192
768	51	39168	8	313344	39168	192	2/3	256
384	51	19584	16	313344	39168	192	3/4	288
192	51	9792	32	313344	39168	192	5/6	320
96	51	4896	64	313344	39168	192	7/8	336
48	51	2448	128	313344	39168	192	1	384

This frame and superframe structure allows for an integer number of RS 204-byte packets to be transmitted in an OFDM superframe, and therefore avoids the need for any stuffing, whatever the constellation, guard interval length, code rate, channel bandwidth, or FFT length.

Forward Link

The available channel bandwidth will be used to transmit OFDM symbols, with the number of OFDM channels (length of the FFT) determined as a function of key channel parameters (e.g. delay spread, doppler frequency, etc.). Four basic signal types are required to assure robust forward link communication: 1) fixed pilot signals; 2) dynamic pilot signals; 3) control signals; and, 4) payload signals. In each case, these signals are transmitted over a defined set of OFDM signals.

Fixed pilot signals

The first task of a subscriber desiring access to the network is to achieve frequency coherence with the forward link signal. To facilitate this task, there will be a small number of fixed pilot signals in the forward link signal. The subscriber can readily achieve synchronization with the downstream link, knowing the modulation on the fixed pilot signals; spreading these fixed pilots uniformly over the channel maximizes protection against frequency-selective fading. A pseudo-random binary sequence (PRBS) will modulate these fixed pilots, eliminating discrete tones in the OFDM symbol which create inter-channel interference. Moreover, while the same PRBS will modulate all fixed pilots, the index of this sequence will advance from fixed pilot to next, supporting coherent detection while eliminating undesirable channel-to-channel correlation. Once the subscriber has synchronized to the PRBS, both frequency and time-synchronization have been achieved.

Dynamic pilot signals

The next important task of the subscriber is to accurately estimate the (dynamically-varying) propagation channel transfer function. This is readily achieved by inserting additional pilot signals, with the spacing of these pilots determined by the maximum delay spread for all channels in the cell. Each of these pilots will be modulated with the same PRBS as the fixed pilots. The dynamic aspect of these pilots is determined by the channel dynamics. Although the inter-pilot spacing is directly tied to the delay spread by the sampling theorem, it is desirable to reduce the overhead penalty associated with channel estimation by transmitting as few of these channel estimation pilots as possible in each successive OFDM symbol. This is readily achievable by exploiting the channels' relative temporal stability. If a channel remains relatively stationary over the time duration of three successive OFDM symbols, it is only necessary to transmit one-third of the total required pilots within each symbol. The degree of constancy of 802.16.3 channels is related to the channel's Doppler frequency. In general, bandwidth efficiency dictates that we transmit the dynamic pilot signals spread across some span (typically <50%) of the period of the most significant Doppler frequency.

Control signals

Once the subscriber is synchronized to the downstream signal, with an accurate propagation channel model, it is simple to extract information from that signal. Critical link management data, embedded within the downstream signal, describes the internal structure of that signal, including the number and types of embedded modulations and code rates. This control signal provides the downlink mechanism by which access is negotiated with each potential new subscriber.

Payload signals

All other useable OFDM channels are available to convey downstream information. These channels reap the benefits from the overhead associated with transmitting pilots, since the OFDM channels avoid the bit-error-rate (BER) flare-out associated with equalized single-carrier transmission over Rayleigh channels, particularly when using bandwidth-efficient higher-order modulations.

Channel distribution

Frequency-selective fading, the key pathology associated with Rayleigh propagation channels, introduces deep attenuation valleys across the channel bandwidth. Some form of transmission-diversity is required to prevent this channel pathology from degrading overall channel quality to unacceptable levels. The simplest form involves spreading the individual channels associated with each function over the entire available OFDM bandwidth, assuring that deep fades can only destroy a small fraction of the total signal function, and either simple redundancy or powerful forward-error-correction coding (FEC) can restore the lost information. While this approach is simple and effective, and has been adopted by all previous OFDM standards, it requires subscribers to process the full OFDM bandwidth, even when their uplink/downlink data could be restricted to a much small bandwidth; this will make an all-software modem more challenging. An alternative approach could use Alamouti's ingenious transmit-diversity scheme to mitigate the impact of those deep fades, thus making it practical to consider clustering subscriber traffic in small subsets of the OFDM channels. Our proposed PHY is compatible with either of these approaches, and even with more complex PHY architectures using multiple-input-multiple-output (MIMO) diversity or space-time coding (STC).

However, to minimize system PHY complexity, we propose a particularly powerful and flexible method for achieving the near-uniform distribution of each of the four key signal types across the full useable OFDM bandwidth. First we describe the core concept; then we expand to clarify exactly how this concept can be used to provide the desired combination of flexibility and implementation simplicity.

The first two columns of table 4 depict a set of 32 OFDM channels, along with the binary 5-tuple corresponding to each channel index number. The various colors are associated with five distinct classes of channel types. Our goal is to *design a channel assignment algorithm which uniformly distributes the signals associated with any function over the entire channel ranges, yet which permits simple modifications to the fraction of channels dedicated to any individual function*. DVB-T and DVB-RCT have defined sets of indices assigned to each of the classes of signals associated with OFDM signaling, but 802.16.3 requires the flexibility to easily modify these assignments in order to optimize channel capacity over a very wide range of channel bandwidths and channel characteristics. To support this requirement, we propose to use a technique which has been validated in various applications for over a decade, and which clearly meets our need for both complete flexibility and negligible implementation complexity.

Table 4. Simple Channel Assignment Algorithm

Index In	*Binary In*	*Binary Out*	*Index Out*	*'Shortened'*
0	00000	00000	0	
1	00001	10000	16	
2	00010	01000	8	
3	00011	11000	24	
4	00100	00100	4	
5	00101	10100	20	
6	00110	01100	12	
7	00111	11100	28	
8	01000	00010	2	
9	01001	10010	18	
10	01010	01010	10	
11	01011	11010	26	
12	01100	00110	6	
13	01101	10110	22	
14	01110	01110	14	
15	01111	11110	30	
16	10000	00001	1	
17	10001	10001	17	
18	10010	01001	9	
19	10011	11001	25	
20	10100	00101	5	
21	10101	10101	21	
22	10110	01101	13	
23	10111	11101	29	
24	11000	00011	3	
25	11001	10011	19	
26	11010	01011	11	
27	11011	11011	27	
28	11100	00111	7	
29	11101	10111	23	
30	11110	01111	15	
31	11111	11111	31	

The technique depicted, consisting of simple reversal of the binary sequence associated with each channel index number achieves near-uniform distribution *without assignment conflicts*, for real-time processing applications. It completely eliminates the complex channel assignment tables/algorithms and inflexibility associated with the DVB-T and DVB-RCT standards, yet accomplishes the required distribution of signal/channel types. The proposed channel assignment algorithm exploits the fact that, while quasi-uniform distribution of the signal types across the entire set of available OFDM channels is desirable, neither protection against frequency-selective fading nor channel interpolation require that the channels be precisely uniformly spread. This permits the use of the simple yet very flexible solution concept described.

