Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**A “Block” Adaptive Modulation and Coding PHY**
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Re:	Call for Contributions: Initial PHY Proposals (IEEE 802.16.3-00/24)
Abstract	A PHY is proposed for 802.16.3 in which modulation format and coding rate can be adjusted on a block by block basis to provide optimum channel utilization for the widest range of channel conditions.
Purpose	This proposal is offered as a PHY layer for the 802.16.3 Task Group
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Patent Policy and Procedures	

Procedures	use of patent(s), including patent applications, if there is technical justification in the opinion of the standards-developing committee and provided the IEEE receives assurance from the patent holder that it will license applicants under reasonable terms and conditions for the purpose of implementing the standard." Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <mailto:r.b.marks@ieee.org> as early as possible, in written or electronic form, of any patents (granted or under application) that may cover technology that is under consideration by or has been approved by IEEE 802.16. The Chair will disclose this notification via the IEEE 802.16 web site <http://ieee802.org/16/ipr/patents/notices>.

A “Block” Adaptive Modulation and Coding PHY

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Overview

In contrast to most wire line networks, wireless networks typically involve network paths having widely different propagation characteristics. In particular for the MAN applications envisioned as the target markets in the IEEE 802.16.3 Functional Requirements Document (IEEE 802.16.3-00/02r4) some subscribers may have unobstructed Line of Sight (LOS) links with ranges of only a few kilometers, while others may have ranges of as much as 50 kilometers, still other links may be only a few kilometers in length but suffer substantial blockage of the LOS path. In many of the wireless networks currently in service, the transmission parameters (modulation format, Forward Error Correction, channel bandwidth, etc) are adjusted to provide an acceptable level of performance to the most impaired link. This approach then limits the performance that might be offered to subscribers with less impaired channels. Clearly this traditional method results in sub-optimal utilization of the total channel capacity.

Schemes offering varied modulation and coding for different classes of channel propagation conditions by assigning user classes to different physical channels are a step in the direction of improved channel utilization, but do not completely address the dynamic nature of network traffic and its impact on required link gains. The proposed PHY layer described below optimizes channel utilization by permitting dynamic adaptation of both modulation format and Forward Error Correction (FEC) rate on a subscriber-by-subscriber basis. Further the proposed PHY also enables the ability to adjust the characteristics of an individual subscriber's modulation format and FEC rate. Thus, if the channel characteristics vary over time, say seasonal variations in path loss caused by the presence or absence of foliage, that subscriber’s modulation and coding parameters can be adjusted to compensate for these changes.

For simplicity and lowest-cost implementation, PHY layer is based upon a single-carrier modulation plan utilizing a Decision Feedback Equalizer to compensate for multipath channels. The optional incorporation of a Frequency Domain Equalizer will provide the means to compensate for a Rayleigh-fading channel in applications where this might be necessary. The PHY layer described here offers the capability to adapt the modulation and coding over a wide range to compensate for varying channel conditions. In particular, the modulation format could be BPSK, QPSK, 8PSK, 16QAM, 64QAM or 256QAM in either upstream or downstream. By using Turbo Product Coding as in 802.16.1 for FEC, adjustment of coding rate over a range of

Parameter	Value
Downstream modulation	BPSK, QPSK, 8-PSK,16-QAM, 32-QAM, 64-QAM required; 128-QAM, 256-QAM optional
Downstream symbol rates	1.4 - 5.36 Msym/s
Upstream modulation	BPSK, QPSK, 8-PSK,16-QAM required; 32-QAM, 64-QAM optional
Upstream symbol rates	0.128 - 2.56 Msym/s

