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Title	**PHY Layer System Proposal for Sub 11 GHz BWA Having SC-FDE and OFDM Modes**
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Re:	This contribution is submitted in response to "Call for Contributions: Session #12" by 802.16.3 Task Group chair on January 2^{6th}, 2001 for submission of "PHY Proposals" for Sub 11 GHz BWA.
Abstract	This document provides team PHY System proposal of a low frequency (Sub 11 GHz) wireless access PHY for point-to-multipoint voice, video and data applications. The submission is for consideration of the Task Group to develop a PHY standard for BWA system.
Purpose	This contribution will be presented and discussed within the Task Group in Session #12 for possible adoption as baseline for a PHY standard Sub 11 GHz BWA.

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1 Scope

This document defines a proposed Physical Layer (PHY) for IEEE802.16.3 Broadband Wireless Access (BWA) systems in licensed frequency bands from 2-11GHz. In the material below both a Single-Carrier with Frequency Domain Equalizer and an OFDM PHY are offered. BWA is a communication system that provides digital two-way voice, data, and video services. The BWA market targets wireless multimedia services to home offices, small and medium-sized businesses and residences. The BWA system shall be a point-to-multipoint architecture comprise of **Subscriber Stations** (SS) and **Base Stations** (BS, Hub station). Figure 1.1 illustrates a BWA reference model.

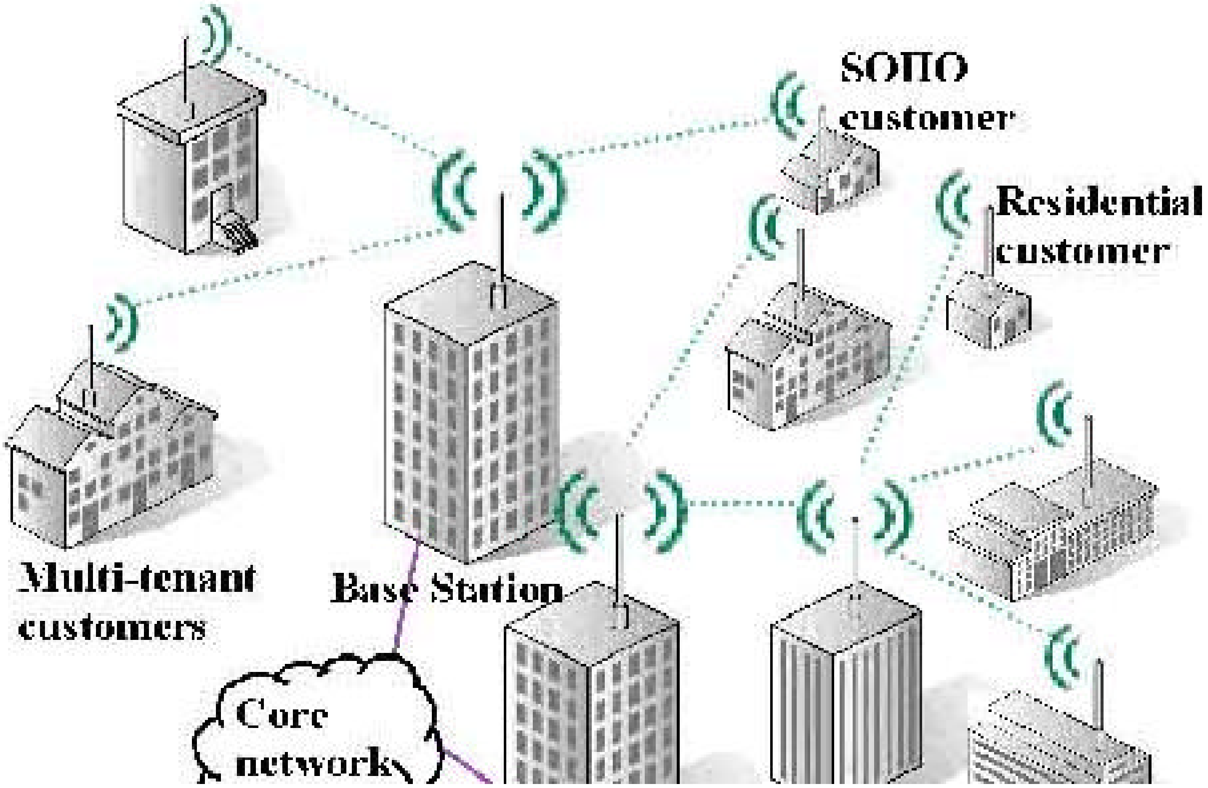

Figure 1.1 Wireless Access Reference Model

2 Introduction

2.1 General

The proposers believe that the 802.16.3 PHY standard should allow both Single Carrier (SC) and OFDM approaches to fully benefit from the features of each technology. This document will address both the SC and the OFDM PHY .

The proposed PHY system adopts TDM/ TDMA bandwidth sharing scheme. The signal is transmitted downstream from the Base Station to all Subscriber Stations assigned to a carrier frequency in broadcast Time Division Multiplex (TDM) mode. The upstream signal is burst from the Subscriber Station sharing the same RF carrier with other Subscriber Stations to the Base Station in Time Division Multiple Access (TDMA) mode. This access scheme can be applied to either FDD or TDD. Both duplexing schemes have intrinsic advantages and disadvantages, so the optimum duplexing scheme to be applied depends on deployment-specific characteristics, i.e., bandwidth availability, Tx-to-Rx spacing, traffic models, and cost objectives.

Operating frequency band will be 2 to 11 GHz and the Base Station can use multiple sectors and will support smart antennas in future applications.

The proposed PHY layers, either Single Carrier (SC) modulation with a Frequency Domain Equalizer (FDE) (SC–FDE) or Orthogonal Frequency Division Modulation (OFDM) technology, are shown to have comparable performance in solving the Non-Line of Sight (NLOS) problem that may arise in the 2 to 10.5 GHz frequency bands. However in the more usual case in which a narrow upstream bandwidth is used, the SC-FDE can offer a less costly CPE implementation due to lower cost of the RF circuitry in upstream path. Furthermore, the proposed frame structure for both SC-FDE and OFDM are identical. **The PHY proposed here is based upon utilizing the structure of the 802.16 MAC.**

The **key benefits of this PHY proposal** include:

1) Common MAC and framing structure for both single-carrier and OFDM
2) Mature and well-proved
3) Adaptive Modulation and Coding to support different QoS objectives
4) Flexible Asymmetry of Downstream and Upstream Paths
5) Scalability
6) Advanced Coding Schemes
7) Reduced System Delay
8) Straight forward migration to diversity receiver and multiple-input/multiple-output (MIMO technology)
9) Both Single-Carrier and OFDM formats.

2.2 Key Features

The PHY proposed here is a Broadband Wireless Access (BWA) **Point-to-Multipoint** communication system that can provide digital, two-way voice, data, Internet and video services. Proposed PHY offers an effective alternative to traditional wire line (cable or DSL) services.

Employing the functions of the 802.16 MAC such as QoS, the BWA system using the PHY proposed here will support services; such as packet data and Constant Bit Rate (CBR) as well as T1-E1, POTS, wide band audio and video services.

To maximize the utilization of limited spectrum resources in the low frequency bands (2 to 11 GHz), the air-interface supports statistical multiplexing over the air-interface using Time Division Multiple Access (TDMA) technology.

The “Block-adaptive” transmission scheme is capable of supporting both single and multicarrier modulation, as well as a variety of packet sizes [1] and channel models [6] with high efficiency and low implementation complexity.

The proposed PHY layer is designed to be compliant with IEEE 802.16.3's FRD (Functional Requirements Document) for Fixed Wireless MMDS Applications [1], and uses an adaptive receiver based on Frequency domain processing to incorporate *both* single and multicarrier modes of operation.

The proposed PHY/MAC interface is based on a DOCSIS-like TDM data distribution for the downstream, and contention-based TDMA in the upstream paths.

MMDS applications are expected to operate in diverse terrains and support a variety of data rates; consequently, there are a large number of parameters in the design space. Some of these parameters, such as channel width, symbol rates (*e.g.,* Table 2.1and Table 2.2), and type of channel [6] would typically be determined by the operator during system installation, with the built-in flexibility to change them at a later stage without requiring any modification in CPE hardware. Other parameters, such as the modulation format (i.e., QAM constellation size), code rate (RS/convolutional/turbo), and Block[1] size would require an "on-the fly" adaptation to instantaneous traffic and channel conditions, in order to maintain a high efficiency of system operation. The PHY and MAC layers discussed in this document provide several mechanisms to support all of the above features.

Channel Width (MHz)	Symbol Rate (Msymbols/sec)
1.75	1.5
3.5	3
7	6
14 (Note 1)	12

Table 2.1 ETSI MMDS Bands

Channel Width (MHz)	Symbol Rate (Msymbols/sec)
1.5	1.25
3	2.5
6	5
12 (Note 1)	10

Table 2.2 US MMDS Bands

Notes to Table 2.1 and Table 2.2:

1. Implementation of these channel widths is optional.

The efficient two-dimensional flexibility is shown in Figure 2.1for SC transmission, and in Figure 2.2 for MC transmission.

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[1] The notion of a PHY "Block" is described in Section 3.2 of this document.

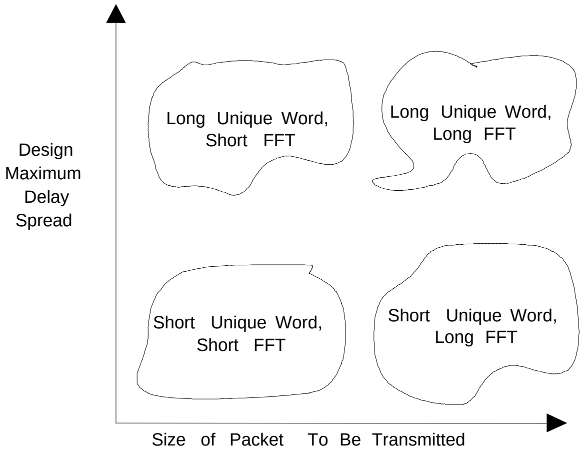

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Figure 2.1 Two-Dimensional Flexibility When Using SC Transmission

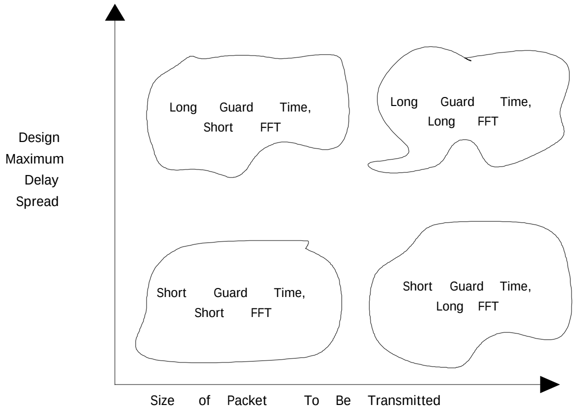

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Figure 2.2 Two-Dimensional Flexibility When Using MC Transmission

In these figures note that the same considerations that will dictate the choice of parameters for SC systems will also determine the MC block construction. This is to be expected, since the PHY “block” has been specifically designed to unify the Single- and Multi-carrier modes of operation.

To summarize, the main features of the proposal are the following:

- Full compatibility with the 802.16 MAC.
- Upstream multiple access scheme is based on TDMA.
- Downstream multiple access scheme is based on broadcast TDM.
- Duplex schemes are based on either TDD or FDD scheme.
- PHY uses a block adaptive modulation and FEC coding in both Upstream and Downstream paths.
- PHY proposal supports high capacity single carrier modulation with frequency Domain Equalization (SC-FDE) in addition to Decision Feedback Equalization in the time domain, or OFDM.

- The use of single carrier modulation techniques results in low cost Subscriber Stations (SS) and Base Stations (BS).
- The proposed modulation scheme is robust in multi-path and other channel impairments
- The two PHY 's are flexible in terms of geographic coverage, in the use of frequency band, and capacity allocation.
- Base Station can use multiple sector antennas. Support for future use of smart antennas is implicit in both PHY design.
- Either PHY can easily accommodate multi-beam and antenna diversity options; such as Multiple-In Multiple-Out (MIMO) and Delay diversity.

3 PHY Proposal

As described in the Functional Requirement Document [1], the equipment employing this PHY and the 802.16 MAC have been designed to address the critical parameters for serving single family residential, SOHO, small businesses and multi-tenant dwellings customers--using **Broadband Wireless Access** technology. These critical parameters are combination of coverage, capacity and equipment cost factors that affect total cost per user. The deployability, maintainability, and product costs associated with the customer premise installation, and the spectrum efficiency and reuse for economically serving the required number of customer locations. Of particular importance to the proposed PHY presented here is the inherent versatility implicit in the Frequency Domain Equalizer (FDE) architecture. Conceptually, a dual mode receiver could be implemented in which the FDE configuration could be changed to receive an OFDM signal. The bases for this approach are shown in Figure 3.1.

3.1 Signal Processing Architecture

2-11 GHz systems may operate on NLOS conditions, in which severe multi-path is encountered. Multi-path delay spread is a major transmission problem, which affects the design of modulation and equalization. Delay spread varies with environment and characteristics of transmit and receive antennas. In typical MMDS operating conditions, average delay spread ~ 0.5 μs, but 2% of measured delay spreads > approx. 8-10 μs [15], [16], [17].

Single carrier modulation, with receiver **linear equalization** (LE) or **decision feedback equalization** (DFE) in frequency domain - approximately equal complexity to OFDM, without the power back-off penalty [17], [18], [19] and [28].

Figure 3.1illustrates a functional block diagram of the proposed PHY layer systems for BWA services. Note that each system contains the same functional blocks, albeit arranged differently. In particular, there is little difference between the baseband complexity of the two versions.

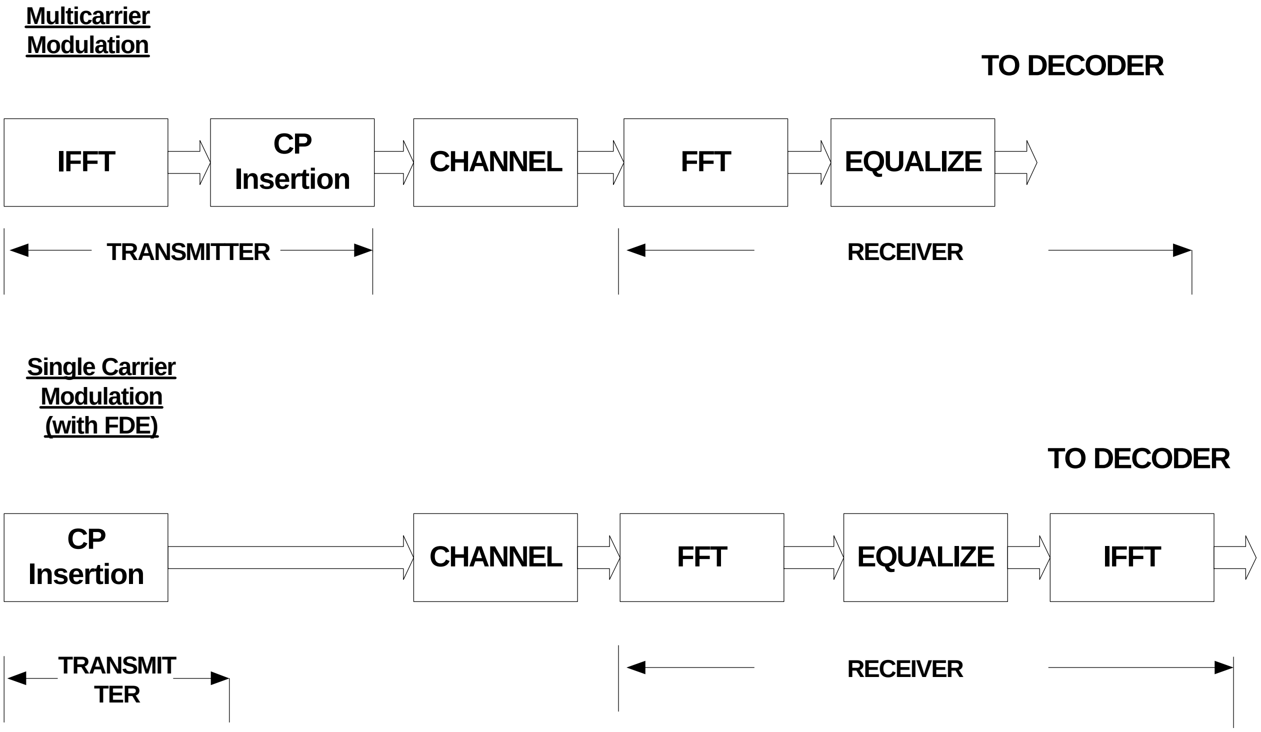


Figure 3.1 Frequency Domain Processing Architecture

Note that with an adaptive receiver based on Frequency Domain processing can handle both OFDM and Single Carrier modulation.