Handling ‘empty’ channels

The channel assignment algorithm just described only works if the number of channels to be assigned is an exact power of two, whereas we know that any practical OFDM system will make available for signaling only some fraction of the total number of FFT bins. This is readily accommodated with the proposed algorithm. Consider that some fraction, call it 10% of the FFT bins will be unavailable for signaling. Then, in addition to the four classes of signals already defined, define a ‘try again’ class. The multiplexer control algorithm determining which signal type to place in each of the 2^N FFT bins consists simply of a binary counter which counts from 0 to 2^N-1 during each OFDM symbol duration. On each increment of the counter, the counter contents are bit-reversed, and this value is compared to the lower and upper boundary values associated with each of the five signal classes. If it falls within one of the four valid signal classes, the next component of that signal class will be placed into the current FFT bin location; however, if the bit-reversed index points within the ‘try again’ binary range, the counter is incremented by 1 and the process repeats. It is a property of the algorithm that the ‘try again’ addresses will never be adjacent, so this simple strategy guarantees a valid solution. Moreover, this simple procedure retains the quasi-uniform distribution property so critical for combating frequency-selective fading.

Description of Basic Channel Assignment Algorithm

Table 1 clearly describes the basic concept proposed for the 802.16.3 PHY channel assignment. This section will describe the mechanics in greater detail. Recall that there are four basic channel types: 1) fixed pilot channels; 2) dynamic pilot channels; 3) control channels; and, 4) payload channels.

Fixed pilot channels must be distributed quasi-uniformly over the set of available OFDM channels to protect against frequency-selective fading. These channels serve to facilitate subscriber synchronization with the downlink signal frequency and PRBS timing. These channel assignments will be static, although the number of fixed pilot channels is programmable.

Dynamic pilot channels are also spread approximately uniformly over the entire OFDM band, with the spacing determined by the channel delay spread. For some 802.16.3 channels, the pilot spacing required would mean that a large fraction of the available channels would be dedicated to pilot signals, significantly reducing overall bandwidth efficiency. Fortunately, measured channel characteristics indicate that 802.16.3 channels vary relatively slowly in their characteristics, exhibiting a doppler frequency of only 2 Hz; this slow channel variation permits a significant enhancement in channel bandwidth efficiency. We will exploit the slow variation by transmitting dynamic pilots on only a fraction of the required channels for each OFDM symbol, then filling in the required other pilots on successive OFDM symbols. This simple approach is also used in the DVB-T standard, and can increase link bandwidth efficiency by over 10% without compromising data fidelity or reliability. This technique is especially simple to implement using the channel assignment algorithm previously described; the contiguous block of channels assigned to the selected fraction is converted into active dynamic pilot channel indices on an OFMD symbol-to-symbol basis. All channels not used for dynamic pilot transmission on any OFDM symbol are available to transport information payload.

Pilot channels, both fixed and dynamic, are the only OFDM channels not pseudo-randomly re-assigned over time. Information-bearing channels, both payload and control, should be pseudo-randomly moved across the entire band in order to assure that no single signal suffers inequitably from frequency-selective interference or distortion. This is readily accomplished by cyclically-rotating the set of channel addresses associated with all these signal types. Specifically, a PRBS value is added (modulo N) to the base address, prior to the bit-reversal mapping. As before, the functional requirement is satisfied, and the implementation complexity is negligible.

Control channels convey the information from the base station to the subscribers by which they establish and maintain reliable links. This information is sent redundantly over several widely separated channels. The number of control channels is readily varied.

Payload channels deliver the BWA service, and since the return-on-investment to the service provider is tied directly to the revenue stream generated by selling link capacity, it is critical to provide adequate flexibility to assure that channel capacity can be maximized for any application. The 802.16.3 standard addresses a wide range of bandwidth, propagation channels and frequency bands up to 11 GHz. The set of design parameters (e.g. FFT length, number and spacing of pilots, modulation order and code rates, etc.) that maximize both link capacity and revenue to the service provider varies greatly for these varied applications. The proposed PHY provides the needed degree of flexibility, coupled with remarkably low implementation complexity. The tables below clearly demonstrate that the proposed PHY can be optimally adapted to any range of channel bandwidths, any range of delay spreads, and any Doppler rates, simply by varying the FFT length and the relative percentage of channels assigned to each of the four signal types previously described. Table 5, 6, 7, and 8 depict the set of bit rates and corresponding spectral efficiencies served by the proposed scalable PHY, for different channel bandwidths of 1.5, 3,.3.5, and 25 MHz. This data corresponds to the available throughput when the system is configured to accommodate a 10 μs delay spread.

Table 5. OFDM Useful Bit Rate (Mbps) and Spectral Efficiency (bps/Hz) for 1.5 MHz Channel

		NFFT											
mod	rate	2048		1024		512		256		128		64	
		Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz
QPSK	1/2	1.2	0.8	1.2	0.8	1.1	0.8	1.1	0.7	1.0	0.7	0.9	0.6
	2/3	1.6	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.4	0.9	1.2	0.8
	3/4	1.8	1.2	1.7	1.2	1.7	1.1	1.7	1.1	1.5	1.0	1.4	0.9
	5/6	1.9	1.3	1.9	1.3	1.9	1.3	1.8	1.2	1.7	1.1	1.5	1.0
	7/8	2.0	1.4	2.0	1.4	2.0	1.3	1.9	1.3	1.8	1.2	1.6	1.1
	1	2.3	1.6	2.3	1.5	2.3	1.5	2.2	1.5	2.1	1.4	1.8	1.2
16QAM	1/2	2.3	1.6	2.3	1.5	2.3	1.5	2.2	1.5	2.1	1.4	1.8	1.2
	2/3	3.1	2.1	3.1	2.1	3.0	2.0	2.9	2.0	2.8	1.8	2.5	1.6
	3/4	3.5	2.3	3.5	2.3	3.4	2.3	3.3	2.2	3.1	2.1	2.8	1.8
	5/6	3.9	2.6	3.9	2.6	3.8	2.5	3.7	2.4	3.4	2.3	3.1	2.0
	7/8	4.1	2.7	4.1	2.7	4.0	2.7	3.9	2.6	3.6	2.4	3.2	2.1
	1	4.7	3.1	4.6	3.1	4.6	3.0	4.4	2.9	4.1	2.8	3.7	2.5
64QAM	1/2	3.5	2.3	3.5	2.3	3.4	2.3	3.3	2.2	3.1	2.1	2.8	1.8
	2/3	4.7	3.1	4.6	3.1	4.6	3.0	4.4	2.9	4.1	2.8	3.7	2.5
	3/4	5.3	3.5	5.2	3.5	5.1	3.4	5.0	3.3	4.6	3.1	4.1	2.8
	5/6	5.8	3.9	5.8	3.9	5.7	3.8	5.5	3.7	5.2	3.4	4.6	3.1
	7/8	6.1	4.1	6.1	4.1	6.0	4.0	5.8	3.9	5.4	3.6	4.8	3.2
	1	7.0	4.7	6.9	4.6	6.8	4.6	6.6	4.4	6.2	4.1	5.5	3.7