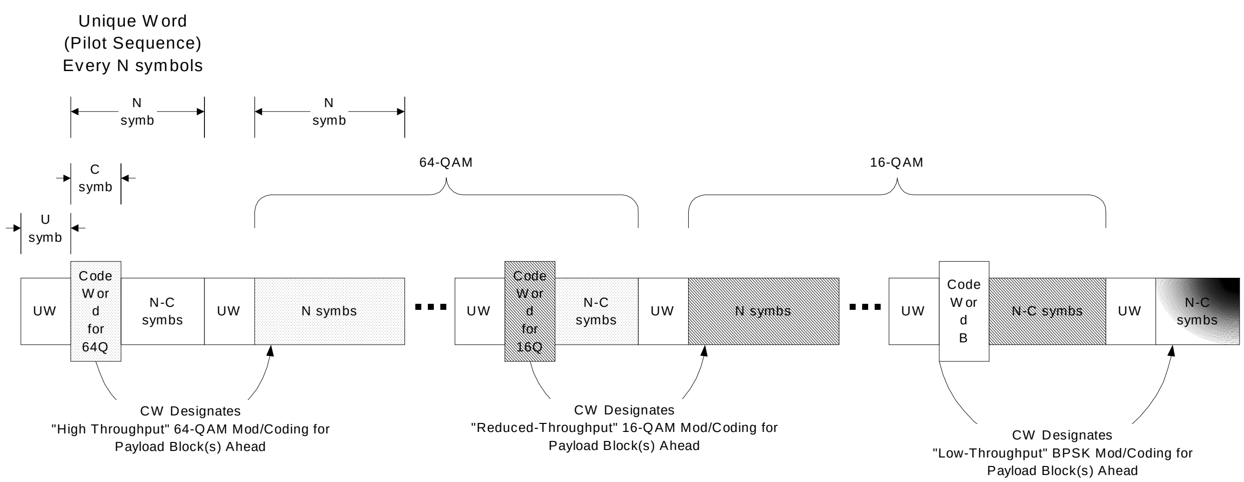
0.2 to .90 is possible. The range of channel parameters is show in Table 1;

Table 1: Channel Parameters

The "Block-Adaptive" PHY

The "Block-Adaptive" PHY is based upon an approach employing DOCSIS-like TDM data distribution in the downstream path and Time Division Multiple Access (TDMA) in the upstream direction. Although it is envisioned that many traffic models will require asymmetric data rates in the downstream and upstream directions, the PHY layer proposed here allows for symmetric data rates if so desired. Further, the proposed PHY will support a wide range of channel bandwidths and assignment plans.

The frame format is simple and block-based, and accommodates both FDD and TDD operation. Figure 1 illustrates downstream FDD operation, while Figure 2 illustrates downstream TDD operation. Figure 3 illustrates upstream operation.



"Figure 1: Framing Structure for FDD system; Downstream.

Block-Adaptive" PHY Frame Structure

Several features characterized the frame formatting. Chief among these is the use of Unique Words, which occur at intervals of N symbols (on the downstream). Every N symbols, one finds a sequence, called the Unique

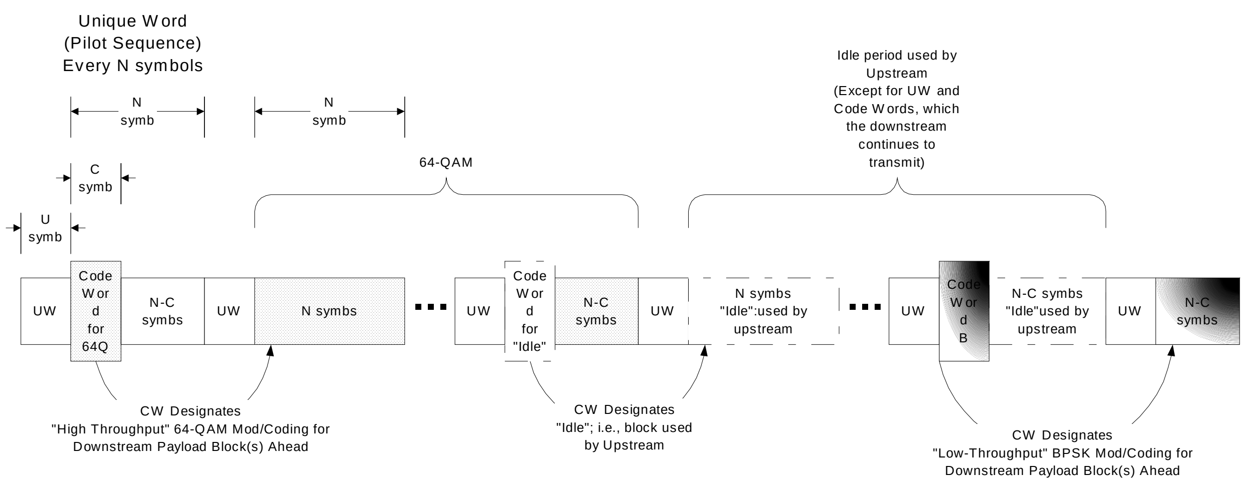


Figure 2: Framing Structure for TDD system; Downstream.