Further note that, Sari Hikmet in References [16 and 28 to 31] has significantly contributed to the development of Single Carrier modulation with Frequency Domain Equalization (SC-FDE). He also introduced the concept of Cyclic prefix to simplify the processing. However, there were few others (about late 80's) in the field who have introduced the concept of Frequency Domain Equalizer with overlap-add methods which can eliminate the need for a cyclic prefix but introduces added complexity in processing and adaptation. We should also mention that Sari [16] was the first to compare SC-FDE explicitly with OFDM.

Furthermore note that OFDM itself existed in the 50's and 60's as part of some military HF modems.

3.1.1 Single Carrier-Frequency Domain Equalization (SC-FDE) and OFDM

OFDM transmits multiple modulated subcarriers in parallel. Each occupies only a very narrow bandwidth. Since only the amplitude and phase of each subcarrier is affected by the channel, compensation of frequency selective fading is done by compensating for each subchannel's amplitude and phase. OFDM signal processing is carried out relatively simple by using two **fast Fourier transforms** (FFT's), at the transmitter and the receiver, respectively.

The single carrier (SC) system transmits a single carrier, modulated at a high symbol rate. Frequency domain equalization in a SC system is simply the frequency domain analog of what is done by a conventional linear time domain equalizer. For channels with severe delay spread it is simpler than corresponding time domain equalization for the same reason that OFDM is simpler: because of the FFT operations and the simple channel inversion operation.

The main hardware difference between OFDM and SC-FDE is that the transmitter's inverse FFT block is moved to the receiver. The complexities are the same. A dual-mode system could be designed to handle either OFDM or SC-FDE by simply interchanging the IFFT block between the transmitter and receiver at each end (see Figure 3.1.)

Both systems can be enhanced by coding (which is in fact required for OFDM systems), adaptive modulation and space diversity. In addition, OFDM can incorporate peak-to-average reduction signal processing to partially (but not completely) alleviate its high sensitivity to power amplifier nonlinearities. SC-FDE can be enhanced by adding decision feedback equalization or maximum likelihood sequence estimation.

3.1.2 Compatibility of Single Carrier (SC-FDE) and OFDM

Comparable SC-FDE and OFDM systems would have the same block length and cyclic prefix lengths. Since their main hardware difference is the location of the inverse FFT, a modem could be converted as required to handle both OFDM and single carrier signals by switching the location of the inverse FFT block between the transmitter and receiver. Therefore, the coexistence of OFDM and SC-FDE as a "convertible" modem can be feasible (see Figure 3.22).

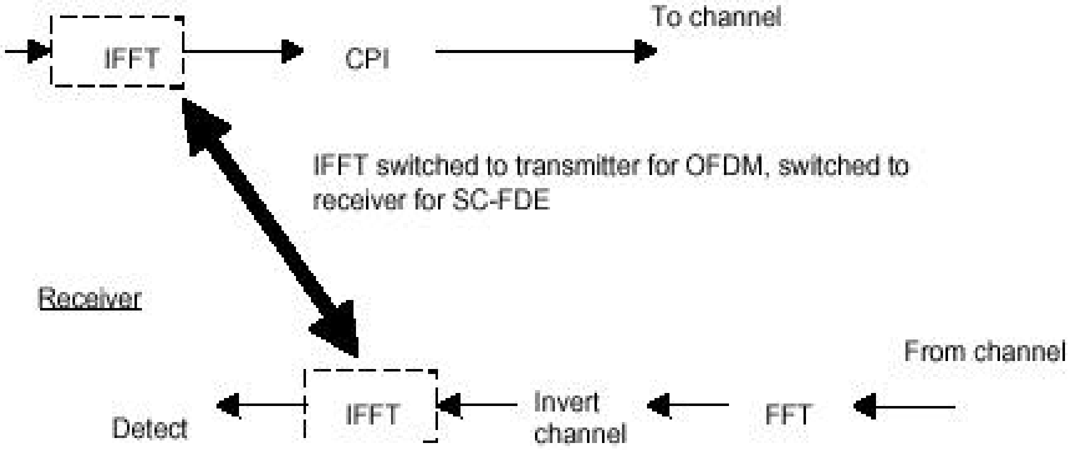


Figure 3.2 OFDM and SC-FDE "Convertible" Modem Approach

3.2 "Block" Structure

The notion of a PHY Block (Figure 3.3) is central to describe the unified operation of the Single Carrier (SC) and Multicarrier (MC) modes of the proposed transmission scheme. In the SC case, a block is defined as a fixed-length sequence of modulated symbols (appended with a "Unique Word" on either side), which forms the basic unit of the Frequency Domain Equalizer (FDE) at the receiver. In the MC mode, a "block" is simply *one* OFDM symbol computed via an N = P+U point FFT, with the last U samples appended in front to serve as the customary "Cyclic Prefix" (CP). In either case, the total block size as well as the modulation scheme over the block may be selected from a variety of supported modes (see Section 3.4), allowing the transmitter to adapt to different traffic and channel conditions. For a given FFT size and a fixed sampling rate, however, the processing of the SC or MC block is equivalent, and may even be implemented using *identical* transceiver hardware, as shown in **Figure 3.2**. The theory of operation of the Single and Multicarrier modes of the proposed PHY is described below.

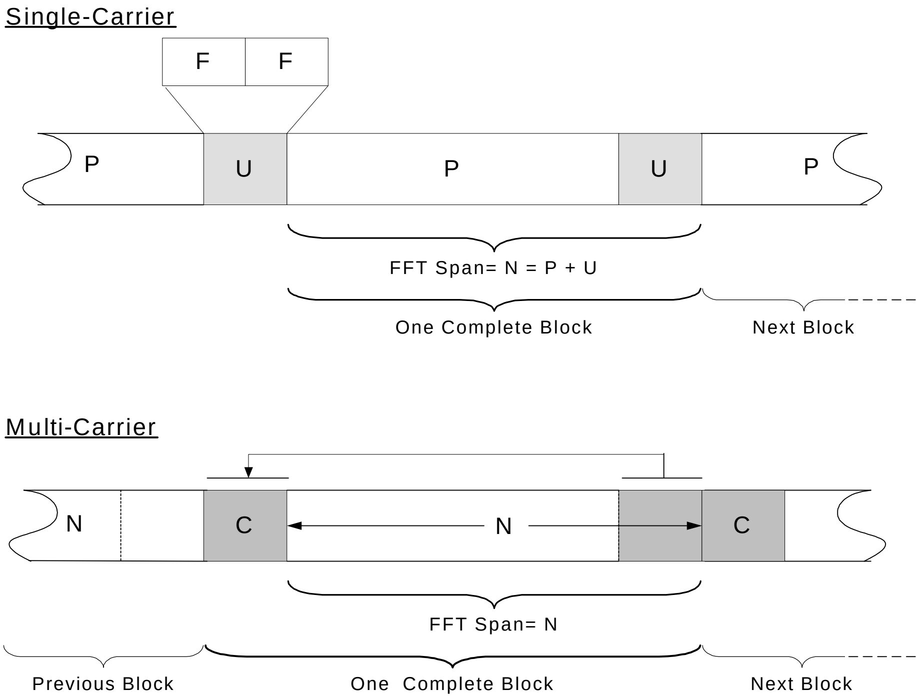


Figure 3.3 The PHY "Block"

3.2.1 Single-Carrier Block

The Single Carrier Block structure is designed to facilitate the use of a Frequency Domain Equalizer (FDE) at the receiver. The FDE has proved to be an attractive means for combating channels with severe multipath spread; see, *for example*, Walzman [32], Sari [16], or Falconer [4] for a relevant discussion. In the following, we demonstrate how the proposed "Block" structure may be used to effectively implement Frequency Domain Equalization in the SC receiver.

3.2.1.1 Unique Word

Figure 3.3depicts how a frequency Domain Equalizer exploits a 'Unique Word sandwich' frame structure. As Figure 3.3illustrates, the FFT span for the frequency domain equalizer is N= P+U symbols in length. Due to the fact that identical Unique Words sandwich the P-symbol payload, the data over any N symbol (FFT) range spanning the payload data is cyclic---much like the 'cyclic prefixes' seen in OFDM processing. Also like OFDM, since the time domain representation is cyclic, no 'edge effects' (i.e., aliasing) are seen when the temporal data is converted into its frequency representation. The frequency domain image is cleanly reproduced.

Unlike OFDM, however, the prefixes are not derived by arbitrary payload data wrapping; they are predetermined, pre-selected sequences (see Section 3.2.1.1.1) with special properties that can be exploited. More explicitly, the Unique Words are specifically designed to have optimal cyclic correlation properties. When used in their other role, as pilot symbols, the properties of the Unique Word greatly facilitates channel identification and estimation. Interpreting this in the frequency domain, the Unique Word sequence spectrally spans the whole signaling bandwidth, so their roles as pilot symbols in channel estimation are not diminished due to frequency selective fading.

The Unique Word also benefits in other ways from its correlation properties. They are helpful in determining optimal symbol timing (which is particularly important in burst demodulators), and also for determining the SNR-optimizing location at which the FFT window should begin (one want to collect as much of the multipath energy from the payload data as possible).

3.2.1.1.1 Design Criteria

The choice of Unique Word is critical, because it is used as both a Cyclic prefix for frequency domain equalizers, and also for channel estimation. Its cyclic prefix role imposes one constraint: the Unique Word must be at least as long as the maximum delay spread to be experienced by an intended receiver. Its channel estimation role imposes another constraint: the Unique Word should have good correlation properties, and a broadband, un-notched frequency response. And lastly, since the Unique Word introduces overhead, it should be no longer than it need be; sectors/installations that experience less delay spread should not be burdened with the overhead of excessively long Unique Words. This implies that some flexibility in the choice (or construction) of Unique Words is required.

The “Unique Words” indicated by “U” in Figure 3.1 a crucial role in facilitating frequency domain equalization. Due to the fact that the P-Symbol payload is encapsulated between *identical* Unique Words, the data over the P+U = N FFT range is rendered cyclic, as long as the unique word exceeds the maximum delay spread of the channel. An FFT-based equalizer operating on the cyclic block can then effectively counter the frequency selectivity of the transmission medium. Note, however, that unlike the Cyclic Prefix in OFDM, the Unique Words are not derived from the payload data in the SC block. In fact, they are composed of predetermined Sequences, specifically designed to have several properties that assist their other functions. These functions are summarized below:

- The most important function of the Unique Words (UW) is to act as “pilots” from which the channel may be estimated at the receiver. For non-decision directed estimation, the duration of the UW must be at least twice the maximum channel multipath spread. This is necessary since the multipath from the previous “block” will contaminate a portion of the UW of length equal to the channel impulse response. For a UW that is twice the delay spread duration, however, the channel response can be still be deconvolved using the uncontaminated portion of the UW at the receiver.

  Note that the nature of estimation using the UWs is somewhat different from estimation using conventional “pilots” in OFDM. In particular, the UW may be viewed as a sequence of temporally congregated pilots (in time domain), as opposed to certain reserved “tones” carrying predetermined information in OFDM. The channel frequency response in this case will be computed from the extracted channel (time) response via zero padding and appropriate extrapolation.

- Since the two halves of the UW have been designed to be identical Sequences (Figure 3.1), a correlation detector operating over the two parts would provide an accurate means for aligning the receiver FFT window at the receiver, thus assisting timing recovery. The same sliding correlator may be used for AGC control, as well as to implement antenna selection in a low-cost switching diversity antenna receiver.

- In the continuous DS mode (Section5.2.2), the repeating train of UWs enables all CPE receivers to continually update their estimates of the DS channel, as well as maintain fine time and frequency lock with the Head-end. In the burst DS mode (Section 3.2), an additional preamble would also be required (per burst) to facilitate initial synchronization and estimation of the channel. This preamble may be created using replications of the same sequences used to create the Unique Word.

- Finally, successive UW pairs on the Downstream serve as block “counters” and help simplify the process of broadcasting the DS schedule in a given MAC Frame (Section4).

3.2.1.1.2 Specific Implementations

3.2.1.1.2.1 Frank Sequence

An example of a 64-symbol long “Frank” sequence, which could be used in some modes of Single Carrier Operation, is given by:

$$s(mK+n) = \exp\left(\frac{j2pmn}{F}\right)$$

where

m = 0,1,…,K-1;

n = 0,1,…,K-1;

$F = \sqrt{64} = 8$, (Number of phases.)

The Frank sequence has the desirable properties of having a perfect periodic autocorrelation function, in addition to being a constant envelope, polyphase signal with small phase alphabet [33].

3.2.1.1.2.2 Modified PN Sequence

Another sequence class that possesses all of the desired properties is the ‘modified PN’ sequence, as described by Milewski in [26]. As the title suggests in [26], this sequence class has ‘optimal properties for channel estimation and fast start-up equalization.’ What’s more, constructions for various sequence lengths are simple, due to their derivation from PN sequences.

The ‘modified PN sequence’ is a complex-valued (I + jQ) sequence that might be described as ‘quasi-BPSK.’ It possesses the following structure:

- The ‘I’ channel component is derived from a PN-generator (linear feedback shift register) of period $U=2^n-1$ (where n is an integer), and
- he ‘Q’ channel component is a small, but non-zero constant sequence, with value $\frac{1}{\sqrt{2^n-1}}$.

Table 3.1 lists the generator polynomials that might be used in generating the 'I' component of the Unique Word, over a range of interesting sequence lengths, U.

Length, U (symbols)	PN Generator Polynomial (Binary, with 100101 <-> $x^5 + x^2 + 1$)
15	10011
31	100101
63	1000011
127	10000011
255	100011101

Table 3.1 UW lengths and Generator Polynomials used to Generate I channel's PN -Sequence.

3.2.2 Multi-Carrier

A MC block is simply an OFDM "symbol" composed of P+U "tones", and with a guard time or Cyclic Prefix of U samples appended in front to render the channel circulant.

3.2.2.1 Windowing

To reduce emissions outside the channel as required to meet the transmitter emission mask (See Section 7.2), a raised cosine window will need to be applied to each end of the OFDM signal in the time domain [3].

3.3 Choice of Block Adaptation Parameters

Different modes of operation are defined for both the SC and the MC versions of the PHY to maximize transmission efficiency depending on system environment and instantaneous traffic. In practice, the System Operator will ordinarily select the mode in three hierarchical Selection Levels: System-Dependent, Link-Dependent and Traffic-Dependent. These levels are described in the following three subsections.

3.3.1 System-Dependent Parameters

- At the highest Selection Level, there are the System-Dependent Parameters of Channel Width, Maximum Delay Spread, Baseband Filter Excess Bandwidth (SC systems only), Spectral Guard Factor (MC systems only), and Symbol Rate.

These parameters are ordinarily specified by the System Operator before the system is constructed. Channel Width will be dictated by license assignments and government regulations in most cases. Maximum Delay Spread will often be permanently selected based on the terrain and intended market. In SC systems, the Baseband Filter Excess Bandwidth, α, is ordinarily chosen as a compromise between spectrum compactness, required backoff in the RF amplifiers, and DSP complexity issues. In MC systems, similar considerations apply to selecting the Spectral Guard Factor, ã. Symbol Rate, in most systems, will be fixed in order to simplify synchronization of all CPE. The Symbol Rate chosen is restricted by the Channel Width and will normally be set close to W/(1+α) or W/(1+ã).

The System Operator may choose to install hardware and/or software that does not support the unusable modes of System-Dependent Parameters.

3.3.2 Link-Dependent Parameters

At the second Selection Level, there are the Link-Dependent Parameters, *i.e.*, the Number of QAM States and Code Rate. These parameters are ordinarily assigned by the base station's MAC at the highest rates which the target CPE has been found capable of efficiently receiving. The MAC may adapt this value in time.

3.3.3 Traffic-Dependent Parameter

At the lowest Selection Level, there is a single Traffic-Dependent Parameter, the FFT size, which largely determines the number of symbols in the block. This is also ordinarily chosen by the base station's MAC, in this case to most efficiently transmit the packet at hand. Ordinarily, it will choose the smallest size which will transmit the entire packet in one Physical Block. If the largest defined Physical Block is too small to fit the entire packet, it will split the packet into several Physical Blocks. When there are many short packets to be transmitted, selecting the FFT size in this way greatly increases the efficiency of spectrum utilization. Due to the butterfly structure of the FFT, this variable size is easily implemented in hardware.