Table 6. OFDM Useful Bit Rate (Mbps) and Spectral Efficiency (bps/Hz) for 3 MHz Channel

		NFFT											
mod	rate	2048		1024		512		256		128		64	
		Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz
QPSK	1/2	2.3	0.8	2.3	0.8	2.2	0.7	2.1	0.7	1.9	0.6	1.5	0.5
	2/3	3.1	1.0	3.0	1.0	2.9	1.0	2.8	0.9	2.5	0.8	2.0	0.7
	3/4	3.5	1.2	3.4	1.1	3.3	1.1	3.1	1.0	2.8	0.9	2.3	0.8
	5/6	3.9	1.3	3.8	1.3	3.7	1.2	3.5	1.2	3.1	1.0	2.5	0.8
	7/8	4.1	1.4	4.0	1.3	3.9	1.3	3.6	1.2	3.2	1.1	2.7	0.9
	1	4.6	1.5	4.6	1.5	4.4	1.5	4.1	1.4	3.7	1.2	3.0	1.0
16QAM	1/2	4.6	1.5	4.6	1.5	4.4	1.5	4.1	1.4	3.7	1.2	3.0	1.0
	2/3	6.2	2.1	6.1	2.0	5.9	2.0	5.5	1.8	4.9	1.6	4.1	1.4
	3/4	7.0	2.3	6.8	2.3	6.6	2.2	6.2	2.1	5.6	1.9	4.6	1.5
	5/6	7.7	2.6	7.6	2.5	7.4	2.5	6.9	2.3	6.2	2.1	5.1	1.7
	7/8	8.1	2.7	8.0	2.7	7.7	2.6	7.3	2.4	6.5	2.2	5.3	1.8
	1	9.3	3.1	9.1	3.0	8.8	2.9	8.3	2.8	7.4	2.5	6.1	2.0
64QAM	1/2	7.0	2.3	6.8	2.3	6.6	2.2	6.2	2.1	5.6	1.9	4.6	1.5
	2/3	9.3	3.1	9.1	3.0	8.8	2.9	8.3	2.8	7.4	2.5	6.1	2.0
	3/4	10.4	3.5	10.3	3.4	9.9	3.3	9.3	3.1	8.3	2.8	6.9	2.3
	5/6	11.6	3.9	11.4	3.8	11.0	3.7	10.4	3.5	9.3	3.1	7.6	2.5
	7/8	12.2	4.1	12.0	4.0	11.6	3.9	10.9	3.6	9.7	3.2	8.0	2.7
	1	13.9	4.6	13.7	4.6	13.2	4.4	12.4	4.1	11.1	3.7	9.1	3.0

Table 7. OFDM Useful Bit Rate (Mbps) and Spectral Efficiency (bps/Hz) for 3.5 MHz Channel

		NFFT											
mod	rate	2048		1024		512		256		128		64	
		Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz
QPSK	1/2	2.70	0.77	2.65	0.76	2.55	0.73	2.38	0.68	2.10	0.60	1.69	0.48
	2/3	3.60	1.03	3.53	1.01	3.40	0.97	3.17	0.91	2.79	0.80	2.26	0.64
	3/4	4.05	1.16	3.97	1.13	3.83	1.09	3.57	1.02	3.14	0.90	2.54	0.73
	5/6	4.50	1.28	4.41	1.26	4.25	1.21	3.96	1.13	3.49	1.00	2.82	0.81
	7/8	4.72	1.35	4.63	1.32	4.46	1.28	4.16	1.19	3.67	1.05	2.96	0.85
	1	5.39	1.54	5.29	1.51	5.10	1.46	4.76	1.36	4.19	1.20	3.38	0.97
16QAM	1/2	5.39	1.54	5.29	1.51	5.10	1.46	4.76	1.36	4.19	1.20	3.38	0.97
	2/3	7.19	2.06	7.06	2.02	6.80	1.94	6.34	1.81	5.59	1.60	4.51	1.29
	3/4	8.09	2.31	7.94	2.27	7.65	2.19	7.14	2.04	6.29	1.80	5.08	1.45
	5/6	8.99	2.57	8.82	2.52	8.50	2.43	7.93	2.27	6.98	2.00	5.64	1.61
	7/8	9.44	2.70	9.26	2.65	8.93	2.55	8.32	2.38	7.33	2.10	5.92	1.69
	1	10.79	3.08	10.59	3.02	10.20	2.92	9.51	2.72	8.38	2.39	6.77	1.93
64QAM	1/2	8.09	2.31	7.94	2.27	7.65	2.19	7.14	2.04	6.29	1.80	5.08	1.45
	2/3	10.79	3.08	10.59	3.02	10.20	2.92	9.51	2.72	8.38	2.39	6.77	1.93
	3/4	12.14	3.47	11.91	3.40	11.48	3.28	10.70	3.06	9.43	2.69	7.62	2.18
	5/6	13.49	3.85	13.23	3.78	12.75	3.64	11.89	3.40	10.48	2.99	8.46	2.42
	7/8	14.16	4.05	13.89	3.97	13.39	3.83	12.49	3.57	11.00	3.14	8.88	2.54
	1	16.18	4.62	15.88	4.54	15.30	4.37	14.27	4.08	12.57	3.59	10.15	2.90

Table 8. OFDM Useful Bit Rate (Mbps) and Spectral Efficiency (bps/Hz) for 25 MHz Channel