Word, of length U. This Unique Word serves as a pilot sequence; the symbols from which it is derived are known at both the transmitter and receiver. The Unique Word can be used for carrier phase tracking, channel tracking, and spectral inversion detection on the downstream---even when the payload data is of a modulation format beyond that detectable by a distant CPE terminal. By its periodic nature, it also is very useful in expediting initial acquisition, and re-acquisition, in the case of a deep fade, when the CPE receiver might lose lock. Note that by this structure, the downstream is considered to be 'continuous' in nature, and the Unique Words aid all CPE receivers in maintaining lock, even when transmitted packets are not meant for them.

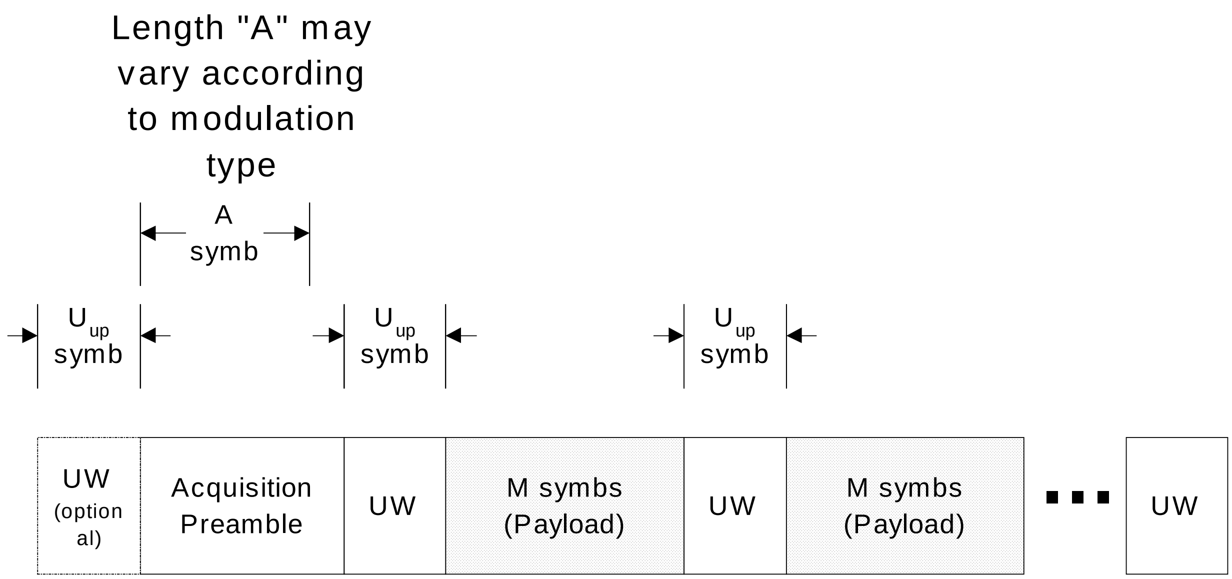


Figure 3: Framing Structure for Upstream (for simplicity, gaps due to potential downstream TDD framing structure ommitted).

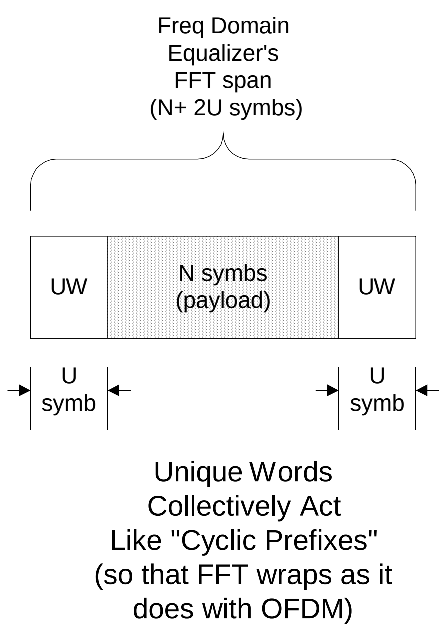


Figure 4: Structure of equalizer which can be exploited by a frequency domain equalization.

The symbol sequence within the Unique Word is selected to have good correlation properties (i.e., its autocorrelation resembles an impulse response), so that the transmission channel response can be identified with high accuracy. For easy demodulation at distant terminals (and optimal correlation sequence choice), the sequence is derived from a QPSK alphabet.

As Figure 4 illustrates, the Unique Word always 'sandwiches' data of length N on the downstream or length M on the upstream. This property is particularly useful for frequency domain equalizers, since these Unique Word segments on each end of the M point data serve as 'cyclic prefixes' so that the FFT used in the frequency domain equalizer 'wraps'. The FFT would be taken over the duration of the Unique Words on both ends of a N (or M) data point data payload. Note that this usage is very similar to the cyclic prefix used in OFDM. Note however, that here, the cyclic prefix is used as both pilot symbols and a cyclic prefix. This may result in higher spectral efficiencies than may be achieved with OFDM.