3.4 Supported Block Adaptation Parameters

The following two sections show supported block adaptation parameters for SC and MC modes, respectively. Note the obvious parallelism between the two modes. This is a direct consequence of the unifying "Block" structure that underlies both operating PHY modes in this document.

3.4.1 Supported Single-Carrier Modes

The Parameters and Values defining the various Operating Modes for Single-Carrier systems are summarized in Table 3.2.

Selection Level	Parameter	Symbol	Set of Values
System-Dependent Parameters	Channel Width (MHz)	W	1.75, 3.5, 7, 14, 1.5, 3, 6, 12
	Design Maximum Delay Spread (μsec)	d	4, 10, 20
	Baseband Filter Excess Bandwidth	α	0.18, 0.25
	Symbol Rate (MSym/sec)	R	See Tables 2.1, 2.2
Link-Dependent Parameters	Number of QAM States	M	4, 16, 64
	Code Rate	r	1/2, 2/3, 3/4, 7/8
Traffic-Dependent Parameter	FFT Size	N	256, 512, 1024, 2048

Table 3.2. Parameters and Values Defining Operating Modes for SC Systems

A number of other parameters follow from the parameters in Table 3.2. These parameters depend mathematically on the Selected parameters from Table 3.2. Guidelines for these subsidiary parameters are shown in Table 3.3

Dependent Parameter	Symbol	Formula	Note
Number of Symbols in Unique Word	U	$2 \bullet R \bullet d$	
Number of Symbols in Training Sequence	F	U / 2	2.
Number of Payload Symbols Per Block	P	N - U	
Frequency Spacing of Available Channel Estimates Measurable In One Block	e	W / F	3.
Block Period	B	N / R	4.

Table 3.3 Guidelines For Subsidiary Parameters in SC Systems

Notes to Table 3.3:

1. The formulae shown here serve as guidelines for selecting the practical values.
2. Round U so that F is a perfect square (only if using Frank sequences).
3. This is nominally sufficient to estimate the peaks and notches of a channel exhibiting the Design Maximum Delay Spread, and fading with a coherence time nominally equal to the Block Period.
4. This includes the payload symbols plus one Unique Word. See Table 3.4.

Table 3.4shows the range of Block Periods which result from different choices of FFT Size and Symbol Rate in SC systems.

FFT Size N	Symbol Rate R (MSym/sec)	Block Period (microseconds)
256	1.25	204.800
	1.5	170.667
	2.5	102.400
	3	85.333
	5	51.200
	6	42.667
	10	25.600
	12	21.333
512	1.25	409.600
	1.5	341.333
	2.5	204.800
	3	170.667
	5	102.400
	6	85.333
	10	51.200
	12	42.667
1024	1.25	819.200
	1.5	682.667
	2.5	409.600
	3	341.333
	5	204.800
	6	170.667
	10	102.400
	12	85.333
2048	1.25	1638.400
	1.5	1365.333
	2.5	819.200
	3	682.667
	5	409.600
	6	341.333
	10	204.800
	12	170.667

Table 3.4 **Block Duration in SC Mode**

3.4.2 Supported Multicarrier Modes

The Parameters and Values defining the various Operating Modes of the Multicarrier transmission of the PHY are summarized in Table 3.5.

Selection Level	Parameter	Symbol	Set of Values
System-Dependent Parameters	Channel Width (MHz)	W	1.75, 3.5, 7, 14, 1.5, 3, 6, 12
	Design Maximum Delay Spread (μsec)	d	4, 10,20
	Spectral Guard Factor	γ	0.18, 0.25
	Sample Rate (MSam/sec)	R	See Tables 2.1, 2.2
	Number of Pilot Tones	L	[Note 1]
	Number of Guard Tones	G	[Depends on adjacent channel constraints (Note 2)]
Link-Dependent Parameters	Number of QAM States	M	4, 16, 64
	Code Rate	r	1/2, 2/3, 3/4, 7/8
Traffic-Dependent Parameter	FFT Size	N	256, 512, 1024, 2048

Table 3.5 Parameters and Values Defining Operating Modes for MC Systems

Notes to Table 3.5:

1. This value should be set to be nominally sufficient to estimate the peaks and notches of a channel exhibiting the Design Maximum Delay Spread, and fading with a coherence time nominally equal to the Block Period.
2. The guard spectrum reserved by switching off the Guard Tones is *in addition* to the spectrum reserved by the Spectral Guard Factor, γ.

A number of other parameters follow from the mode definitions in Table 3.5. These parameters depend mathematically on the parameters from Table 3.5. Guidelines for these subsidiary parameters are shown in Table 3.6.

Dependent Parameter	Symbol	Formula	Note
Number of Samples in Cyclic Prefix+Postfix	C	2 • R • d	2.
Number of Payload Subcarriers	P	N - G - L	
Frequency Spacing of Available Channel Estimates Measurable In One Block	e	W / L	
OFDM Symbol Period	S	(N + C - w) / R	
OFDM Subcarrier Spacing	s	R / N	3.

Table 3.6 Guidelines for Subsidiary Parameters In MC Systems

Notes to Table 3.6:

1. The formulae shown here serve as guidelines for selecting the practical values to be included in the actual standard.
2. In addition to the cyclic prefix (which needs only to be as long as the maximum channel delay spread), C includes two windows, each of length w samples (applied as prefix and postfix for spectral shaping.)
3. See Table 3.7

Table 3.7 shows the range of Subcarrier Spacings that result from different choices of FFT Size and Symbol Rate in MC systems.

FFT Size N	Sample Rate R (MSam/sec)	Subcarrier Spacing (Hz)
256	1.25	4882.813
	1.5	5859.375
	2.5	9765.625
	3	11718.750
	5	19531.250
	6	23437.500
	10	39062.500
	12	46875.000
512	1.25	2441.406
	1.5	2929.688
	2.5	4882.813
	3	5859.375
	5	9765.625
	6	11718.750
	10	19531.250
	12	23437.500
1024	1.25	1220.703
	1.5	1464.844
	2.5	2441.406
	3	2929.688
	5	4882.813
	6	5859.375
	10	9765.625
	12	11718.750
2048	1.25	610.352
	1.5	732.422
	2.5	1220.703
	3	1464.844
	5	2441.406
	6	2929.688
	10	4882.813
	12	5859.375

Table 3.7 Subcarrier Spacing in MC Mode

3.5 Baseband Pulse Shaping (SC Only)

Prior to modulation, I and Q signals shall be filtered by square-root raised cosine filters defined by the following transfer function H(f):

$$H(f) = 1 \qquad for \quad | f | \; \langle \; f_N (1 - a)$$

$$H(f) = \left\{ \frac{1}{2} + \frac{1}{2} \sin \frac{p}{2 f_N} \left[\frac{f_N - | f |}{a} \right] \right\}^{1/2} \qquad for \quad f_N (1 - a) \leq | f | \leq f_N (1 + a)$$

$$H(f) = 0 \qquad for \quad | f | \geq f_N (1 + a)$$

$$f_N = \frac{1}{2T_S} = \frac{R_S}{2}$$

Where:

f_N is the Nyquist frequency, and Ts is modulation symbol duration.

4 PHY/MAC INTERFACE

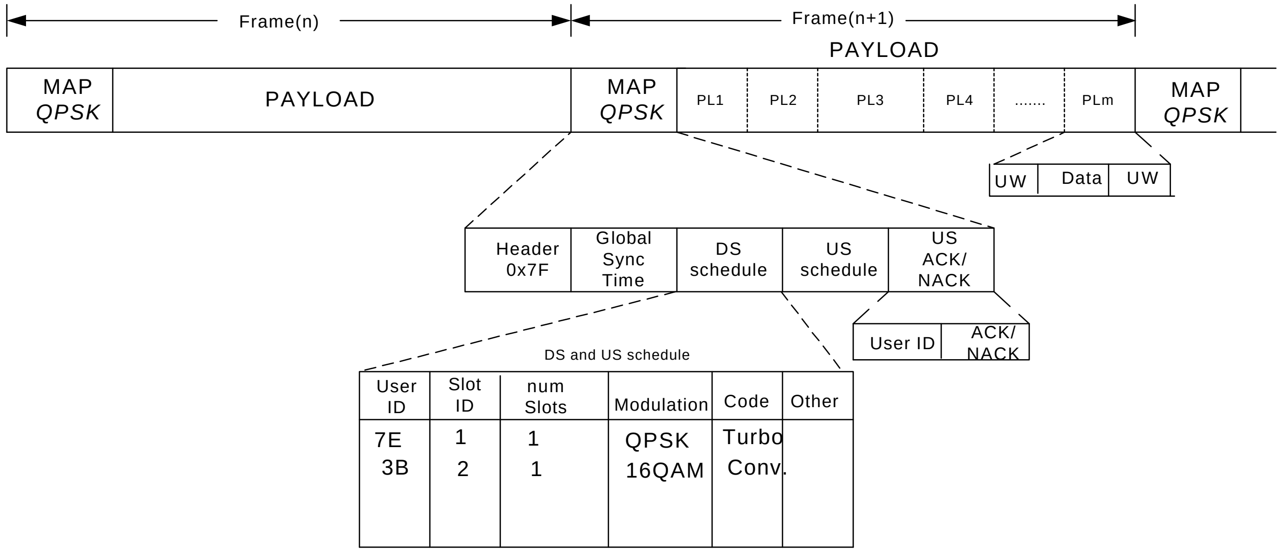
The PHY/MAC Interface in this proposal has been designed to maximize commonality with the cable (DOCSIS) baseline spec, while providing support for Block adaptation, as discussed in Section 3.4. Four modes may be considered:

- Continuous Transmission, Downstream, *e.g.* in an FDD-only system
- Burst Transmission, Downstream, *e.g.* in a TDD-only system
- Upstream Transmission, FDD
- Upstream Transmission, TDD

These modes are summarized in Sections 4.1 through 4.4 below.

4.1 Downstream, Continuous Transmission (FDD)

Continuous Downstream



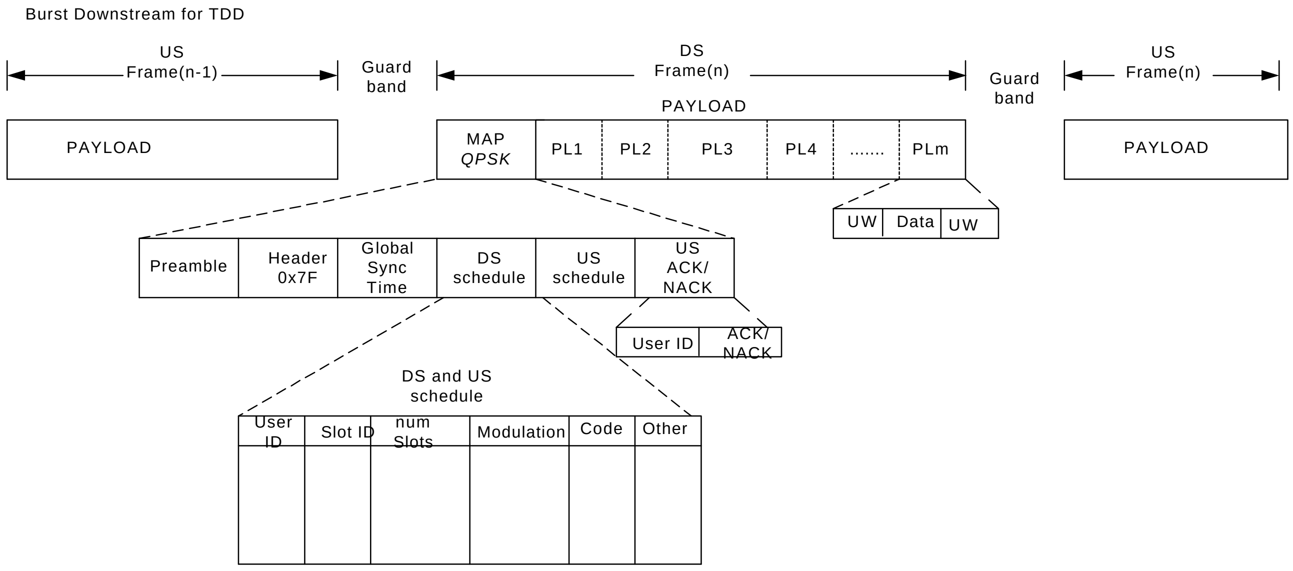
User ID	Slot ID	num Slots	Modulation	Code	Other
7E	1	1	QPSK	Turbo	
3B	2	1	16QAM	Conv.	

1. PL1,PL2,PL3,PLm are payloads for user-1, user-2,user-3, user-m respectively, all independently modulated.

2. Global Sync Time is used by all users as Network time to synchronize DS and US frames.

3. If DS slots are assigned with progressive modulation (QPSK,16QAM,64QAM) then users towards tail end of the frame will receive more synchronization sequences, assisting higher modulation schemes.

4.2 Downstream, Burst Transmission (TDD)

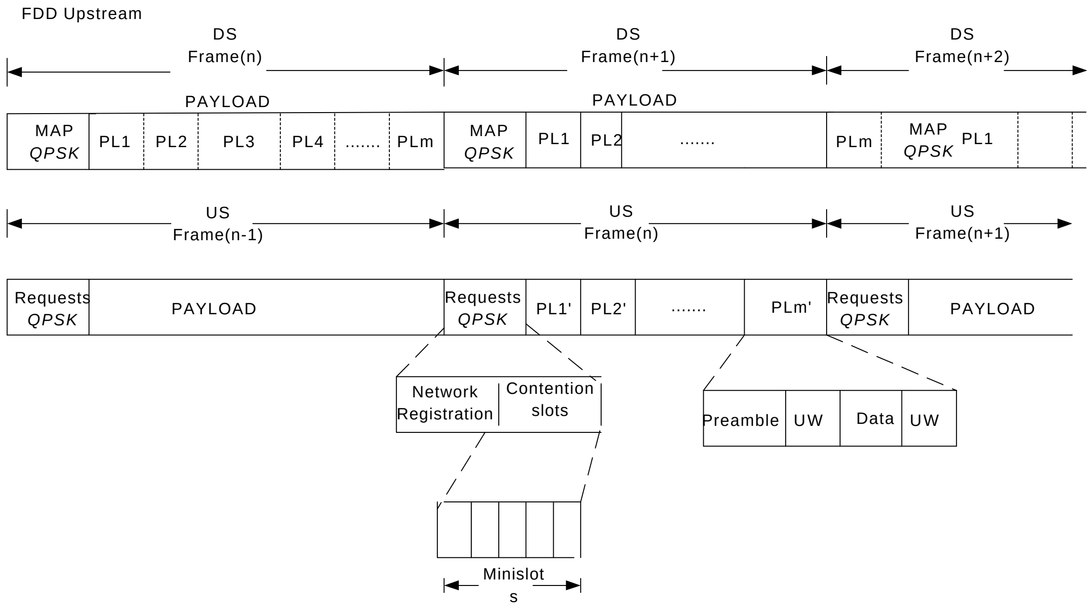


1. PL1,PL2,PL3,PLm are payloads for user-1, user-2,user-3, user-m respectively

2. Global Sync Time is used by all users as Network time to synchronize DS and US frames.

3. In TDD mode, a Guard time is sandwiched between DS and US frames.In this time, the base station switches mode from transmitter to receiver and all users switch their mode from receiver to transmitter.

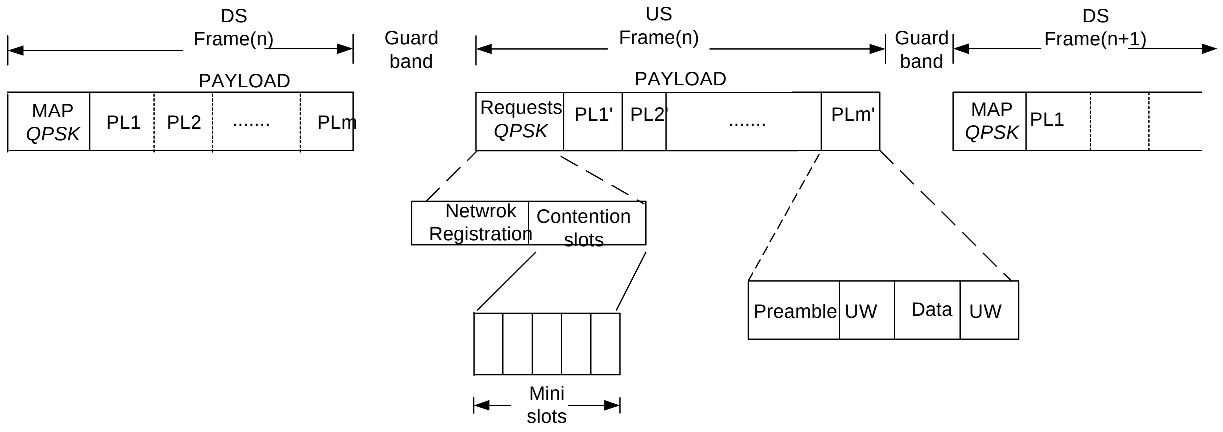
4.3 Upstream Transmission (FDD)



1. PL1',PL2',PL3',PLm' are uplink payloads for user-1, user-2,user-3, user-m respectively, and are all independently modulated.