BW=25		NFFT											
mod	rate	2048		1024		512		256		128		64	
		Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz	Mbps	bps/Hz
QPSK	1/2	17.24	0.69	15.35	0.61	12.60	0.50	9.28	0.37	6.07	0.24	3.59	0.14
	2/3	22.98	0.92	20.47	0.82	16.80	0.67	12.37	0.49	8.10	0.32	4.79	0.19
	3/4	25.85	1.03	23.03	0.92	18.90	0.76	13.92	0.56	9.11	0.36	5.39	0.22
	5/6	28.73	1.15	25.59	1.02	21.00	0.84	15.46	0.62	10.12	0.40	5.99	0.24
	7/8	30.16	1.21	26.87	1.07	22.06	0.88	16.24	0.65	10.63	0.43	6.29	0.25
	1	34.47	1.38	30.71	1.23	25.21	1.01	18.56	0.74	12.15	0.49	7.18	0.29
16QAM	1/2	34.47	1.38	30.71	1.23	25.21	1.01	18.56	0.74	12.15	0.49	7.18	0.29
	2/3	45.96	1.84	40.95	1.64	33.61	1.34	24.74	0.99	16.20	0.65	9.58	0.38
	3/4	51.71	2.07	46.06	1.84	37.81	1.51	27.83	1.11	18.22	0.73	10.78	0.43
	5/6	57.45	2.30	51.18	2.05	42.01	1.68	30.93	1.24	20.24	0.81	11.97	0.48
	7/8	60.33	2.41	53.74	2.15	44.11	1.76	32.47	1.30	21.26	0.85	12.57	0.50
	1	68.94	2.76	61.42	2.46	50.41	2.02	37.11	1.48	24.29	0.97	14.37	0.57
64QAM	1/2	51.71	2.07	46.06	1.84	37.81	1.51	27.83	1.11	18.22	0.73	10.78	0.43
	2/3	68.94	2.76	61.42	2.46	50.41	2.02	37.11	1.48	24.29	0.97	14.37	0.57
	3/4	77.56	3.10	69.09	2.76	56.71	2.27	41.75	1.67	27.33	1.09	16.16	0.65
	5/6	86.18	3.45	76.77	3.07	63.01	2.52	46.39	1.86	30.37	1.21	17.96	0.72
	7/8	90.49	3.62	80.61	3.22	66.17	2.65	48.71	1.95	31.88	1.28	18.86	0.75
	1	103.42	4.14	92.13	3.69	75.62	3.02	55.67	2.23	36.44	1.46	21.55	0.86

Relationship between FFT and Physical Channel Bandwidth

Previous discussion described the various signal classes which must be included in the 802.16.3 forward link, and the manner in which the available FFT channels can be optimally allocated for any combination of link parameters (e.g. channel delay spread, Doppler frequency, number of fixed and dynamic pilots, control channels and payload channels). The final system design consideration concerns the manner in which the FFT is created and its relationship to the assigned channel bandwidth. Figure 4 depicts a simplified example illustrating the concepts discussed to this point.

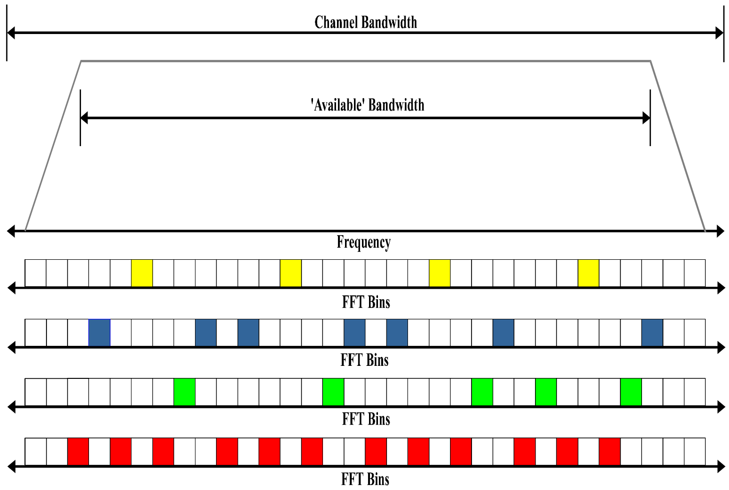

Figure 4. FFT and Signal Channel Assignments vs. Available Channel Bandwidth

The assigned channel bandwidth cannot be completely filled, since practical limits on inexpensive filter shape factors require appreciable filter transition bandwidths. In a single-carrier application, this effective bps/Hz loss would appear as the ratio between the symbol rate and the channel bandwidth; in the OFDM case, is appears as a fraction of the FFT length that is filled with zero bins. In either case, it represents an unavoidable efficiency loss associated with using realizable filters, and not an OFDM inefficiency.

In this case, the yellow signal set corresponds to the small number of fixed pilots that are spread across the band to facilitate subscriber synchronization to the base station frequency and timing. The blue signal set corresponds to the dynamic pilots that are also transmitted in order to accurately estimate the channel characteristic. Depending on the Doppler frequency associated with any application, only a fraction of these dynamic pilots need to be sent during any single OFDM symbol, with the remaining ones sent on successive symbols. The green signal set correspond to the control channels, which convey redundant information, assuring that the subscriber's are reliably controlled, even in the presence of frequency-selective fading. Finally, the red signal set corresponds to the payload itself. The simplistic example used only 12 of the 28 'available' channels to convey payload; this is not representative of the actual bandwidth efficiency levels which can be readily achieved using the proposed PHY, as the preceding tables demonstrate.

Payload Data

In order to assure that service providers can maximize BWA capacity in any of the wide range of likely application scenarios, the proposed PHY supports fully dynamic modulation and coding. As depicted in figure 5, the aggregate forward link data is portioned, under MAC control, into two distinct data streams. Each of these streams exploits the exceptional combination of FEC performance and decoder simplicity associated with concatenating a Reed-Solomon block code with an inner trellis code, using a convolutional interleaver in between each coder/decoder. In addition, data quality is further enhanced by using bit-level block-based interleaving on each of the separate symbol streams from the trellis encoder, defined in ETSI EN 300 744 v1.2.1., (DVB-T).