What is particularly attractive about the Unique Words is that, post-equalization, the known unique words can be cross-correlated against the Unique Word block regions---to to estimate the channel (delay spread) estimation error, and feed that back into channel response updates (used to equalize future blocks). A particular advantage over OFDM-type approaches is that these pilot symbols span the whole frequency spectrum, and thus are less affected by the notches due to multipath (frequency selectivity) of the channel. Note however, that this approach does not presuppose use of a frequency domain equalizer.

A DFE or other time-domain equalizer can also exploit these known pilot sequences to improve both their channel estimation and equalization performance. In particular, the use of periodic known sequences can reduce the propagation of decision errors within a DFE.

Another feature of the proposed framing is that optional Code Words of length C can be used at intervals to indicate the modulation type of the data payload that will follow the next Unique Word. In other words, there could be a Code Word for 64 QAM, another for 16 QAM, another for QPSK, and another for BPSK, etc. Note that the intervals for a given modulation may span several Unique Words, and the minimum duration of a given modulation type, i.e., the spacing between Code Words, might be a system parameter. These Code Words duplicate information contained in MAP messages, but can allow for more robust and rapid acquisition.

Also, if the TDD option is exercised, then another Code Word, called ‘Idle Channel’ is used, to tell the CPE that the next data segment will be idle. The upstream may subsequently be utilized by one of the CPE users which have requested bandwidth. In the TDD mode, the Base Station will send idle slots, even when no upstream bandwidth grants have been made, so that CPE users may signal grant requests.

As Figure 3 illustrates, the upstream is slightly different from the downstream in that Code Words are not used. The reason that Code Words are not used, is that since the Base Station allocates BW grants, it can indicate the modulation type it expects within the MAC protocol. Moreover, on the contention channels, a fixed modulation type is probably preferable. Another characteristic of the upstream is that it is of burst nature; each user bursts on and off. For this reason, an acquisition sequence serves as a preamble, so that the channel can be learned. Note that this acquisition sequence can also be sandwiched by Unique Words. Note also that the Unique Words for the upstream are not expected to be the same length as those found in the downstream. The reason for this is that the base station is the only user expected to utilize the data, so terminals operating at disadvantaged SNRs which can only track via the Unique Word are not assumed. However, if a frequency domain equalizer is to be used to equalize blocks, then a periodic Unique Word structure is necessary.

Benefits of the “Block-Adaptive” PHY

The most important benefit of the “Block-Adaptive” PHY is the ability to adjust the gain for each link so that each subscriber has just enough link gain to maintain the grade of service required for that link. By doing so, the optimal spectral efficiency is maintained. Note that in the case of the “Block-Adaptive” PHY the usual metric of spectral efficiency, bits/second/Hz, is not totally relevant since a given link might include transmission at several different modulation formats and coding rates depending on mix of traffic and the impairments present in each subscribers channel. Higher layer scheduling protocols offer the mechanism to optimize the mix of traffic to satisfy QoS requirements for each subscriber.

Exploitation of the correlation properties of the Unique Words offers a mechanism for quickly establishing block synchronization, upon either initial channel acquisition or if the subscriber station were reassigned to another downstream channel. Since all the modulation waveforms are coherent to a common carrier frequency, a single carrier acquisition loop in the receiver would be capable of tracking all the modulation waveforms. The Downstream Channel Descriptor (DCD) and the Downstream Link MAP (DL-MAP) messages in the 802.16 MAC will be sent at the lowest order modulation at the most robust FEC on that carrier, ensuring their reception by the most impaired subscribers on that carrier. This information will be used to set the modulation format and FEC rate for that subscriber. In the acquisition process, the subscriber station will return information to the base station indicating the quality of the downstream channel. Once these parameters are set, the subscriber station need only look for Unique Words at rates equal to, or lower than the matching combination of modulation and FEC assigned by the base station.

Table 2 illustrates the range over which the link can be adjusted to match the requirements for the characteristics of an individual channel. In Table 2 the link gain is normalized to the combination of 64QAM modulation. From Table 2 it can be seen that by adjusting modulation format 24 dB of control can be affected in the link gain.