4.4 Upstream Transmission (TDD)

TDD Upstream



1. PL1',PL2',PL3',PLm' are payloads for user-1, user-2,user-3, user-m respectively, all independently modulated.

2. In TDD mode Guard time is sandwiched between DS and US frames. In this time, the base station switches mode from transmitter to receiver and all users switch their mode from receiver to transmitter.

5 MAC

5.1 Multiple Access Formats and Framing

In this Section, we introduce multiple access formats, and the PHY framing and MAC/ PHY interface structures necessary to accommodate these formats.

5.1.1 MAC Layer Framing

5.1.1.1 Introduction

Starting with a simple fundamental frame component and two formats, we intend to construct MAC structures that can be applied to several multiple access techniques. Before we start the building, however, let us introduce the fundamental formats that we will address them later.
Two fundamental MAC block formats options are available:

1. one used for continuous transmissions, and

2. another used for burst transmission.

The continuous transmission format is used on the downstream of one type of a FDD system. The burst format might be seen on the upstream of an FDD system, or on the upstream and downstream of a TDD system or on the downstream of a burst-FDD system. The burst format may be further categorized into TDMA and TDM sub-formats. A TDMA burst contains information intended for one audience (which could be a single user, or a broadcast user). In contrast a TDM burst contains multiplexed, concatenated information addressed to multiple audiences.

5.1.1.2 Continuous Transmission Format

As its name suggests, the continuous transmission format is utilized for a continuous channel, which is tracked by all Subscriber Stations (SS)s within a Base Station (BS) cell sector. In the broadband wireless application, this would be a (continuous) FDD downstream channel.

5.1.1.2.1 Adaptive Modulation

5.1.1.2.1.1 Introduction to Adaptive Modulation

Many SSs receive the continuous downstream channel. Due to differing conditions at the various SS sites (e.g., variable distances from the BS, presence of obstructions), SS receivers may observe significantly different SNRs. For this reason, some SSs may be capable of reliably detecting (non-pilot) data only when it is derived from certain lower-order modulation alphabets, such as QPSK. Similarly, SNR-disadvantaged SSs may require more powerful and redundant FEC schemes. On the other hand, SNR-advantaged stations may be capable of receiving very high order modulations (e.g., 64-QAM), with high code rates. Obviously, to maximize the overall capacity of the system, the modulation and coding format should be adapted to each class of SS, based on what the SS can receive reliably. Define the adaptation of modulation type and FEC to a particular SS (or group of SSs) as 'adaptive modulation', and the choice of a particular modulation and FEC as an 'adaptive modulation type.' The continuous transmission mode (as does the burst transmission mode) supports adaptive modulation and the use of adaptive modulation types.

5.1.1.2.1.2 Frame Control Header Information

Frame Control MAC messages are periodically transmitted over the continuous channel, using the most robust supported adaptive modulation type. These Frame Control headers provide adaptive modulation type formatting instructions. So that, the beginning of MAC message containing Frame Control headers may be easily recognized during initial channel acquisition or re-acquisition, the transmitter PHY inserts an uncoded, TBD (known) uncoded QPSK code word, of length TBD symbols, immediately before the beginning of a MAC message containing Frame Control information, and immediately after a Unique Word. Note that this implies the interval between broadcasts containing DL_MAPs should be an integer multiple of F (the interval between Unique Words).

5.1.1.2.1.3 Adaptive Modulation Sequencing

Within the MAC, a PHY control map (DL_MAP) is used to indicate the beginning location of each of adaptive modulation type payload that follows. However, the DL_MAP does not describe the beginning locations of the payload groups that immediately follow; it describes the payload distributions some MAC-prescribed time in the future. This delay is necessary so that FEC decoding of MAC information (which could be iterative, in the case of turbo codes) may be completed, the adaptive data interpreted, and the demodulator scheduling set up for the proper sequencing.

Following DL_MAP instructions, payload groups are sequenced in increasing order of robustness (e.g., first QPSK, then 16-QAM, then 64-QAM). This improves the receiver performance, because this forces them to track only the modulation types that they can reliably receive. This sequencing also facilitates changes of modulation type at locations that are not contiguous to Unique Word boundaries.

5.1.1.2.1.4 UW Boundary-free Transitions Between Modulation Types

Note also that adaptive modulation type-to-other-modulation type changes are not restricted to occur only at Unique Word boundaries. They may change anywhere that the DL_MAP message indicates that they should change.

5.1.1.2.1.5 Per-Adaptive Modulation Type FEC Encapsulation

So that disadvantaged-SNR SSs are not adversely affected by transmissions intended for other advantaged-SNR users, FEC blocks end when a particular adaptive modulation type ends. Among other things, this implies that the FEC interleaver depth and code blocks are adapted to accommodate the span of a particular adaptive modulation type.

5.1.1.2.2 Empty payloads

When data is available for transmission, part of a payload may be empty. However, the transmitter cannot shut completely down. The unique words are always transmitted, so that all listening SSs may track the channel, and maintain synchronization.

5.1.1.2.3 Additional Pilot Symbols

When multipath delay spread spans almost the entire unique word interval, very little data remains that is not uncorrupted by delay spread from the arbitrary, a priori unknown payload symbols. In such an environment, non-decision aided channel (delay profile) estimation could become increasingly difficult. The only recourse, then, would be increased utilization of decision-aided channel estimation.

To add an extra measure of robustness, many system operators may prefer, instead, to opt for the addition of additional pilot symbols. For this reason, the addition of extra pilot symbols is allowed, as (contiguous) cyclic extensions of the Unique Word. Figure 5.1 illustrates three cases where pilot symbols have been added: one for a case when only a few symbols have been added, another where the number of added pilot symbols and Unique Word symbols are the same (i.e., the Unique Word has been replicated), and one for a case where the number of pilot symbols is much greater than the number of Unique Word symbols (i.e., where the UW is replicated at least once, then cyclically extended.)

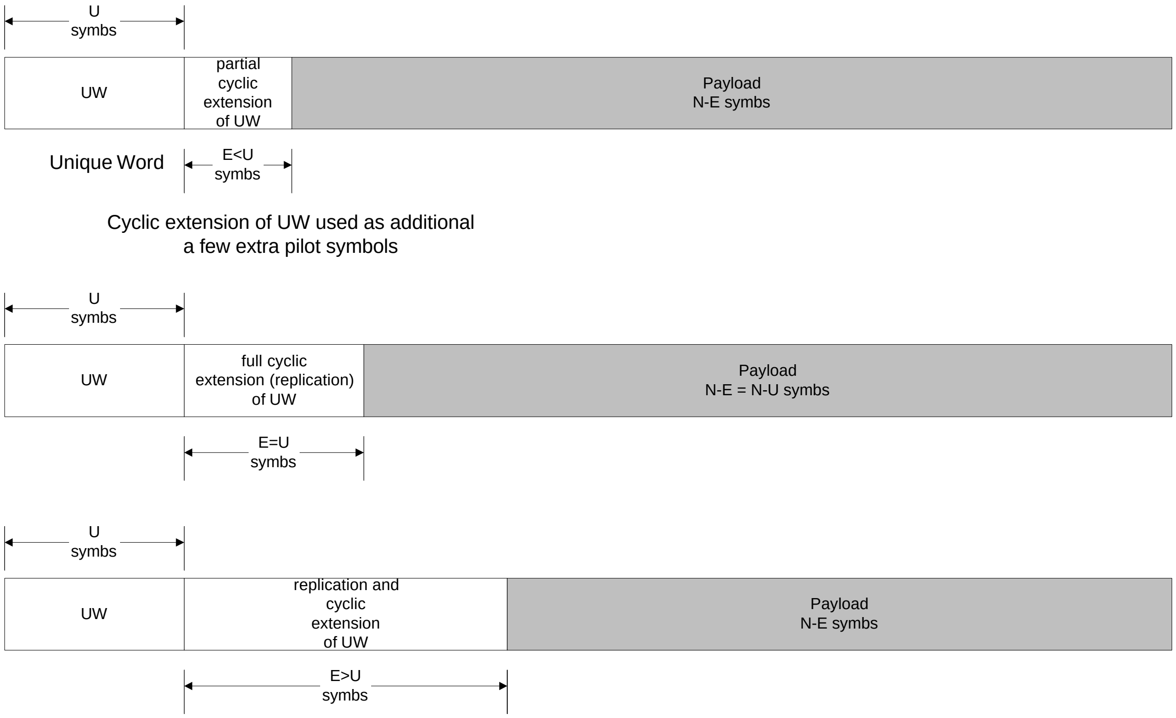


Figure 5.1: Three examples where extra pilot symbols have been added, via cyclic extension of the Unique Word [UW]. (top) pilots symbols less than UW symbols; (middle) pilot symbols equal to UW symbols; (bottom) pilot symbols greater than UW symbols.

5.1.1.3 Burst Transmission Format

A second transmission format is the burst transmission format. As its name suggests, the burst transmission format is utilized for burst transmissions, all of which may or may not be monitored by all SSs within a BS cell sector. In the broadband wireless application, one might see bursts on the (multiple-access) upstream, a TDD upstream and downstream, or a burst-FDD downstream. As described in the MAC/PHY Interface Layer Description, half duplex burst FDD operation is also possible using this format.

Burst transmission supports both TDMA and TDM operation. As Figure 5.1 illustrates, the primary difference between TDM and TDMA operation is that a single TDMA burst only supports one modulation format per burst and, generally, one SS---except in the case of broadcast messages. In contrast, TDM operation multiplexes several users together within a single burst, and may, in fact, duplex upstream and downstream components together on a single carrier in a TDD application. This point is illustrated in Figure 5.3, which depicts a TDD example.

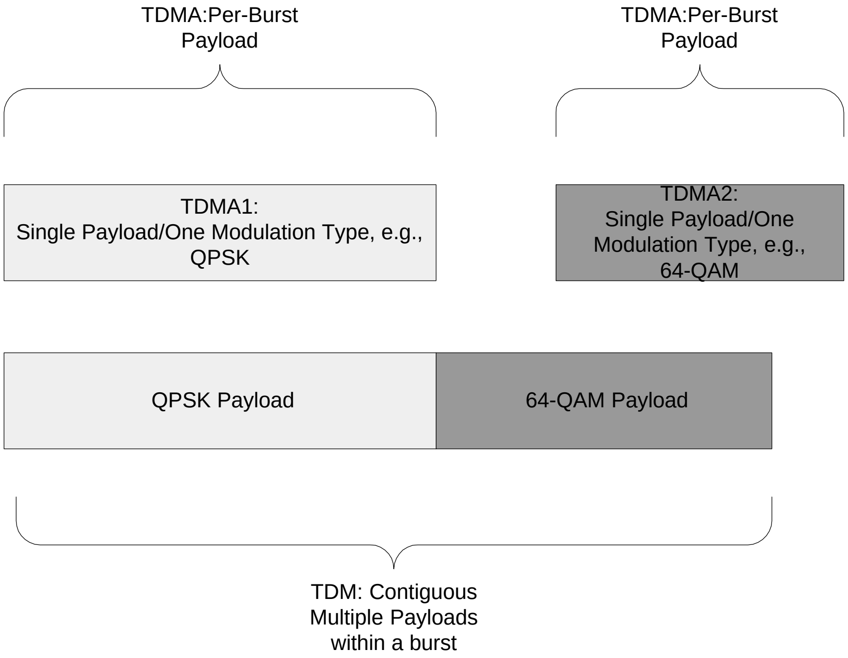


Figure5.2: Comparison of a TDMA and a TDD Burst

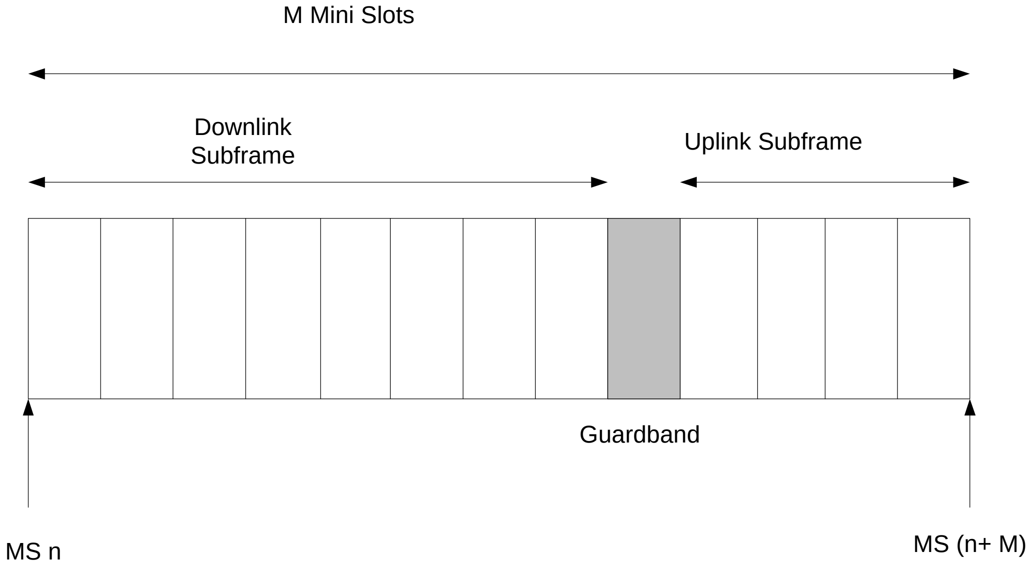


Figure 5.3: Example of a TDD Frame.

5.1.1.3.1 Burst TDMA Operation

As previously indicated, TDMA bursts are bursts targeted at one audience. Since SSs typically only contain one user, burst TDMA is the transmission format for all upstream transmissions. They may also include downstream transmissions in a burst-FDD application with no user concatenation.

The burst TDMA format is illustrated Figure 5.4.

Note that this format is much the same as the continuous format, with the periodic insertion of Unique Words. These Unique Words facilitate frequency domain equalization, and also assist in demodulator parameter estimation and tracking. Unlike the continuous format, however, the burst has a beginning point, and an ending point.

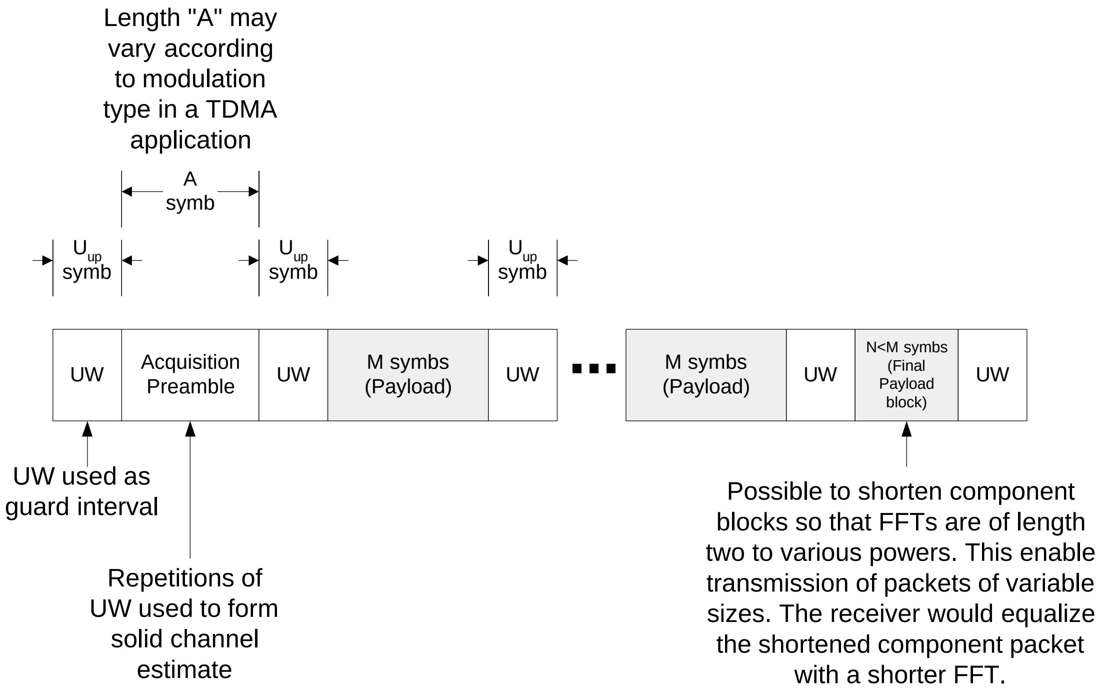


Figure5.4: Block Format for Burst TDMA Transmission.