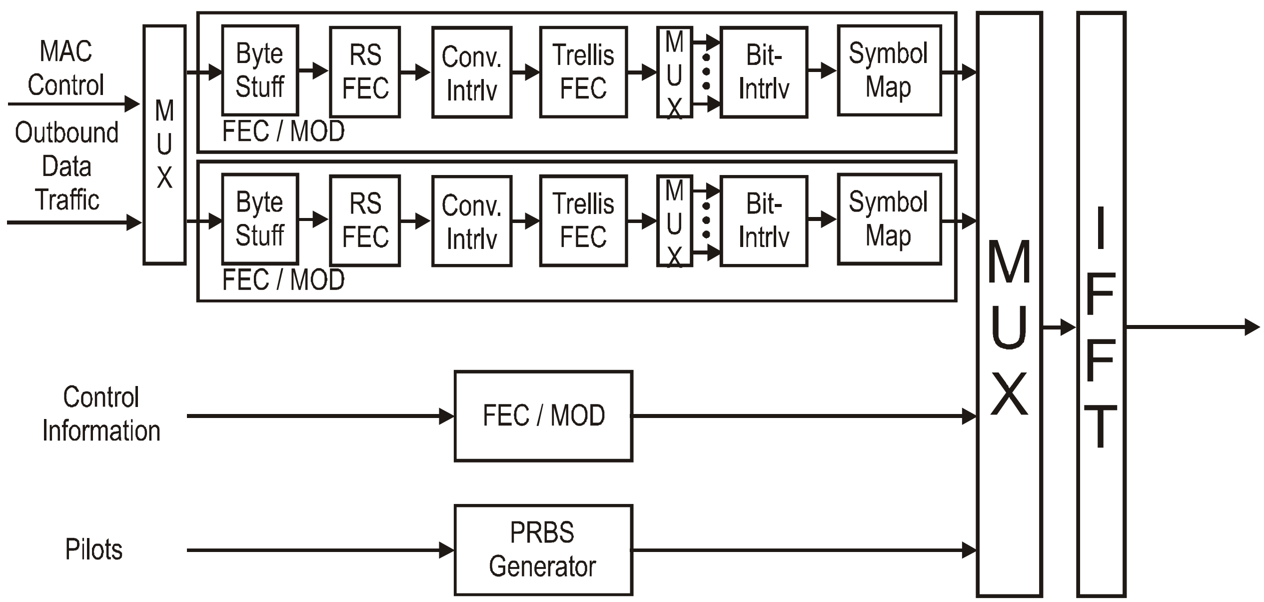

Figure 5. Dynamic Modulation and Coding

These exceptional benefits require attention to the latency associated with the interleaving structures. The proposed PHY addresses this issue by incorporating a byte-stuffing mechanism at the input to each payload stream. If the latency guaranteed by the service contract would be exceeded due to lack of adequate stream throughput, this mechanism generates and inserts 'stuff' bytes into the MPEG transport stream in order to rapidly flush valid data through the interleaving structures; such flush bytes are discarded by data receivers in accordance with standard MPEG transport protocol.

The proposed PHY permits the forward link data stream to be partitioned into two streams, and for each of those streams to employ any of a wide range of modulation orders and coding rates to reliably transport data. While further partitioning does incrementally increase system capacity, the small additional increments fail to warrant the large increase in MAC complexity associated with managing the higher complexity system.

Control Data

The final signal type to be served by the PHY structure conveys all information to the subscribers to assure that the BWA system functions smoothly and efficiently. The channel assignment algorithm already described shows how the proposed PHY can allocate and distribute any number of control channels across each OFDM symbol. The purpose of these allocated control channels is simply to direct any PHY-level changes in the forward link waveform. All control channels carry the same information, providing frequency diversity; specifically, control channels carry the state information necessary to re-configure either of the payload streams, as well as to re-distribute the OFDM channels among the various signal types. Since super-frame durations are short compared to the time-frame associated with channel pathologies which might induce link reconfiguration, we can reduce the real-time processing burden by defining a single super-frame delay between receipt of the new configuration and the adoption of that configuration. Thus a subscriber modem will receive control information during one super-frame, but will not immediately (at the start of the subsequent super-frame) reconfigure according to those instructions; the new configuration will start with the following super-frame, according to figure 6.

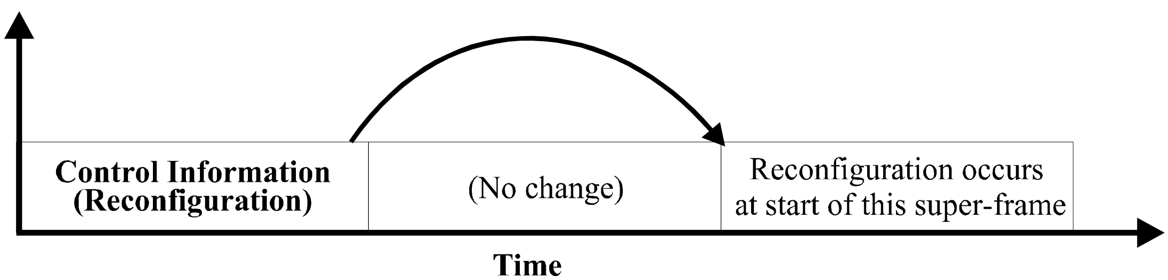

Figure 6. Control Channel Reconfiguration Timing

Return Link

As in the case of the forward link, the available channel bandwidth will be used to transmit OFDM symbols, with the number of OFDM channels (length of the FFT) determined as a function of key channel parameters (e.g. delay spread, doppler frequency, etc.). While the proposed PHY concepts are applicable to FDD as well as TDD applications, to illustrate return channel operation, consider a specific example of operation in the TDD mode. While the propagation channels are (in general) distinct for every distinct subscriber, those channels are reciprocal in the forward and return links, so each subscriber possesses an accurate channel model. Each subscriber is also already frequency and time synchronized to the forward link. For these reasons, neither fixed nor dynamic pilot signals are required in the return link. The return link does require transmission of both control and payload signals, and these will be interleaved over the full available band in the manner described for the forward link, depicted conceptually in figure 7.

Return payload signals

The 802.16 medium access controller (MAC) will assign each subscriber specific numbers of OFDM channels for specific time intervals to convey payload traffic, and the subscriber will modulate these channels and interleave to minimize the impact of frequency-selective fading.