Modulation Format	Relative Link Gain
BPSK	18 dB
QPSK	12 dB
16QAM	6 dB
64QAM	0 dB
256QAM	-6 dB

Table 2: Control Range of Link Gain and Channel Capacity

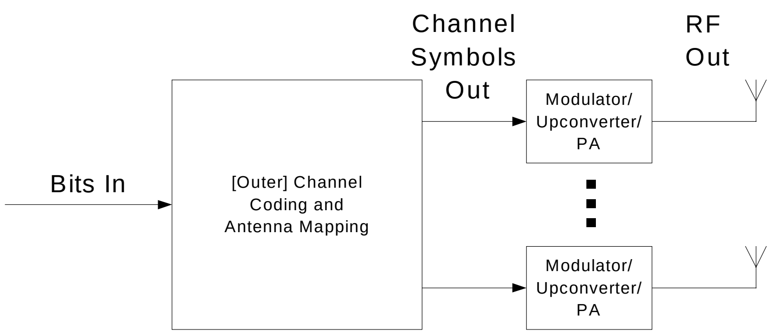
Support for Multiple Antenna Spatial Diversity

While the adaptive modulation and coding systems described here offer mechanisms to dynamically allocate network resources to subscribers based on the link requirements, the concepts can be extended to exploit spatial diversity to extend system capacity. The conceptual structure for a dual transmitter spatial diversity implementation is shown in Figure 6. In the system the data stream is encoded by the inner code and interleaved then passed to the outer coder and mapped to the two transmit antennas. On the receiver end of the link the symmetric process takes place and the two streams are combined in a structure analogous to a Decision Feedback Equalizer.

Figure 6 Spatial Diversity Conceptual Structure

Performance in a Multipath Environment

It has been shown that OFDM systems offer no advantages over Single Carrier modulation forms in severe multipath–see [1]. In particular [1] compares the performance of a coded OFDM signal in multipath



environments and shows that single carrier systems offer superior performance in all but a very limited number of cases. If the Single Carrier system also employs a Frequency Domain Equalizer, then the alleged advantages of OFDM in a multipath environment disappear and a system having superior performance while still enjoying the low cost advantages of a Single Carrier system will result. In [2] it is shown that the performance of a Single Carrier with Frequency Domain Equalizer (SC–FDE) technique can outperform OFDM in performance when the channels of communication suffer from deep multi-path fading in addition to the usual AWGN noise. Figures 7 is taken from [2] and illustrate the comparative performance of Frequency Domain Equalized Single Carrier and OFDM systems each employing QPSK modulation in the relatively severe SUI6 Channel.

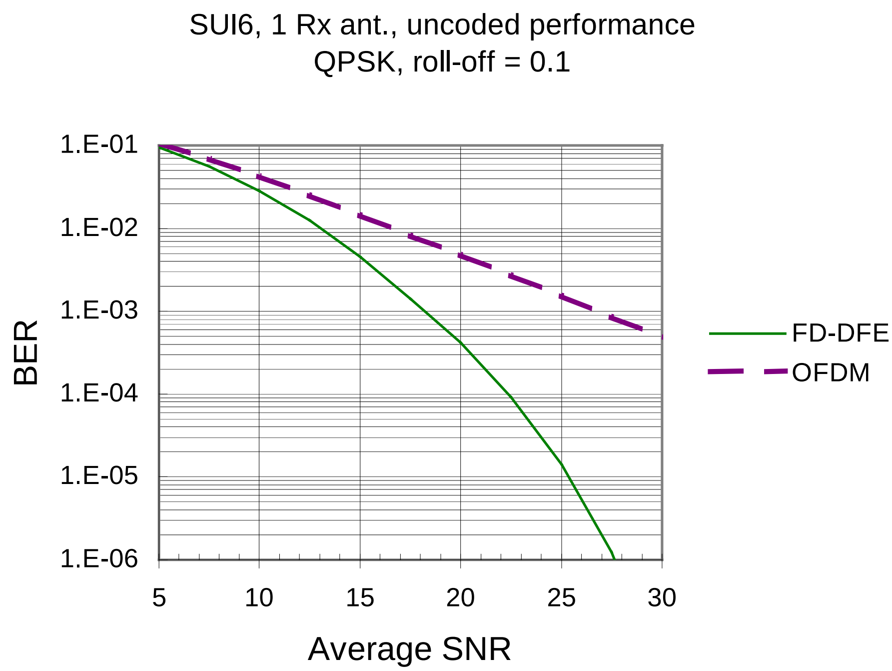


Figure 7 SC-FDE and OFDM, uncoded

Base Station and Subscriber Station Cost Optimization

The relative complexity of the baseband circuitry needed to implement the “Block Adaptive” PHY especially if a Frequency Domain Equalizer is employed is approximately the same as an OFDM system. In fact, it has been suggested that a dual-mode SC-FDE/OFDM receiver might be constructed and simply reconfigured under software control. However, even if the baseband complexity of PHY and MAC are equal, the RF circuitry for a Single Carrier system maintains a significant cost advantage because of less stringent phase noise requirements in the up and down convertors and more lenient linearity requirements, especially in the transmit chains in both BS and SS. These two topics are discussed separately below.