5.1.1.3.1.1 TDMA Burst Elements

At the head of the burst, is an initial Unique Word. This Unique Word serves primarily as a guard interval. It may be used to ramp up the transmitter. At the receiver it may act as a guard interval for delay spread from another multiple access user, after that user has stopped transmitting. What's more, the receiver may sample the initial part of the Unique Word, and use it to determine which antenna is best to be used in a low-cost antenna switching diversity receiver implementation.

Following the initial Unique Word, is an acquisition preamble. This preamble is used to obtain a good estimate of the channel, and is composed of replicas of the Unique Word.

All subsequent Unique Words are used as cyclic prefixes for frequency domain equalization and/or as pilot symbols for demodulator parameter estimation and tracking.

The frame terminates with a Unique Word following the final payload block. This enables a receiver to apply frequency domain equalization to the final payload block. Note that if extra ramp down symbols are needed, the Unique Word can be cyclically extended.

5.1.1.3.1.2 Variable Burst Sizes

A characteristic of the burst format is that, for efficient operation, it may be necessary to accommodate many different burst sizes. These burst sizes could be different from some integer multiple of the nominal FFT size, $F=M+U_{up}$, of a frequency domain equalizer.

3.3.1.3.1.2.1 Variable Burst Sizes and Frequency Domain Equalizers

Even for implementations using a frequency domain equalizer, the single carrier burst PHY using frequency domain has some flexibility in this regard. For messages intended for a receiver with a frequency domain equalizer, the final payload block can be shortened to the length M_{short}, under the constraints $M_{short}+U_{up} = 2^n$, n is an integer, and $2^n \geq U_{up}$.

Shortened block processing is feasible at the receiver because the same FFT hardware can be reused for FFTs of length 2 to smaller powers. What's more, in at least one channel estimation implementation, the channel (delay spread profile) may be estimated in the time domain, zero-padded to the proper FFT length, and then FFTed to form an interpolated frequency estimate. Since interpolation is generally used for the longer block lengths, and less interpolation is actually used for the shortened block lengths, the only necessity in this application context is that the FFT used by the frequency domain equalizer be at least the length of the temporal channel estimate.

3.3.1.3.1.2.2 Variable Burst Sizes and Time Domain Equalizers

For receivers using time domain equalizers (such as decision feedback equalizers), the shortened length of the last block, M_{short}, can be completely arbitrary, and is only limited by MAC packet length granularity restrictions.

3.3.1.3.1.2.3 Variable Length Negotiation

Exchange of information regarding receiver capabilities during initial registration is one method to ensure that message granularities always conform to a burst receiver's capabilities to process them.

3.3.1.3.1.2.4 Broadcast Messages

Broadcast messages would always be sent assuming a frequency domain equalizer's granularity limitations, since those limitations are more restrictive.

5.1.1.3.1.2.1 Adaptive Modulation

In the TDMA application, only one 'audience' exists for a particular burst message, so no modulation changes occur within the burst. (With the exception of the fact that the pilot symbols and Unique Words may not be derived from the same alphabet as the payload symbols.) However any given burst may have a different modulation type, as directed by a DL_MAP message sent down from the MAC.

5.1.1.3.1.3 Additional Pilot Symbols

To add an extra measure of robustness to transmission, additional pilot symbols, may be added to a TDMA transmission. The additional pilot symbols would be contiguous cyclic extensions of the periodically inserted Unique Words already found in the burst. Figure 5.1 illustrates some examples of how these additional symbols might be added.

A MAC burst profile determines whether or not these additional pilot symbols will be inserted.

5.1.1.3.2 Burst TDM Operation

In addition to TDMA bursts, another type of burst format is accommodated: TDM bursts.
As previously indicated (and illustrated in Figure 5.2), TDM bursts target multi-party audiences, with different payloads addressed to different SSs. What's more, TDM bursts may be bi-directional, as is the case with TDD (see Figure 5.3).

Some applications that use burst TDM are the aforesaid TDD, as well as burst-FDD downstreams, which concatenate packets intended for several SSs together.

5.1.1.3.2.1 Block Format for Burst TDM Transmission

Burst TDM is somewhat an amalgam of the continuous transmission and burst TDMA transmission. The block format is identical to the block format illustrated for TDMA in Figure 5.4.

At the head of the burst, is an initial Unique Word. This Unique Word serves primarily as a guard interval. It may be used to ramp up the transmitter. At the receiver it may act as a guard interval for delay spread from another multiple access user, after that user has stopped transmitting. What's more, the receiver may sample the initial part of the Unique Word, and use it to determine which antenna is best to be used in a low-cost antenna switching diversity receiver implementation.
Following the initial Unique Word, is an acquisition preamble. This preamble is used to obtain a good estimate of the channel, and is composed of replicas of the Unique Word.

All subsequent Unique Words are used as cyclic prefixes for frequency domain equalization and/or as pilot symbols for demodulator parameter estimation and tracking.

The frame terminates with a Unique Word following the final payload block. By so terminating the block, a receiver may frequency domain equalization on the final payload block. Note that if extra ramp down symbols is needed, the Unique Word can be cyclically extended.

5.1.1.3.2.2 Variable Burst Sizes

A characteristic of the burst format is that, for efficient operation, it may be necessary to accommodate many different burst sizes. These burst sizes could be different from some integer multiple of the nominal FFT size, $F=M+U_{up}$, of a frequency domain equalizer.

3.3.1.3.3.2.1 Variable Burst Sizes and Frequency Domain Equalizers

Even for implementations using a frequency domain equalizer, the single carrier burst PHY using frequency domain has some flexibility in this regard. For messages intended for a group of receivers with a frequency domain equalizer, the final payload block can be shortened to the length M_{short}, under the constraints $M_{short}+U_{up} = 2^n$, n is an integer, and $2^n \geq U_{up}$.

3.3.1.3.3.2.2 Variable Burst Sizes and Time Domain Equalizers

For groups of receivers using time domain equalizers (such as decision feedback equalizers), the shortened length of the last block, M_{short}, can be completely arbitrary, and is only limited by MAC packet length granularity restrictions.

3.3.1.3.3.2.3 Variable Burst Length Negotiation

Exchange of information regarding receiver capabilities during initial registration is one method to ensure that message granularities always conform to a burst receiver's capabilities to process them. If any one receiver in a TDM group is incapable of equalizing arbitrary block sizes, the frequency domain equalizer block size restrictions are enforced, since they are more restrictive. Burst profiles derived from the MAC designate the format of transmitted blocks

5.1.1.3.2.3 Adaptive Modulation

In the TDM application, several payloads are borne, and addressed to destinations. Due to differing propagation conditions, the destination receivers may observe significantly different SNRs. For this reason, some receivers may be capable of reliably detecting (non-pilot) data only when it is derived from certain lower-order modulation alphabets, such as QPSK. Similarly, SNR-disadvantaged receivers may require more powerful and redundant FEC schemes. On the other hand, SNR-advantaged stations may be capable of receiving very high order modulations (e.g., 64-QAM), with high code rates. Obviously, to maximize the overall capacity of the system, the modulation and coding format should be adapted to each class of receiver, based on what the receiver can reliability decode. Define the adaptation of modulation type and FEC to a particular SS (or group of SSs) as 'adaptive modulation', and the choice of a particular modulation and FEC as an 'adaptive modulation type.' The continuous transmission mode (as does the burst transmission mode) supports adaptive modulation and the use of adaptive modulation types.

3.3.1.3.3.3.1 Frame Control Header Information

Frame Control MAC messages are periodically transmitted, using the most robust supported adaptive modulation type. These Frame Control headers provide adaptive modulation type formatting instructions for TDM bursts which follow.

3.3.1.3.3.3.2 Adaptive Modulation Sequencing

Following DL_MAP instructions, payload groups are sequenced in increasing order of robustness (e.g., first QPSK, then 16-QAM, then 64-QAM) within a packet. This improves the receiver performance, because this forces them to track only the modulation types that they can reliably receive. This also facilitates changes of modulation type at locations that are contiguous to Unique Word boundaries.

3.3.1.3.3.3.3 UW Boundary-free Transitions Between Modulation Types

Note also that adaptive modulation type-to-other-modulation type changes are not restricted to occur only at Unique Word boundaries. They may change anywhere that the DL_MAP message indicates that they should change.

3.3.1.3.3.3.4 Per-Adaptive Modulation Type FEC Encapsulation

So that disadvantaged-SNR SSs are not adversely affected by transmissions intended for other advantaged-SNR users, FEC blocks always end when a particular adaptive modulation type ends. Among other things, this implies that the FEC interleaver depth and code blocks are adapted to accommodate the span of a particular adaptive modulation type. Depending on the burst profile, these bursts may terminate earlier, on an addressee-by-addressee basis.

5.1.1.3.2.4 Additional Pilot Symbols

To add an extra measure of robustness to transmission, additional pilot symbols, may be added to a TDMA transmission. The additional pilot symbols would be contiguous cyclic extensions of the periodically inserted Unique Words already found in the burst. Figure 5.1 illustrates some examples of how these additional symbols might be added.

5.2 MAC and PHY Interface Layer

5.2.1 Overview

Two modes of operation have been defined for the point-to-multi-point downlink channel:

- One targeted to support a **Continuous transmission** stream format, and
- One targeted to support a **Burst transmission** stream format.

Having this separation allows each format to be optimized according to its respective design constraints, while resulting in a standard that supports various system requirements and deployment scenarios.

In contrast, only one mode of operation is defined for the **Upstream channel**:

- One targeted to support a **Burst transmission** stream format.

This single mode of operation is sufficient for the upstream, since the upstream transmissions are point-to-point burst transmissions between each transmitting Subscriber Station (SS) and each receiving Base Station (BS).

5.2.1.1.1 Downlink and Uplink Operation

Two different downlink modes of operation are defined: Mode A and Mode B. Mode A supports a continuous transmission format, while Mode B supports a burst transmission format. The continuous transmission format of Mode A is intended for use in an FDD-only configuration. The burst transmission format of Mode B supports burst-FDD as well as TDD configurations.

The Mode A and B options give service providers choice, so that they may tailor an installation to best meet a specific set of system requirements. Standards-compliant subscriber stations are required to support at least one (Mode A or Mode B) of the defined downlink modes of operation.

A single uplink mode of operation is also defined. This mode supports TDMA-based burst uplink transmissions. Standards-compliant subscriber stations are required to support this uplink mode of operation.

5.2.1.1.1.1.1 Mode A (Continuous Downlink)

Mode A is a downlink format intended for continuous transmission. The Mode A downlink physical layer first encapsulates MAC packets into a convergence layer frame as defined by the transmission convergence sublayer. Modulation and coding which is adaptive to the needs of various SS receivers is also supported within this framework.

Data bits derived from the transmission convergence layer are first randomized. Next, they are block FEC encoded. The resulting FEC-encoded bits are mapped to QPSK, 16-QAM, or 64-QAM signal constellations. Detailed descriptions of the FEC, modulation constellations, and symbol mapping formats can be found within the FEC and modulation sections. Following the symbol mapping process, the resulting symbols are modulated, and then transmitted over the channel.

In Mode A, the downstream channel is continuously received by many SSs. Due to differing conditions at the various SS sites (e.g., variable distances from the BS, presence of obstructions), SS receivers may observe significantly different SNRs. For this reason, some SSs may be capable of reliably detecting data only when it is derived from certain lower-order modulation alphabets, such as QPSK. Similarly, more powerful and redundant FEC schemes may also be required by such SNR-disadvantaged SSs. On the other hand, SNR-advantaged stations may be capable of receiving very high order modulations (e.g., 64-QAM) with high code rates. Collectively, let us define the adaptation of modulation type and FEC to a particular SS (or group of SSs) as 'adaptive modulation', and the choice of a particular modulation and FEC as an 'adaptive modulation type.' Mode A supports adaptive modulation and the use of adaptive modulation types.

A MAC Frame Control header is periodically transmitted over the continuous Mode A downstream, using the most robust supported adaptive modulation type. So that the start of this MAC header may be easily recognized during initial channel acquisition or re-acqusition, the PHY inserts an uncoded, TBD (but known) QPSK code word, of length TBD symbols, at a location immediately before the beginning of the MAC header, and immediately after a Unique Word. (See PHY framing section for more details on the Unique Word). Note that this implies the interval between Frame Control headers should be an integer multiple of F (the interval between Unique Words).

Within MAC Frame Control header, a PHY control map (DL_MAP) is used to indicate the beginning location of adaptive modulation type groups which follow. Following this header, adaptive modulation groups are sequenced in increasing order of robustness.
However, the DL_MAP does not describe the beginning locations of the payload groups that immediately follow; it describes the payload distributions some MAC-prescribed time in the future. This delay is necessary so that FEC decoding of MAC information (which could be iterative, in the case of turbo codes) may be completed, the adaptive data interpreted, and the demodulator scheduling set up for the proper sequencing.

Note that adaptive modulation groups or group memberships can change with time, in order to adjust to changing channel conditions.

In order that disadvantaged SNR users are not adversely affected by transmissions intended for other advantaged SNR users, FEC blocks end when a particular adaptive modulation type ends. Among other things, this implies that the FEC interleaver depth is adapted to accommodate the span of a particular adaptive modulation type.

5.2.1.1.1.2 Mode B (Burst Downlink)

Mode B in a downlink format intended for burst transmissions, with features that simplify the support for both TDD systems and half-duplex terminals. A Mode B compliant frame can be configured to support either TDM or TDMA transmission formats; i.e., a Mode B burst may consist a single user's data, or a concatenation of several users' data. What's more, Mode B supports adaptive modulation and multiple adaptive modulation types within these TDMA and TDM formats.

A unique (acquisition) preamble is used to indicate the beginning of a frame, and assist burst demodulation. This preamble is followed by PHY/MAC control data. In the TDM mode, a PHY control map (DL_MAP) is used to indicate the beginning location of different adaptive modulation types. These adaptive modulation types are sequenced within the frame in increasing order of robustness (e.g., QPSK, 16-QAM, 64-QAM), and can change with time in order to adjust to the changing channel conditions.

In the TDMA mode, the DL_MAP is used to describe the adaptive modulation type in individual bursts. Since a TDMA burst would contain a payload of only one adaptive modulation type, no adaptive modulation type sequencing is required. All TDMA format payload data is FEC block encoded, with an allowance made for shortening the last codeword (e.g., Reed Solomon codeword) within a burst.

The Mode B downlink physical layer goes through a transmission convergence sublayer that inserts a pointer byte at the beginning of the payload information bytes to help the receiver identify the beginning of a MAC packet.

Payload data bits coming from the transmission convergence layer are first randomized. Next, they are block FEC encoded. The resulting FEC-encoded bits are mapped to QPSK, 16-QAM, or 64-QAM signal constellations. Detailed descriptions of the FEC, modulation constellations, and symbol mapping formats can be found within the FEC and modulation sections. Following the symbol mapping process, the resulting symbols are modulated, and then transmitted over the channel.

5.2.1.1.1.3 Uplink Access

The uplink mode supports TDMA burst transmissions from an individual SSs to a BS. This is functionally similar (at the PHY level) to Mode B downlink TDMA operation. As such, for a brief description of the Physical Layer protocol used for this mode, please read the previous section on Mode B TDMA operation.

Of note, however, is that many of the specific uplink channel parameters can be programmed by MAC layer messaging coming from the base station in downstream messages. Also, several parameters can be left unspecified and configured by the base station during the registration process in order to optimize performance for a particular deployment scenario. In the upstream mode of operation, each burst may carry MAC messages of variable lengths.

5.2.1.2 Multiplexing and Multiple Access Technique

The uplink physical layer is based on the combined use of time division multiple access (TDMA) and demand assigned multiple access (DAMA). In particular, the uplink channel is divided into a number of 'time slots.' The number of slots assigned for various uses (registration, contention, guard, or user traffic) is controlled by the MAC layer in the base station and can vary over time for optimal performance.

As previously indicated, the downlink channel can be in either a continuous (Mode A) or burst (Mode B) format. Within Mode A, user data is transported via time division multiplexing (TDM), i.e., 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. Within Mode B, the user data is bursty and may be transported via TDM or TDMA, depending on the number of users that are to be borne within the burst.