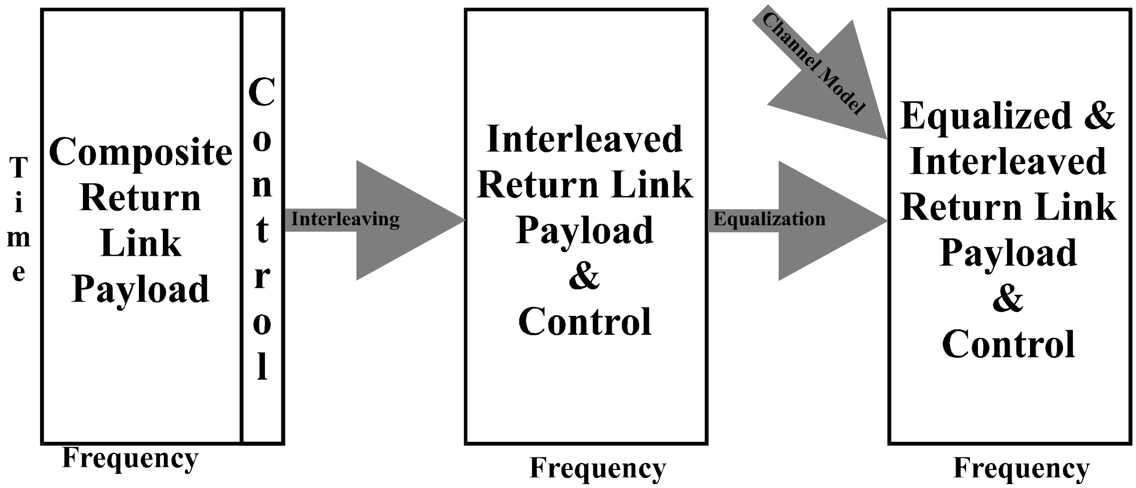

Figure 7. Return Link Processing Concepts

Return Control Signals

The subscriber must employ the control signaling to: 1) determine round-trip propagation delay and corresponding epoch offsets; and, 2) request modifications in BWA service. There will also be some number of channels allocated for control; these channels will also be interleaved across the band. The proposed PHY will allocate some subset of available return channel channels to implement a ranging function, using the procedure described in the DVB-RCT standard EN 300 v1.0.6, paragraph 6.9.3. As defined in that standard, upon entering the system a new user will employ a subset of ranging codes to establish propagation delay and accurate time alignment. A different subset of ranging codes will be used for maintenance ranging by users already connected to the system. Finally, a third subset of ranging codes will be used to issue requests for modifications to existing subscriber capacity. The detailed manner in which these control channels operate under control of the MAC will require more discussion and compromise among the members of the 802.16.3 task group.

Transmit-Diversity

As noted in the initial description of the conceptual approach used in developing this PHY proposal, a very critical difference between DVB-T/DVB-RCT and the service required by the 802.16.3 FRD concerns the acceptability of link outages due to frequency-selective fading in a Rayleigh propagation channel. Unlike the simple outage mitigation options available to video transport, we must incorporate some structural modification to the base DVB technical approach to greatly reduce fading-induced link outages. In our initial PHY proposal, we recommended adoption of the transmit-diversity scheme developed by Alamouti [3], and already embraced by several 3G standards. It represents a rare opportunity to substantially enhance the robustness of 802.16.3 links while posing a negligible increase in system complexity. Unlike the MIMO techniques in vogue for the past decade, which require multiple antennas at both subscriber and base station, Alamouti's elegant approach requires use of two antennas only at the base station, yet it assures ***full two-fold spatial diversity in both the forward and return links***. Figure 8 depicts the bit-error-rate (BER) curves associated with an OFDM link in a severe fading environment, showing the severe BER degradation suffered in either of two deep fade channels; the individual channel characteristics are depicted in figure 9. In spite of the severe distortion over each of these deep-fade channels, the almost trivial processing required to exploit Alamouti's technique is able to dramatically enhance link quality, as shown in these figures.

We continue to strongly recommend adoption of Alamouti's remarkable transmit-diversity technique in the 802.16.3 PHY standard, as an alternative to complex schemes requiring multiple antennas a the cost-sensitive subscriber premises.