Phase Noise

A typical SS transceiver operating in the 2.5 or 3.5 GHz bands will be designed using a dual conversion architecture in both transmitter and receiver chains. Designs are well known in which the local oscillators for each path can be synthesized from a common reference oscillator. Typical performance of a LO chain implemented using low-cost CMOS Silicon IC and a low-cost TCXO as a reference oscillator will yield an RMS phase error of about 0.75 degrees when using a loop bandwidth of approximately 2 KHz. This results in a

SSB phase noise of about –80 dBc/Hz at 10 KHz offset and about –100 dBc/Hz at 100 KHz offset. This translates into a residual SNR for the receiver of about 38 dB. Referring to Figure 8 for a BER of 1.0E-8, if only thermal noise were present (residual SNR greater than 40 dB) a SNR of ~27 dB would be required. For a residual SNR of 38 dB (the case for a low-cost transceiver) the SNR for a BER=1.0E-8 will be approximately 29 dB, or a degradation of about 2 dB. This should be contrasted to the published requirements for a –97 dBc/Hz phase noise at 10 KHz to achieve a comparable BER in an OFDM system.

Linearity

The peak to average power ratio (PAPR) of an OFDM signal is about 4.5 dB higher than a 64QAM signal. The impact of this in terms of back-off from 1 dB compressed output power is shown in Figures 9 and 10. In Figure 9 the spectrum of a single carrier with 64QAM is shown at the output of a GaAs power amplifier operating at about 10 dB below its 1dB compression point. This signal meets the adjacent channel power ratio requirements of the FCC's MMDS transmitter regulations [47CFR21.908]. Figure 10 shows the simulated results of a 1023 carrier, 64QAM OFDM signal at differing levels of back-off from the 1 dB compression point. From Figure 10, it is apparent that more than 12 dB back-off from the 1 dB gain compression point is required. The published requirement is 14 dB.

To understand the significance of this difference, consider the case of two transmitters having a required output power of 23 dBm: for the single-carrier 64QAM case an amplifier with a 33 dBm (2 watt) 1 dB compressed output power will be required to meet the adjacent channel power ratio specification. For an OFDM system having the same 23 dBm rated output power, a 5 watt amplifier will be required.