5.2.1.2.1 Duplexing Techniques

Several duplexing techniques are supported, in order to provide greater flexibility in spectrum usage. The continuous transmission downlink mode (Mode A) supports Frequency Division Duplexing (FDD) with adaptive modulation; the burst mode of operation (Mode B) supports FDD with adaptive modulation or Time Division Duplexing (TDD) with adaptive modulation. Furthermore, Mode B in the FDD case can handle (half duplex) subscribers incapable of transmitting and receiving at the same instant, due to their specific transceiver implementation.

5.2.1.2.1.1 Mode A: Continuous Downstream for FDD Systems

In a system employing FDD, the uplink and downlink channels are located on separate frequencies and all subscriber stations can transmit and receive simultaneously. The frequency separation between carriers is set either according to the target spectrum regulations or to some value sufficient for complying with radio channel transmit/receive isolation and de-sensitization requirements. In this type of system, the downlink channel is (almost) “always on” and all subscriber stations are always listening to it. Therefore, traffic is sent in a broadcast manner using time division multiplexing (TDM) in the downlink channel, while the uplink channel is shared using time division multiple access (TDMA), where the allocation of uplink bandwidth is controlled by a centralized scheduler. The BS periodically transmits downlink and uplink MAP messages, which are used to synchronize the uplink burst transmissions with the downlink. The usage of the mini-slots is defined by the UL-MAP message, and can change according to the needs of the system. Mode A is capable of adaptive modulation.

5.2.1.2.1.2 Mode B: Burst Downstream for Burst FDD Systems

A burst FDD system refers to a system in which the uplink and downlink channels are located on separate frequencies but the downlink data is transmitted in bursts. This feature enables the system to simultaneously support full duplex subscriber stations (ones which can transmit and receive simultaneously) and, optionally, half duplex Subscriber Stations (ones which cannot transmit and receive simultaneously). If half duplex subscriber stations are supported, this mode of operation imposes a restriction on the bandwidth controller: it cannot allocate uplink bandwidth for a half duplex subscriber station at the same time that the subscriber station is expected to receive data on the downlink channel.

Figure 5.6 illustrates the basics of the burst FDD mode of operation. In order to simplify the bandwidth allocation algorithms, the uplink and downlink channels are divided into fixed sized frames. A full duplex subscriber station must always attempt to listen to the downlink channel. A half duplex subscriber station must always attempt to listen to the downlink channel when it is not transmitting on the uplink channel.

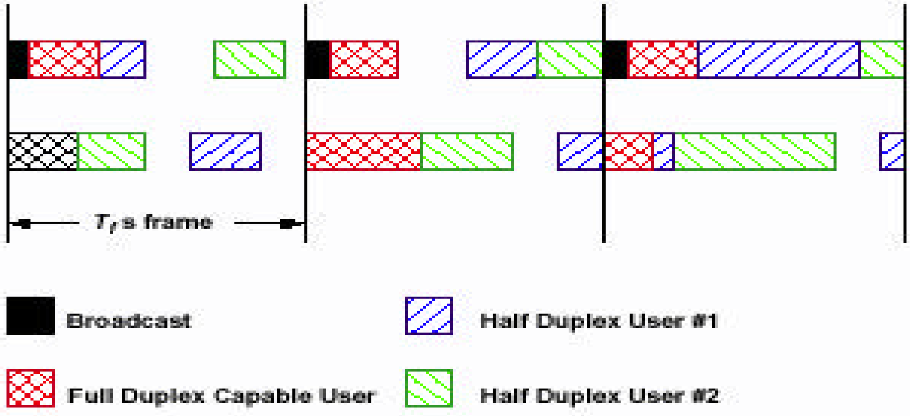


Figure 139—Example of Burst FDD Bandwidth Allocation

Figure 5.6:: Example of Burst FDD bandwidth Allocation.

5.2.1.2.1.2.1 Mode B: Burst Downstream for Time Division Duplexing (TDD) Systems

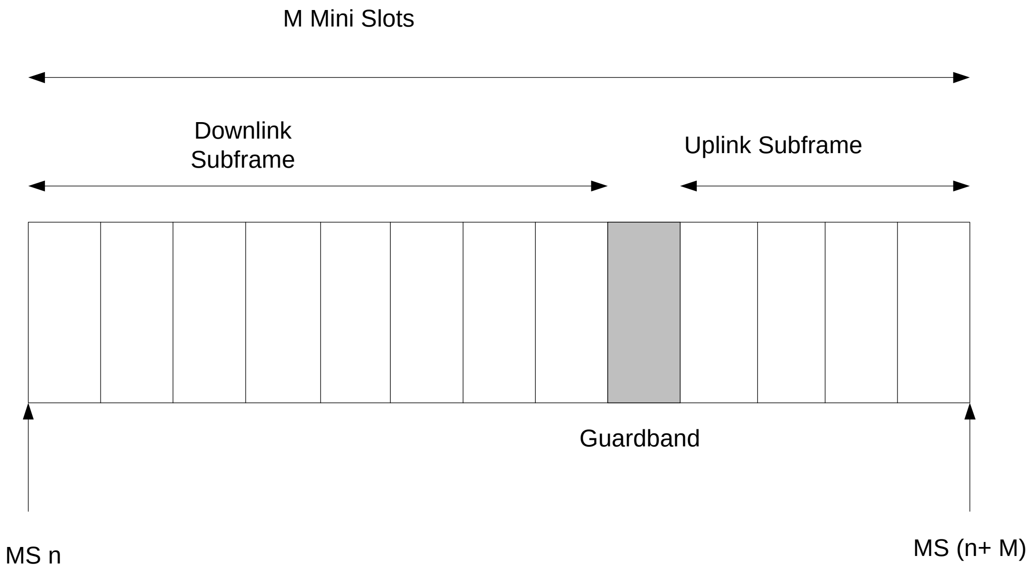


Figure 5.7: TDD Frame Structure

In the case of TDD, the uplink and downlink transmissions share the same frequency, but are separated in time (Figure 5.7). A TDD frame also has a fixed duration and contains one downlink and one uplink subframe. The frame is divided into an integer number of 'mini slots' (MS), which facilitate the partitioning of bandwidth. These mini slots are in turn made up of a finer unit of time called 'ticks', which are of duration 1 us each. TDD framing is adaptive in that the percentage of the bandwidth allocated to the downlink versus the uplink can vary. The split between uplink and downlink is a system parameter, and is controlled at higher layers within the system.

3.3.2.2.1.3.1 Tx /Rx Transition Gap (TTG)

The TTG is a gap between the Downlink burst and the Uplink burst within a TDD system. The TTG allows time for the BS to switch from transmit mode to receive mode and SSs to switch from receive mode to transmit mode. During this interval, the BS and SS do not transmit modulated data. Therefore, the BS transmitter may ramp down, Tx / Rx antenna switches on both sides may actuate, the SS transmitter may ramp up, and the BS receiver section may activate. After the TTG, the BS receiver will look for the first symbols of uplink burst. The TTG has a variable duration, which is an integer number of mini slots. The TTG starts on a mini slot boundary.

3.3.2.2.1.3.2 Rx /Tx Transition Gap (RTG)

The RTG is a gap between the Uplink burst and the Downlink burst. The RTG allows time for the BS to switch from receive mode to transmit mode, and SSs to switch from transmit mode to receive mode. During this interval, the BS and SS do not transmit modulated data. Therefore, an SS transmitter may ramp down, delay spread may clear the BS receiver, the Tx / Rx antenna switch to actuate on both links, the BS transmitter may ramp up, and the SS receiver sections may activate. After the RTG, the SS receivers will look for the first symbols of modulated acquisition sequence data in the downlink burst. The RTG is an integer number of mini slots. The RTG starts on a mini slot boundary.

5.2.1.2.1.3 Mode B: Downlink Data

The downlink data sections are used for transmitting data and control messages to specific SSs. This data is always FEC coded and is transmitted at the current operating modulation of the individual SS. In the burst mode cases, data is transmitted in robustness order in the TDM portion. In a burst TDMA application, the data is grouped into separately delineated bursts, which do not need to be in modulation order. The DL-MAP message contains a map stating at which mini slot the burst profile change occurs. If the downlink data does not fill the entire downlink sub-frame and Mode B is in use, the transmitter is shut down. The DL-MAP provides implicit indication of shortened FEC (and/or FFT) blocks in the downlink. Shortening the last FEC block of a burst is optional. The downlink map indicates the number of MS, *p* allocated to a particular burst and also indicates the burst type (modulation

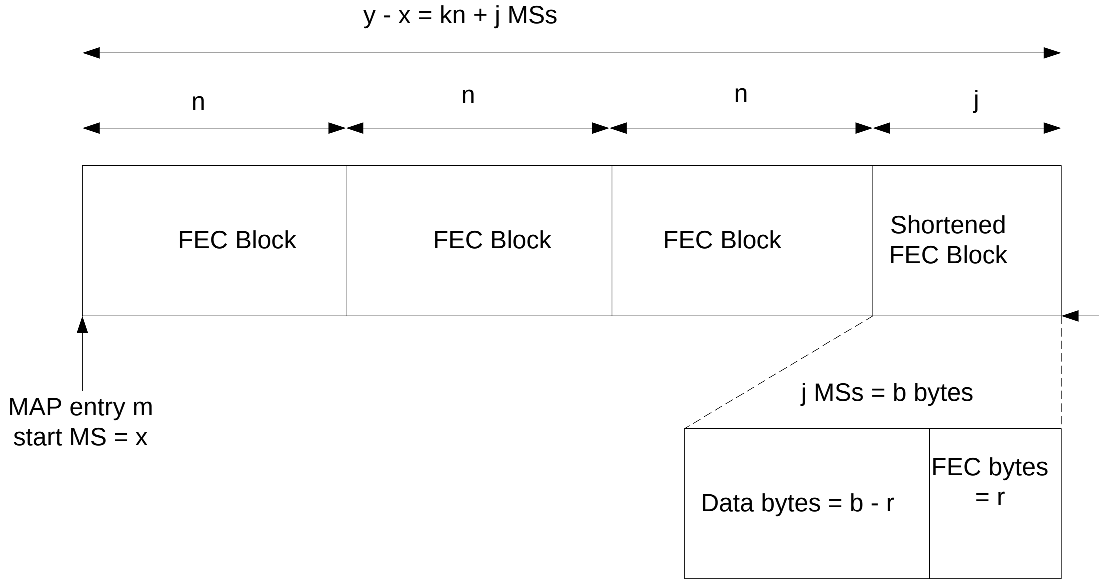


Figure 5.8: Downlink MAP usage and Shortened FEC Blocks

and FEC). Let *n* denote the number of MS required for one FEC block of the given burst profile. Then, *p= kn + j*, where *k* is the number of integral FEC blocks that fit in the burst and *j* is the number of MS remaining after integral FEC blocks are allocated. Either *k* or *j*, but not both, may be zero. *j* denotes some number of bytes b. Assuming *j* is not 0, it must be large enough such that *b* is larger than the number of FEC bytes *r*, added by the FEC scheme for the burst. The number of bytes available to user data in the shortened FEC block is *b - r*. These points are illustrated in Figure 5.8. Note that a codeword may not possess less than 6 information bytes.

In the TDM mode of operation, SSs listen to all portions of the downlink burst to which they are capable of listening. For full-duplex SSs, this implies that a SS shall listen to all portions that have a adaptive modulation type (as defined by the DIUC) which is at least as robust as that which the SS negotiates with the BS. For half-duplex SSs, the aforesaid is also true, but under an additional condition: an SS shall not attempt to listen to portions of the downlink burst that are coincident---adjusted by the SS's Tx time advance---with the SS's allocated uplink transmission, if any.

In the burst TDMA mode of operation, bursts are individually identified in the DL_MAP. Hence, a SS is required to turn on its receiver only in time to receive those bursts addressed to it. Unlike the TDM mode, there is no requirement that the bursts be ordered in order of increasing robustness.

5.2.1.2.2 Uplink Burst Subframe Structure

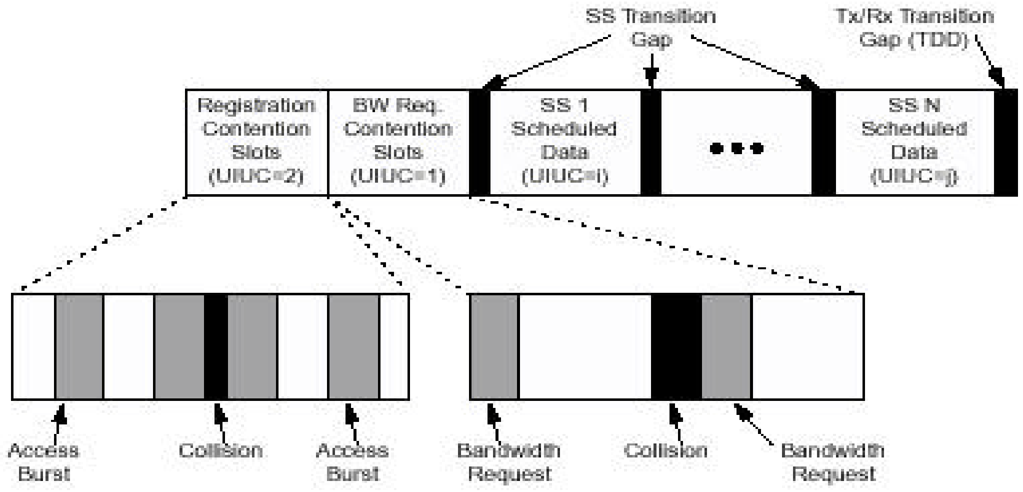


Figure 5.9: Uplink Sunframe Structure.

The structure of an uplink subframe used by SSs to transmit with a BS is shown in Figure 5.9. Three main classes of bursts are transmitted by SSs during an uplink subframe:

a) Those that are transmitted in contention slots reserved for station registration.
b) Those that are transmitted in contention slots reserved for response to multicast and broadcast polls for bandwidth needs.
c) Those that are transmitted in bandwidth specifically allocated to individual SSs.

5.2.1.2.2.1 Mode A and Mode B: Uplink Burst Profile Modes

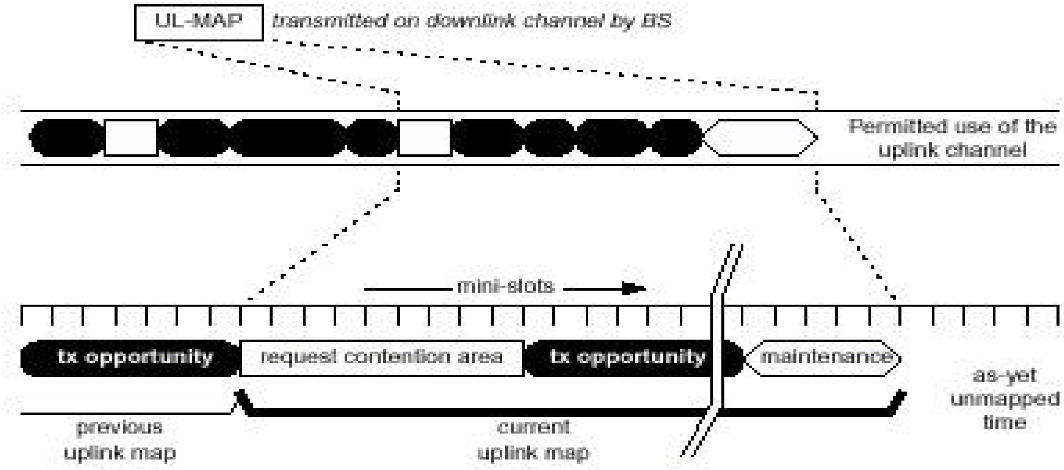


Figure 5.10: Uplink Mapping in the Contiuous Downstream FDD Case.

The uplink uses adaptive burst profiles, in which the base station assigns different modulation types to different SSs. In the adaptive case, the bandwidth allocated for registration and request contention slots is grouped together and is always used with the parameters specified for Request Intevals (UIUC=1). (Remark: It is recommended that UIUC=1 will provide the most robust burst profile due to the extreme link budget and interference conditions of this case). The remaining transmission slots are grouped by SS. During its scheduled allocation, an SS transmits with the burst profile specified by the base station. Considerations which may influence this specification include the effects of distance, interference and environmental factors on transmission to and from that SS. SS Transition Gaps (STG) separate the transmissions of the various SSs during the uplink subframe. The STGs contain a gap to allow for ramping down of the previous burst, followed by a preamble allowing the BS to synchronize to the new SS. The preamble and gap lengths are broadcast periodically in a UCD message. Shortening of FEC and/or FFT blocks in the uplink is identical to the handling in the downlink, as described in 3.3.2.1.4.