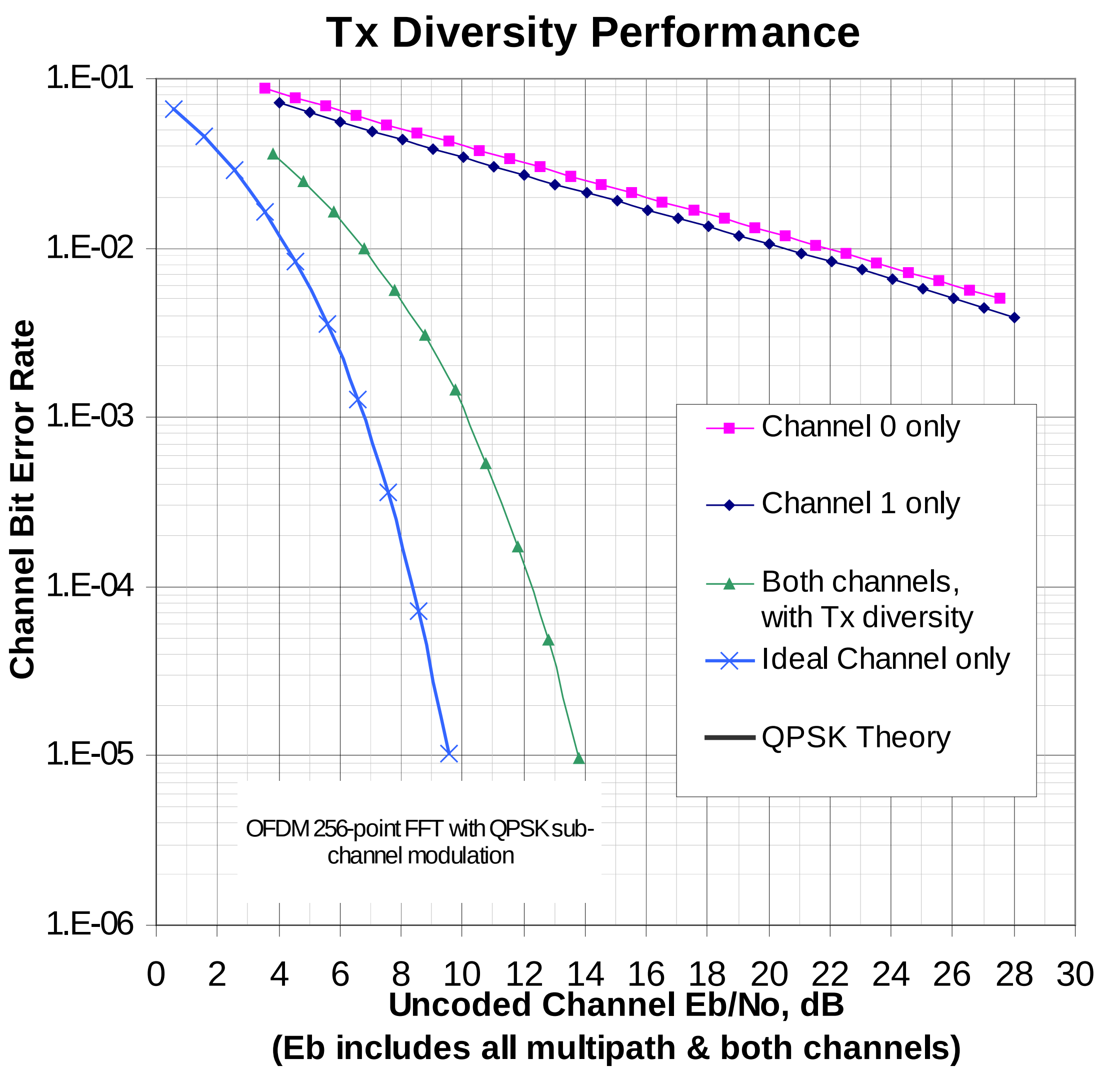

Figure 8. Transmit Diversity BER Performance

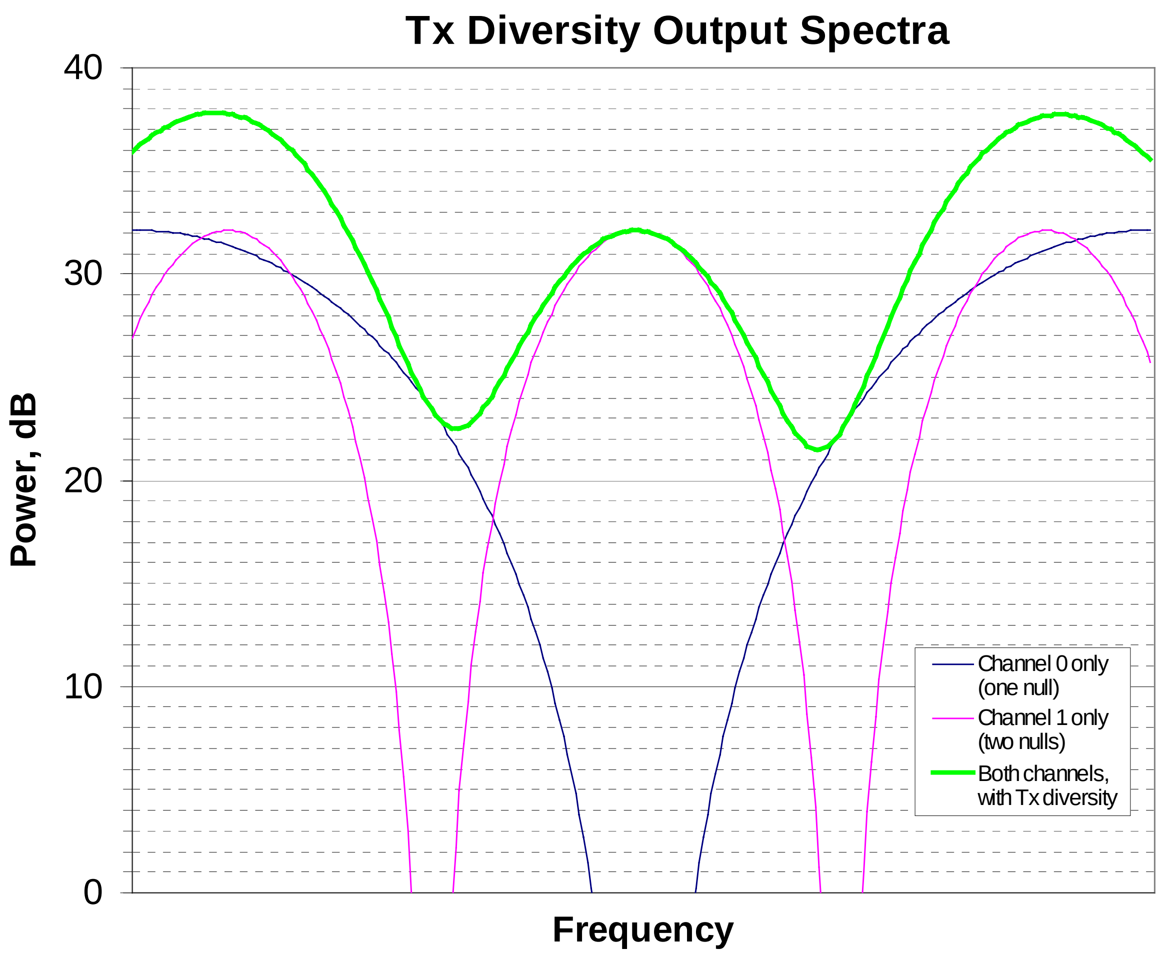

Figure 9. Transmit Diversity Output Spectra

Relation to Existing Standards

The proposed PHY standard has very little in common with the two standards based on the cable-modem PHY technology, specifically, ITU-R JRG 8A-9B and DOCSIS 1.1. However, the proposed PHY solution is very similar to other open standards for terrestrial video broadcast and return channels (DVB-T and DVB-RCT) and those for wireless LANs (IEEE 802.11a and ETSI HIPERLAN2). The differences between the proposed PHY and these standard wireless PHY solutions is motivated by the differences between the link distances and channel distortion for the 802.16.3 channel versus terrestrial video broadcast and LAN channels. We propose to address the greater propagation loss of the 802.16.3 channel by introducing an optional iterative decoding, with the specific iterative coding approach identical to that adopted as an option to the 802.16.1 PHY standard. Furthermore, reflecting the far greater distortion of the 802.16.3 channels, we propose an additional option, transmit-diversity, to address the phenomenon of channel outage in a very economical way.

Benefits of the Proposed PHY

The primary benefits of the proposed PHY approach are readily summarized:

OFDM is the most highly robust modulation technique available, with its implicit channelization rendering all channels effectively non-dispersive. This in turn makes OFDM highly robust to even severe propagation channel distortion, even over links characterized by very low K-factors (Ricean links), even K=0 (Rayleigh links). Moreover, OFDM offers a very flexible means, symbol erasures, of adapting to channel dynamics in a simple and robust manner.

This PHY is directly based on existing standards, thus offering rapid time-to-market. Service providers cannot afford to wait for PHY solutions that will not be available for years. However, numerous IC vendors already have modem solutions nearing completion to support the 802.11a and ETSI HIPERLAN standards. These modem ICs may be readily adapted to serve the 802.16.3 marketplace, satisfying the time-to-market constraints, while capitalizing on the already large demand for modem ICs satisfying those large and growing markets.

The proposed optional modifications to these standard PHY solutions address the challenges posed by the added distortion associated with 802.16.3 links, and with the much larger propagation loss. Optional iterative decoding on return link enhances capacity while reducing the peak power levels required of the subscriber high-power amplifiers. The encoders associated with this feature add negligible complexity to the cost-sensitive subscriber equipment; the added complexity of the decoding is borne by the less cost-sensitive hub equipment. Similarly, optional use of transmit-diversity requires negligible increase in subscriber equipment complexity, yet offers very large improvements in service over links exhibiting Rayleigh fading. In markets and applications that exhibit low K-values, use of this optional feature can dramatically improve link availability.

More specifically, using Alamouti’s technique, it is relatively simple to obtain full two-fold diversity using a single subscriber antenna and two hub antennas. Simply put, links over Rayleigh fading channels will always exhibit signal drop-out, with the frequency of this outage event tied to the channel statistics and the signal bandwidth. Two-way diversity means that the link remains reliable so long as either of the independent links remains viable; figure 10 depicts this situation. In other words, two-way diversity means that, instead of a link offering 99% availability, the same link would support 99.99% availability. That such a significant link availability improvement is achievable with negligible incremental complexity is remarkable, and is a strong argument for including transmit-diversity in the 802.16.3 PHY standard.