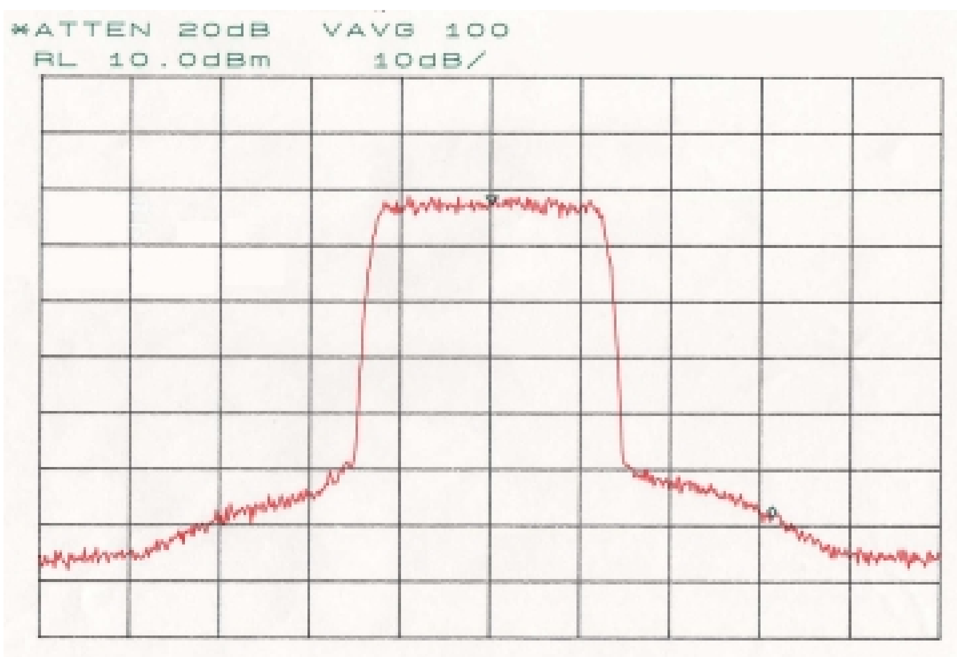
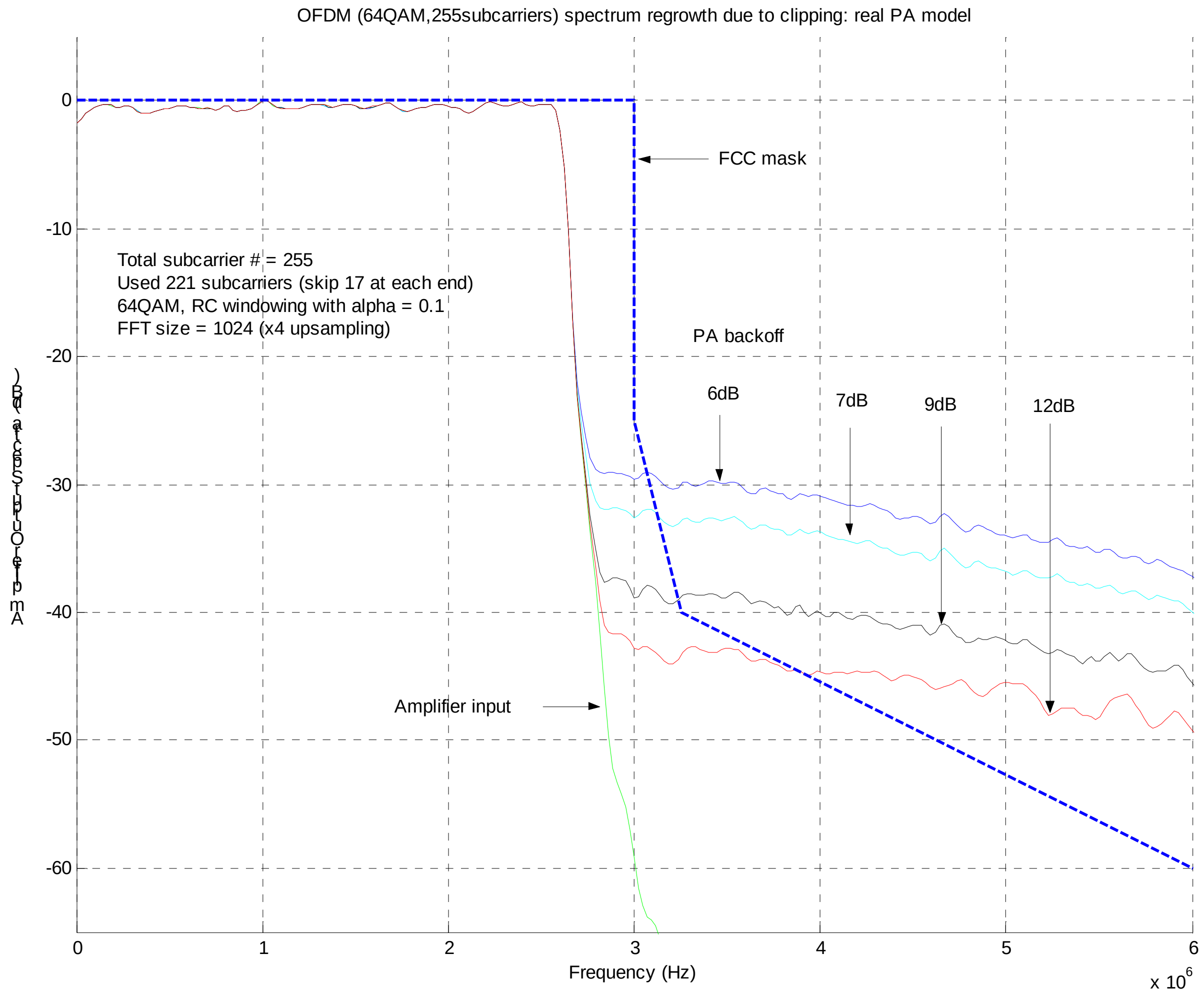


Figure 9: 64QAM at ~10 dB back-off

Figure 10: OFDM spectral regrowth at different PA back-off



Relationship to Existing Standards

The "Block-Adaptive" PHY proposed here generally follows the Downstream-Upstream access methods of DOCSIS and 802.16. The MAC sections of the Draft 802.16 Air Interface Standard provide appropriate means of controlling Media Access for the PHY proposed here.