5.2.2 Downlink Modes of Operation

This section describes the two different downlink modes of operation that have been adopted for use in this proposal. Mode A has been designed for continuous transmission formats, while Mode B has been designed to support burst transmission formats. Subscriber stations must support at least one of these downlink modes.

5.2.2.1.1 Physical layer type (PHY type) encodings

The value of of the PHY type parameter as defined must be reported as shown in Table 3.3.

Table5.2: Mode Selection Parameters.

Mode	Value	Comment
Mode B (TDD)	0	Burst Downlink in TDD Mode
Mode B (FDD)	1	Burst Downlink in FDD Mode
Mode A (FDD)	2	Continuous Downlink

5.2.2.1.2 Mode A: Continuous Downlink Transmission

This mode of operation has been designed for a continuous transmission stream in a FDD system. The physical media dependent sublayer has no explicit frame structure, other than the incorporation of regular pilot symbols. Adaptive modulation and multiple adaptive modulation types are supported.

5.2.2.1.3 Downlink Mode A: Message field definitions

5.2.2.1.3.1 Downlink Mode A: Required channel descriptor parameters

The following parameters shall be included in the UCD message:

TBD

5.2.2.1.3.2 Mode A:Required DCD parameters

The following parameters shall be included in the DCD message:

TBD

3.3.2.4.3.3.1 Downlink Mode A: DCD, Required burst descriptor parameters

TBD

5.2.2.1.3.2.1 Mode A: DL-MAP

For PHY Type = 2, a number of information elements follows the Base Station ID field. The MAP information elements must be in time order. Note that this is not necessarily IUC order or connection ID order.

3.3.2.4.3.3.1 Mode A: DL-MAP PHY Synchronization Field definition

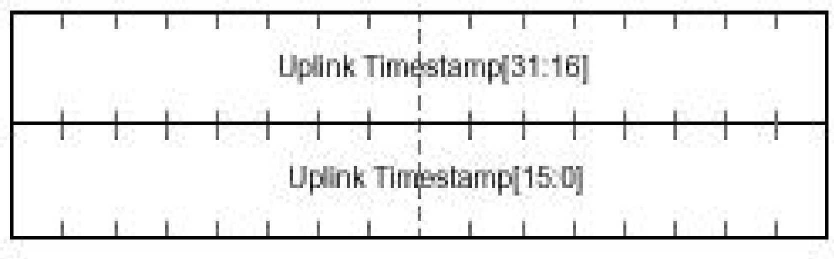


Figure 5.11: PHY Synchronization Field (PHY Type 2).

The format of the PHY Synchronization field is given in Figure 5.11. The Uplink Timestamp jitter must be less than 500 ns peak-to-peak at the output of the Downlink Transmission Convergence Sublayer. This jitter is relative to an ideal Downlink Transmission Convergence Sublayer that transfers the TC packet data to the Downlink Physical Media Dependent Sublayer with a perfectly continuous and smooth clock at symbol rate. Downlink Physical Media Dependent Sublayer processing shall not be considered in timestamp generation and transfer to the Downlink Physical Media Dependent Sub-layer. Thus, any two timestamps N1 and N2 (N2 > N1) which were transferred to the Downlink Physical Media Dependent Sublayer at times T1 and T2 respectively must satisfy the following relationship:

$$(N2 - N1)/(4 \times \text{Symbol Rate}) - (T2 - T1) < 500 \text{ ns}.$$

The jitter includes inaccuracy in timestamp value and the jitter in all clocks. The 500ns allocated for jitter at the Downlink Transmission Convergence Sublayer output must be reduced by any jitter that is introduced by the Downlink Physical Media Dependent Sublayer.

5.2.2.1.3.3 Mode A: UL-MAP Allocation Start Time definition

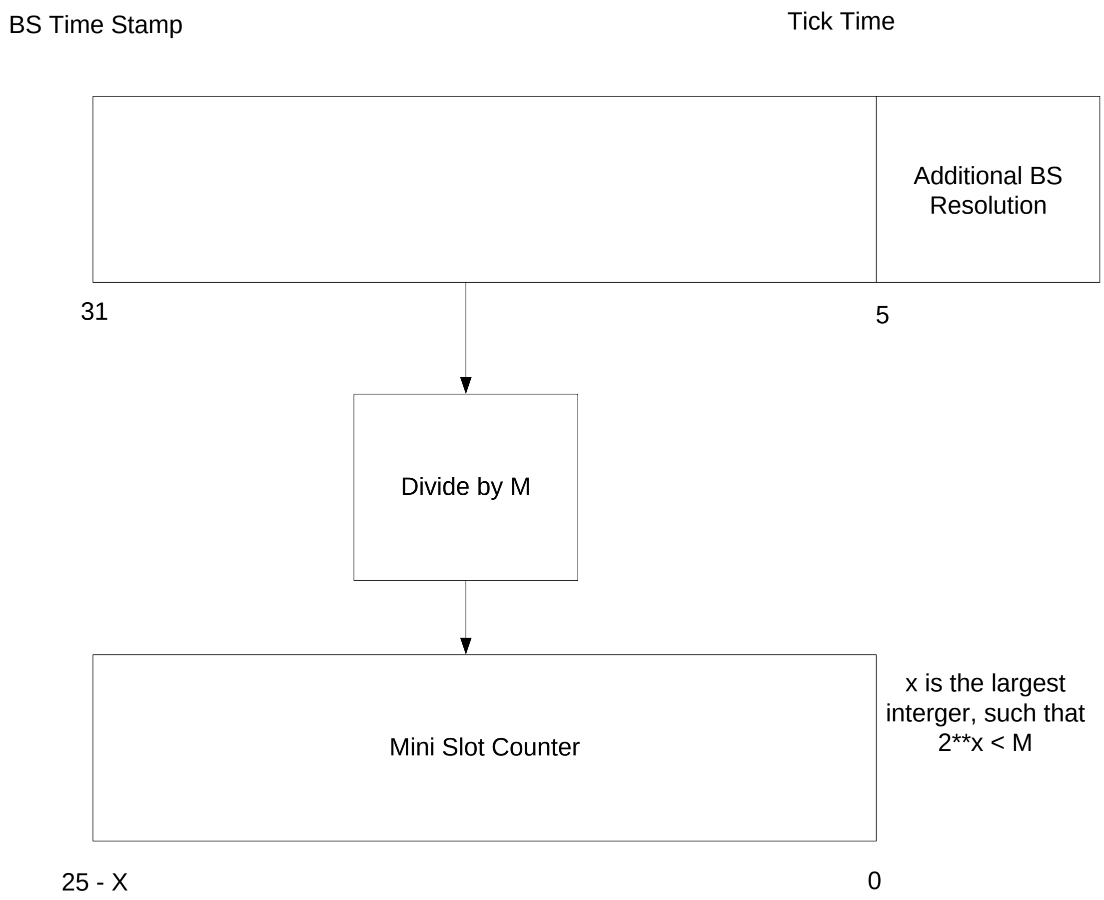


Figure 5.12: Maintained Time Stamp Relation between the BS to the BS Mini-slot Counters.

The Alloc Start Time is the effective start time of the uplink allocation defined by the UL-MAP or DL_MAP in units of mini-slots. The start time is relative to the time of BS initialization (PHY Type = 5). The UL-MAP/DL_MAP Allocation Start Time is given as an offset to the Time Stamp defined in 3.3.4.3.3.1. Figure 5.12 illustrates the relation of the Time Stamp maintained in the BS to the BS Mini-slot Counter. The base time unit is called a tick and is of duration 1 us, independent of the symbol rate, and is counted using a 26 bit counter. The additional BS resolution is of duration (1 tick/ 64) = 15.625 ns. The Mini-Slot count is derived from the tick count by means of a divide by M operation. Note that the **divisor M is not necessarily a power of 2**.

For arbitrary symbol rates, the main constraint in the definition of a mini slot, is that the number of symbols per mini slot be an integer. For example given a symbol rate of R Symbols/tick, and M ticks/mini-slot, the number of symbols per mini-slot N, is given by N = M*R. In this situation, M should be chosen such that N is an integer. In order to accommodate a wide range of symbol rates, it is important not to constrain M to be a power of 2. Since the additional BS resolution is independent of the symbol rate, the system can use an uniform time reference for distance ranging.

In order to show that the time base is applicable to single carrier and OFDM symbol rates, consider the following examples: (a) Single Carrier System - Given a symbol rate of 4.8 Msymbols/s (on a 6MHz channel), if the mini-slot duration is chosen to be 10 ticks (i.e., M = 10), then there are 48 symbols/mini-slot. Given 16QAM modulation this corresponds to a granularity of 24 bytes/mini-slot (b) OFDM System - Given an OFDM symbol

-slot duration is also chosen to be 50 ticks (i.e., M = 50). In this case there is only a single OFDM symbol per mini-slot.

5.2.2.1.3.4 UL-MAP Ack Time definition

The Ack Time is the latest time processed in uplink in units of mini-slots. This time is used by the SS for collision detection purposes. The Ack Time is given relative to the BS initialization time.

5.2.2.1.4 Mode B: Burst Downlink Transmission

Mode B supports burst transmission on the downlink channel. In particular, this mode is applicable for systems using TDD, which requires a burst capability in the downlink channel. In order to simplify phase recovery and channel tracking, a fixed frame time is used. At the beginning of every frame, an acquisition sequence/preamble is transmitted in order to allow for phase recovery and equalization training. A description of the framing mechanism and the structure of the frame is further described in 3.3.2.4.5.1.

5.2.2.1.4.1.1 Mode B: Downlink Framing

In the burst mode, the uplink and downlink can be multiplexed in a TDD fashion as described in subsection 3.3.2.2.1.3, or in an FDD fashion as described in 3.3.2.1.2. Each method uses a frame with duration as specified in subsection 3.3.2.5.1. Within this frame are a downlink subframe and an uplink subframe. In the TDD case, the downlink subframe comes first, followed by the uplink subframe. In the burst FDD case, uplink transmissions occur during the downlink frame. In both cases, the downlink subframe is prefixed with information necessary for frame synchronization.

The available bandwidth in both directions is defined with a granularity of one mini slot (MS). The number of mini slots within each frame is independent of the symbol rate. The frame size is selected in order to obtain an integral number of MS within each frame. For example, with a 10 us MS duration, there are 500 MS within a 5-ms frame, independent of the symbol rate.

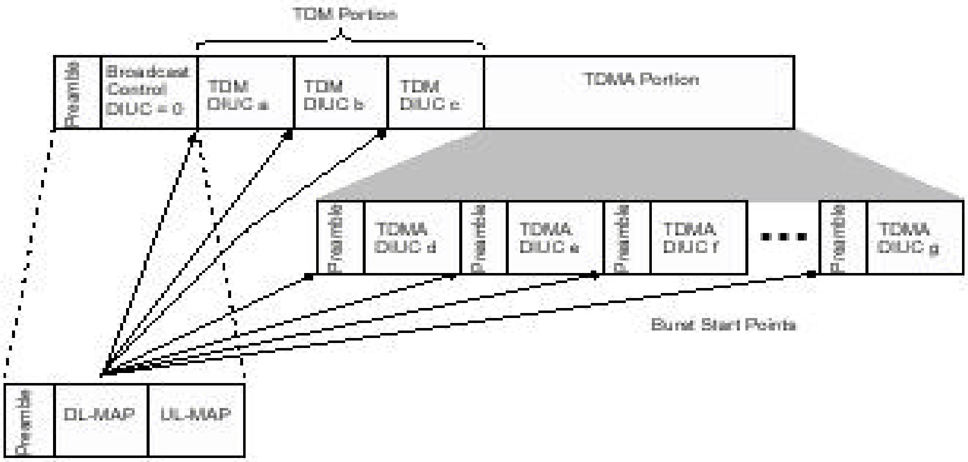


Figure 5.13: Mode B Downlink Subframe Structure.

The structure of the downlink subframe used by the BS to transmit to the SSs, using Mode B, is shown in Figure 5.13. This burst structure defines the downlink physical channel. It starts with a Frame Control Header, that is always transmitted using the most robust set of PHY parameters. This frame header contains a preamble used by the PHY for synchronization and equalization. It also contains control sections for both the PHY and the MAC (DL_MAP and UL_MAP control messages) that is encoded with a fixed FEC scheme defined in this standard in order to ensure interoperability. The Frame Control Header also may periodically contain PHY Parameters as defined in the DCD and UCD.

There are two ways in which the downstream data may be organized for Mode B systems:

- Transmissions may be organized into different modulation and FEC groups, where the modulation type and FEC parameters are defined through MAC layer messaging. The PHY Control portion of the Frame Control Header contains a downlink map stating the MSs at which the different modulation/FEC groups begin. Data should be transmitted in robustness order. For modulations this means QPSK followed by 16-QAM, followed by 64-QAM. If more than 1 FEC is defined (via DCD messages) for a given modulation, the more robust FEC / modulation combination appears first. Each SS receives and decodes the control information of the downstream and looks for MAC headers indicating data for that SS.
- Alternatively, transmissions need not be ordered by robustness. The PHY control portion contains a downlink map stating the MS (and modulation / FEC) of each of the TDMA sub-bursts. This allows an individual SS to decode a specific portion of the downlink without the need to decode the whole DS burst. In this particular case, each transmission associated with different burst types is required to start with a short preamble for phase re-synchronization.

There is a Tx / Rx Transition Gap (TTG) separating the downlink subframe from the uplink subframe in the case of TDD.

5.2.2.1.4.1.2 Frame Control

The first portion of the downlink frame is used for control information destined for all SS. This control information must not be encrypted. The information transmitted in this section is always transmitted using the well known DL Burst Type with UIUC=0. This control section must contain a DL-MAP message for the channel followed by one UL-MAP message for each associated uplink channel. In addition it may contain DCD and UCD messages following the last UL-MAP message. No other messages may be sent in the PHY/MAC Control portion of the frame.

5.2.2.1.4.2 Downlink Mode B: Required DCD parameters

TBD

3.3.2.4.5.3.1 Downlink Mode B: DCD, Required burst descriptor parameters

TBD

5.2.2.1.4.3 Downlink Mode B: Required UCD parameters

TBD

5.2.2.1.4.4 Downlink Mode B: DL-MAP elements

For PHY Type = {0, 1}, a number of information elements follows the Base Station ID field. The MAP information elements must be in time order. Note that this is not necessarily IUC order or connection ID order.

5.2.2.1.4.4.1 Allowable frame times

Table 3.3 indicates the various frame times that are allowed for the current downlink Mode B physical layer. The actual frame time used by the downlink channel can be determined by the periodicity of the frame start preambles.

Table 3.3 - Allowable Frame Times

Frame Length Code	Frame Time	Units
0x01	0.5	ms
0x02	1.0	ms
0x03	1.5	ms
0x04	2.0	ms
0x05	2.5	ms
ox06	3.0	ms
0x07	3.5	ms
0x08	4.0	ms
0x09	4.5	ms
0x0A	5.0	ms

3.3.2.4.3.3.1 Mode B: DL-MAP PHY Synchronization Field definition

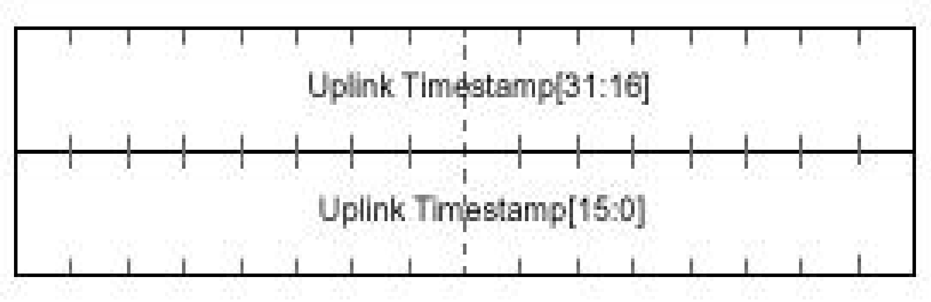


Figure 5.14: PHY Synchronization Field (PHY Type = {0,1})

The format of the PHY Synchronization field is given in Figure 5.14 . The Uplink Timestamp jitter must be less than 500 ns peak-to-peak at the output of the Downlink Transmission Convergence Sublayer. This jitter is relative to an ideal Downlink Transmission Convergence Sublayer that transfers the TC packet data to the Downlink Physical Media Dependent Sublayer with a perfectly continuous and smooth clock at symbol rate. Downlink Physical Media Dependent Sublayer processing shall not be considered in timestamp generation and transfer to the Downlink Physical Media Dependent Sub-layer. Thus, any two timestamps N1 and N2 ($N2 > N1$) which were transferred to the Downlink Physical Media Dependent Sublayer at times T1 and T2 respectively must satisfy the following relationship:

$$(N2 - N1)/(4 \times \text{Symbol Rate}) - (T2 - T1) < 500 \text{ ns}$$

The jitter includes inaccuracy in timestamp value and the jitter in all clocks. The 500ns allocated for jitter at the Downlink Transmission Convergence Sublayer output must be reduced by any jitter that is introduced by the Downlink Physical Media Dependent Sublayer.