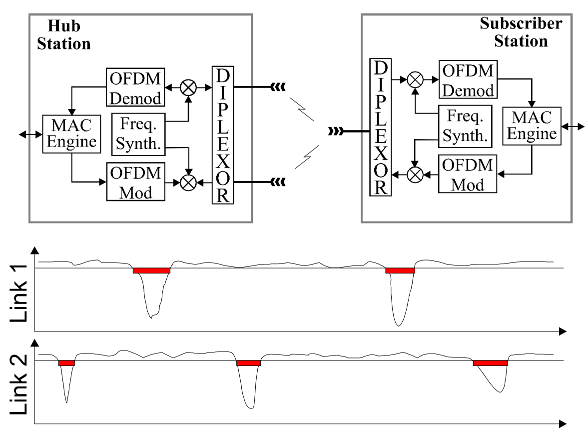

Figure 10. Impact of Two-way Diversity on Link Availability/Outage

Drawbacks of Proposed PHY

The primary drawback of the proposed PHY architecture is that it is not interoperable with PHY architectures based on cable-modem technology. This PHY is optimized specifically for fixed broadband wireless access, with features tailored precisely to the unique character of the costs and complexities of the propagation channels associated with those links. As such, it represents a need to evolve beyond the simple cable modem technologies already brought to this market. However, while this represents a discontinuity, it also offers the opportunity for the dramatic cost reductions and link reliability improvements required to make fixed BWA a commercial success.

Intellectual Property Rights

As noted on the cover page, this PHY proposal is made subject to the IEEE rules regarding intellectual property. In addition, the optional iterative decoding technique has already been submitted to the 802.16.1 standard as an optional part of that standard's PHY layer, where IEEE IPR conditions have been met. Finally, the transmit-diversity scheme proposed as an option has already been adopted by all 3G mobile wireless standards, including: WCDMA, 3GPP FDD mode, WCDMA 3GPP TDD mode, CDMA2000 and EDGE; the receiver processing for this transmit-diversity scheme is mandatory for all cited 3G mobile standards.

References

1. ETSI EN 300 744 v1.2.1 Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television (1999-07).
2. ETSI EN 300 xxx v1.0.6 Digital Video Broadcasting (DVB); Interaction channel for Digital Terrestrial Television (2000-11-25).
3. S. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," ***IEEE J. Select. Areas Commun***., vol. 16, pp. 1451-1458, October 1998.
4. P80211aD7.0. – Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High Speed Physical Layer in the 5 GHz Band.
5. ETSI TS 101 475 v1.1.1 Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Physical (PHY) Layer (2000-04)

Table 9. PHY Assessment Using 802.16.3 Evaluation Criteria

#	Evaluation Criterion	Assessment
1	Meets System Requirements	The proposed PHY satisfies all requirements of the 802.16.3 Functional Requirements Document (FRD), except that the 50 km range is questionable in light of the recently adopted 802.16.3 channel models.
2	**Channel Spectrum Efficiency**	The PHY scales to support many channel bandwidths (1.5, 1.75, 3, 3.5, 6, 7, 8, 12, and 14, optional 28) with bandwidth-efficient modulations (QPSK, 16QAM and 64QAM), and a range of coding rates. Uplink OFDMA further enhances system-level spectral efficiency.
3	**Realization Simplicity**	OFDM uses a highly optimized FFT engine to permit a low-complexity low power dissipation modem solution. The specific PHY protocol proposed achieves the high degree of parametric flexibility required by 802.16.3's diverse channels with simple structures, and permits a very simple MAC-PHY SAP to be defined. This PHY modem leverages off proven FFT technology from DVB-T and readily-available FEC technology. The robust PHY proposed should permit $200 SS cost. This PHY should permit a $1000 BS cost. Installation cost is minimized by use of robust OFDM technology.
4	**Spectrum Resource Flexibility**	The proposed PHY offers virtually limitless scalability, supporting any available channelization, band-pairing and link asymmetries in both TDD and FDD duplex modes. Moreover, the most spectrally-efficient mix of modulation and coding is selectable for any channel and signal-to-noise-ratio (SNR) conditions
5	**System Spectrum Efficiency**	The proposed PHY supports a range of highly bandwidth-efficient modulations and code rates. Even more importantly, the well-piloted OFDM format minimizes the amount of overhead required to assure robust operation even using higher-order modulations. We will need to define a common channel (distortion, impairments and interference) in order to quantify this PHY in terms of bps/Hz/cell, but it will excel in this metric.
6	**System Service Flexibility**	The proposed PHY supports all optional services defined in table 4 of the FRD, including subscriber channel hopping, flexible modulation types and power level adjustment; its high degree of parametric flexibility assures support of a wide range of future services.
7	**Protocol Interfacing Complexity**	The PHY PMD provides a simple interface to the PHY TC sublayer (to be defined). In addition, the parametric flexibility offers effective "macros" to support service access point (SAP) requirements.
8	**Reference System Gain**	The combination of OFDM's very robust BER-vs-E_bN_o, strong forward error-correction coding (FEC), and power concentration assures maximum coverage for any link pathologies. However, until we formally define a reference system model (e.g. transmitter EIRP, receiver noise figure, etc.), it will be misleading (for comparative purposes) to include

		any specific link budget.
9	**Robustness to Interference**	OFDM waveforms are the most robust to interference, and is also the most compatible with multiple antenna technology offering additional interference rejection.
10	**Robustness to Channel Impairments**	OFDM waveforms are very robust to channel distortion, permitting rapid and accurate channel estimation, and simpler channel distortion mitigation than single-carrier techniques.
11	**Robustness to Radio Impairments**	OFDM waveforms are very robust to radio distortion, which is treated as channel distortion. However, OFDM waveforms exhibit greater sensitivity to radio phase noise than single-carrier waveforms. However, phase-locking the subscriber to the hub reference phase eliminates this concern for all but very high (e.g. 2048 and higher) FFT order. OFDM's high peak-to-average-power-ratio (PAPR) requires adoption of one of many PAPR-reduction techniques to permit use of nonlinear high-power amplifiers (HPAs).
12	**Support of Advanced Antenna Techniques**	Advanced antenna technologies span from simple transmit-diversity to dynamic beam-forming networks at both ends of the link. In all these cases, OFDM waveforms are preferable to single-carrier waveforms.
13	**Compatibility with Existing Standards/Regulations**	The proposed PHY is compatible with all existing standards and regulations.