Scalability

The PHY proposed here does not impose limits on the ability to efficiently transport the several data types described in the 802.16.3 Functional Requirements Document. In particular the adaptive nature of the PHY in concert with higher layer scheduling algorithms offers the ability to extend QoS controls to a wider range of subscribers in a given coverage area.

Disadvantages of the "Block-Adaptive" PHY

The principal disadvantage of the "Block-Adaptive" PHY is the overhead imposed by the Unique Word when employing short blocks. Under some combinations of poor channel conditions it is advantageous to shorten the length of the transmitted block to minimize bandwidth lost to retransmissions. In other circumstances, the data traffic and its assigned Class of Service may be better served with short packets. Voice traffic is an example of this type of data traffic. Under these conditions, the overhead of the unique word can become an appreciable portion of the total symbol count. The impact of this overhead is mitigated by two mechanisms: The fact that in a given coverage region, only a fraction of the subscribers might need the additional protection offered by a short block; and the potential to concatenate short packets reduces the need for minimal length blocks. Thus the capability of the PHY to adjust link parameters to provide the required level of service to each subscriber works to limit the negative impact of the Unique Word by assuring that only the individual links needing this additional protection get it.

Compliance to Evaluation Criteria

Meets system requirements	**This proposal is believed to meet the requirements described in the current version of TG3 FRD.**
Channel spectrum efficiency	**The average of bps /Hz in a typical deployment (TDD or FDD) is about 3 bps/Hz. In FDD mode, the spectrum efficiency of the system ranges from 1.46 for QPSK and to 2.9 bps/Hz for 16 QAM modulation for the Uplink. For the Downlink, 3.38 for 16-QAM and to 5.0 bps/Hz for 64 QAM modulation.**
Simplicity of implementation	**The major functions of the proposed PHY (i.e., QAM, FEC and OFDM) are well known or they are becoming available technologies and do require complex implementations.**
SS cost optimization	**Similarity that exists between this proposal with other standards mentioned above, will facilitate the availability of chip-sets to be used for the SS with lower cost. SC AT THE SUBSCRIBER UNIT TRANSMITTER REDUCES ITS POWER AMPLIFIER COST**
BS cost optimization	**The use of OFDM at the BS can be a drawback from the complexity and PA Back-off requirements, but this feature will be advantageous for future addition of Smart antenna capability to the system.**
Spectrum resource flexibility	**The proposed PHY can be scaled to any channel spacing. Modem bit rate can be easily modified to support 10 to 40 Mbps.**
Channel Rate Flexibility	**This data rate scalability can be obtained by changing FEC code rate and modulation scheme. The changes will have to meet the specified QoS in the FRD.**
System service flexibility	**The proposed PHY in conjunction with MAC layer will support various services defined within FRD that may require variable data rates and with different QoS requirements.**
Protocol interfacing complexity	**The proposed PHY will efficiently carry variable length packets and will comply with the delay and speed requirements by upper protocol layers.**
Reference system gain	**The system gain for 16QAM, 3.5GHz band, and 3.5 MHz BW Gain=103.5 and** **The system gain for 16QAM, 10.5GHz band, and 3.5 MHz BW Gain=96.5.**
Robustness to interference	**The proposed PHY uses powerful coding scheme with interleaving and good interference rejection capabilities.**
Robustness to channel impairments	**The multi-path robustness of FDE an important capability of the system and it reduces (almost removes) the impact of small and large scale fading.**
Robustness to radio Impairments	**The proposed PHY has the capability to support multiple data rates, modulations, and power control circuitry. When the radio channel attenuation becomes severe, then through the MAC control loop, the PHY system can re-adjust the transmission level to the appropriate level to keep the good quality of service intact.**
Support of advanced antenna techniques	**The proposal supports the need for advanced antenna techniques such as smart antenna into the standard. This feature, in conjunction with OFDM can be powerful feature for the system.**
Compatibility with existing standards and regulations	**This proposal is compliant with ETSI, FCC, and other existing standards and regulations as provided in Table 2.**

References:

[1] V. Aue, G.P. Fettweis and R. Valenzuela, “Comparison of the Performance of Linearly Equalized Single Carrier and Coded OFDM over Frequency Selective Fading Channels Using the Random Coding Technique”, Proc. ICC ’98, p. 753-757University Of South Australia School Of Electronic Engineering; February, 1995

[2] D. Falconer and S. L. Ariyavisitakul, “Frequency Domain Equalization for 2 –11 GHz Fixed Broadband Wireless systems”, Tutorial, t o be presented during Session#11 of IEEE802.16 in Ottawa, Canada, January 22, 2001.