5.2.2.1.4.4.2 Mode A: UL-MAP Allocation Start Time definition

The Alloc Start Time is the effective start time of the uplink allocation defined by the UL-MAP or DL_MAP in units of mini-slots. The start time is relative to the time of BS initialization (PHY Type = 5). The UL-MAP/DL_MAP Allocation Start Time is given as an offset to the Time Stamp defined in 3.3.4.3.3.1. Figure 5.12 illustrates the relation of the Time Stamp maintained in the BS to the BS Mini-slot Counter. The base time unit is called a tick and is of duration 1 us, independent of the symbol rate, and is counted using a 26 bit counter. The additional BS resolution is of duration (1 tick/ 64) = 15.625 ns. The Mini-Slot count is derived from the tick count by means of a divide by M operation. Note that the divisor M is not necessarily a power of 2.

For arbitrary symbol rates, the main constraint in the definition of a mini-slot, is that the number of symbols per mini-slot be an integer. For example given a symbol rate of R Symbols/ tick, and M ticks / mini-slot, the number of symbols per mini-slot N, is given by N = M*R. In this situation, M should be chosen such that N is an integer. In order to accommodate a wide range of symbol rates, it is important not to constrain M to be a power of 2. Since the additional BS resolution is independent of the symbol rate, the system can use an uniform time reference for distance ranging.

In order to demonstrate that the time base is applicable to single carrier and OFDM symbol rates, consider the following examples: (a) Single Carrier System - Given a symbol rate of 4.8 Msymbols/s (on a 6MHz channel), if the mini-slot duration is chosen to be 10 ticks (i.e., M = 10), then there are 48 symbols/mini-slot. Given 16QAM modulation this corresponds to a granularity of 24 bytes/mini-slot (b) OFDM System - Given an OFDM symbol time of 50 us, the mini-slot duration is also chosen to be 50 ticks (i.e., M = 50). In this case there is only a single symbol per mini-slot.

5.2.2.1.4.5 UL-MAP Ack Time definition

The Ack Time is the latest time processed in uplink in units of mini-slots. This time is used by the SS for collision detection purposes. The Ack Time is given relative to the BS initialization time.

5.2.3 MAC/ PHY Framing Considerations for Adaptive Antennas

This is an added feature of the proposed framing structure to support beam forming and adaptive antenna technologies. The use of advanced antenna technology introduces an additional level of Media Access Control (MAC) complexity. The MAC/PHY has an added spatial/ beam component that must be factored into MAC coordination of the PHY. On a subscriber by subscriber (link by link) basis the MAC/PHY must coordinate the following parameters:

- Communications burst duration
    - Individual uplink or downlink for TDD
    - Joint up/down link for FDD
- Modulation Complexity
- FEC Rate
- Beam/Combining parameters.

The following figure illustrates the concept of coordinating MAC/PHY with the beam forming antenna element. While this standard does not attempt to define the specific technology or implementation of the beam forming technology the design of the MAC and PHY must take into account that the beam forming subsystem places distinct restrictions on MAC/ PHY management and the coordination and passing of parameters necessary to support advanced beam forming.

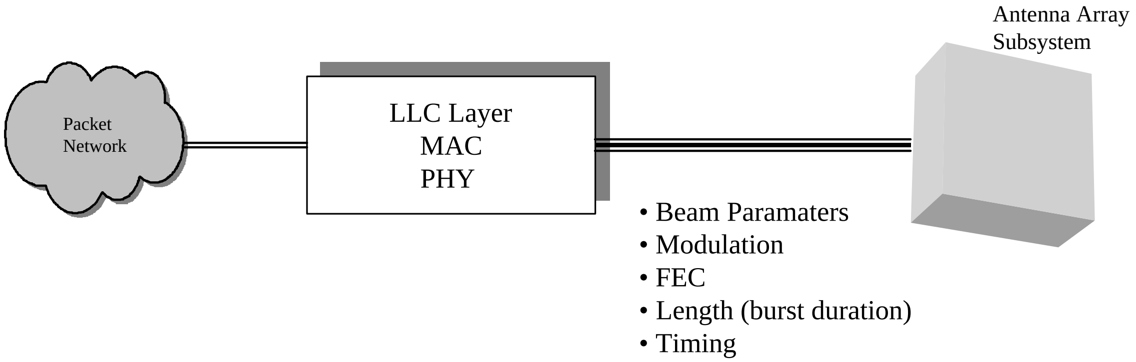


Figure 5.15: The concept of Coordinating MAC/ PHY with the Beam Forming Antenna.

Beam forming and advanced antennas remove the basic paradigm that all subscribers have the capability of simultaneously receiving broadcast information from the Base Station. Beams are formed to optimize communications to a given subscriber with a channel response $H_n(t)$ and beam parameters $B_n(t)$. The following figure illustrates a sector of a basestation that is communicating with 3 separate subscribers. Each subscriber is spatially distinct from the other subscribers. The transmission bursts sent to or from subscriber #1 would not be received by subscribers #2 or #3.

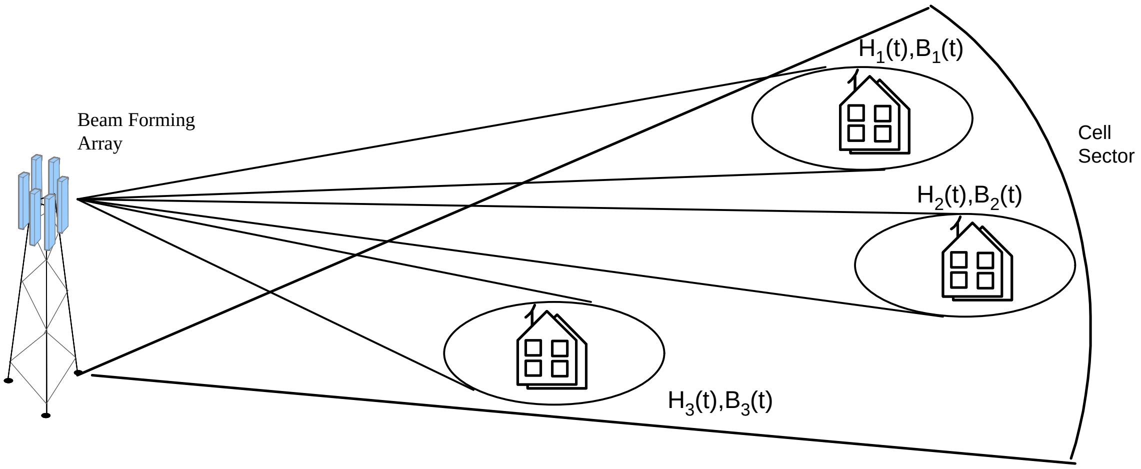


Figure 5.16: A Sector of a Base Station Communication with 3 Separate Subscribers.

In the described scenario, the Base Station is sequentially forming the beam and either sending or receiving from the subscribers in an order determined by the MAC.

To support advanced antenna systems both FDD and TDD links must be designed to provide transmissions based on self-contained bursts.

The following diagram illustrates the beam forming burst concept for both FDD and TDD.

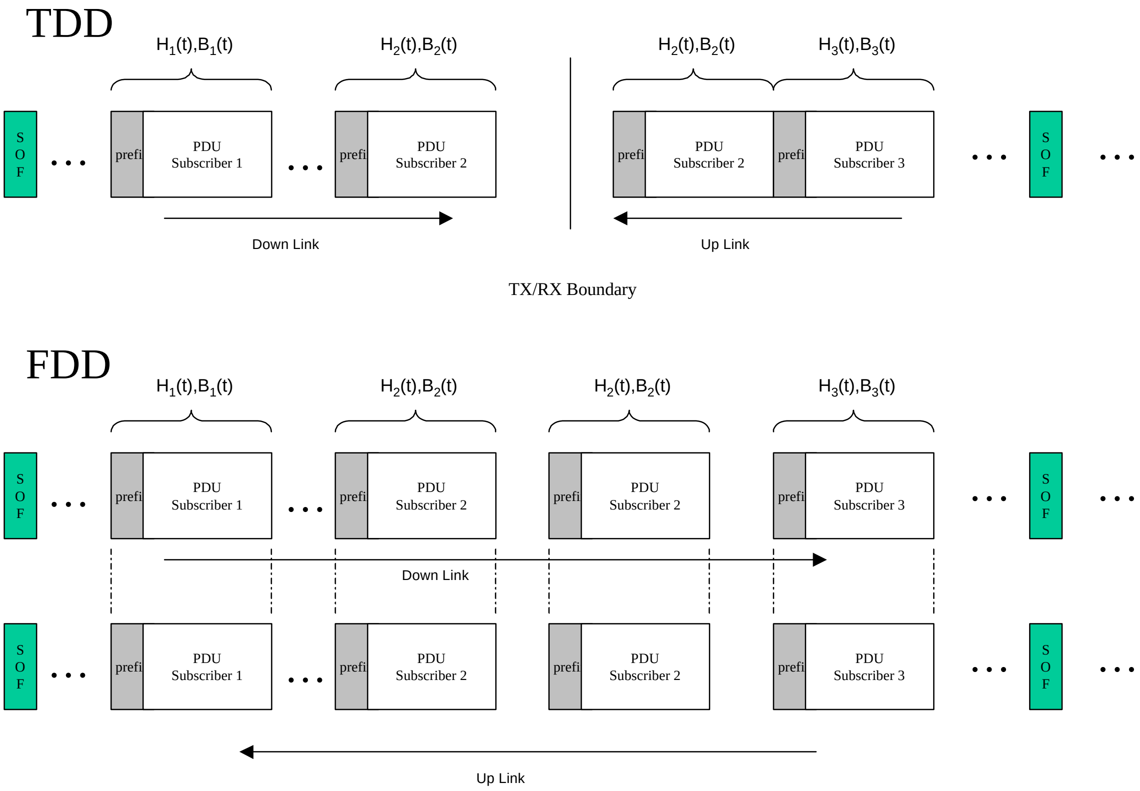


Figure 5.17: Beam forming Concept for TDD and FDD Cases.

Conceptually, TDD is easy to understand. A beam is formed for each transmitted burst in either the upstream or the down stream. The FDD solution can work one of two ways:

- Single beam forming for the Up/ Down Link
- Independent Up and Down Link beam forming. The system can support 2 independent formations of the beam on the up link frequency and the down link frequency (below)

FDD with Independent beam forming

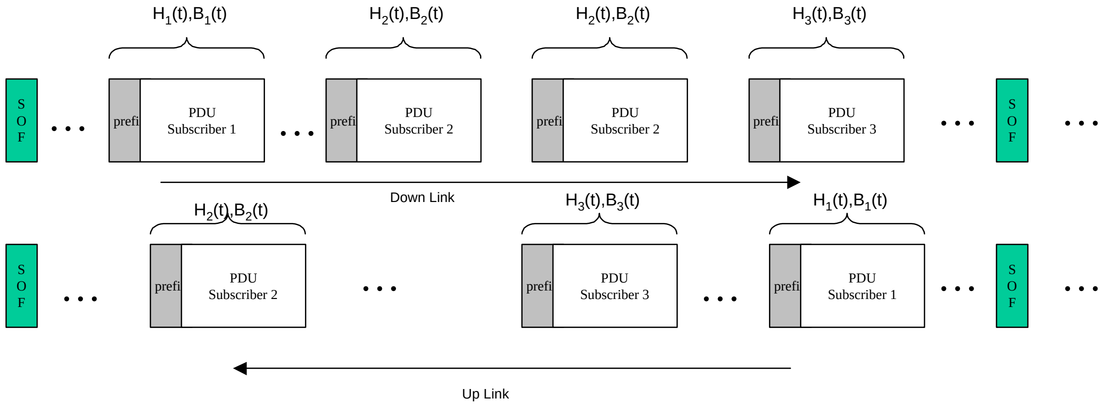


Figure 5.18: An Example of FDD with Independent Up / Down Link Beam Forming

These simple sequential cases can be expanded to advanced beam forming techniques to provide simultaneous multiple access to spatially independent users. A beam-forming network can create 2 or more independent beams with low self-interference that allow simultaneous communications using the same frequency. While beam-forming complexity is increased, spectral reuse is also increased. The complexity of PHY hardware and MAC scheduling software also increase proportionally with the number of beams created.

The MAC and PHY also need to perform burst scheduling and transmission based on "spatial concatenation". One or more subscribers can be supported by a single set of beam-forming parameters due to close physical proximity as shown in the following figure. For this case, bursts to the subscribers that share the same beams.

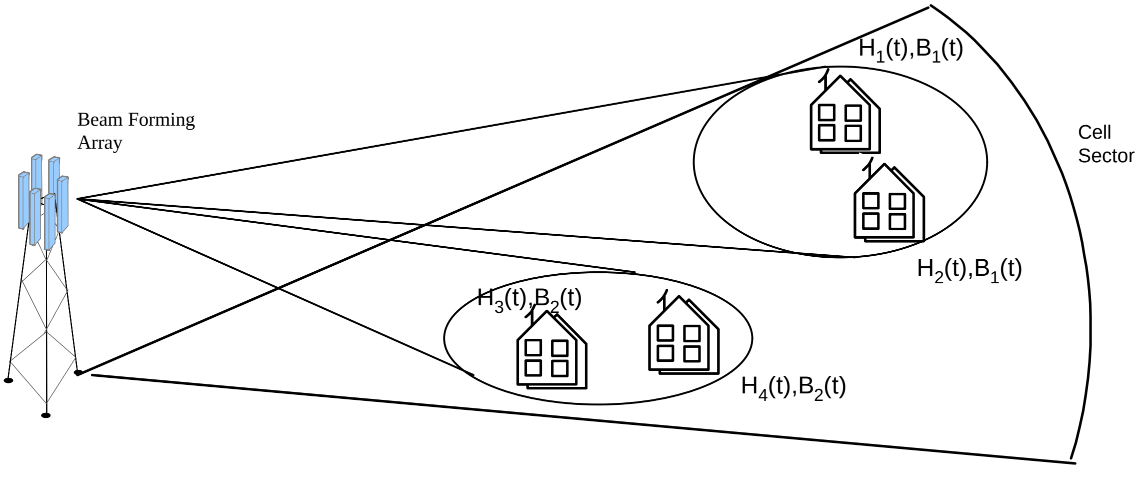


Figure 5.19: A Sectored Base Station Communicating with 4 Separate Subscribers in a Spatial Concatenated manner.

The following figure illustrates how packets are grouped (concatenated) and transmitted by based on physical proximity for a TDD Physical layer.

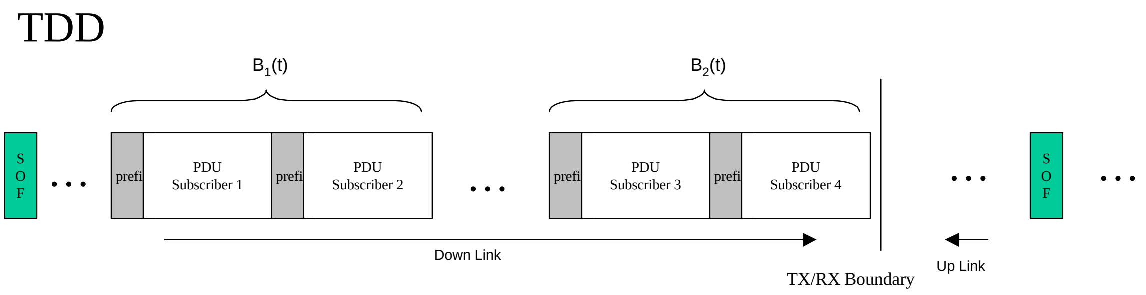


Figure 5.20: An Example of TDD with Concatenated Packet transmissions.

The proposed PHY based on block processing and burst packet formats meets all the requirements to support advanced antenna processing techniques. As the standard progresses we must address the following issues in greater detail:

- Beam forming Transition/ Set-up time definition in the MAC (passing parameters to PHY)
- Method for broadcasting Uplink and Downlink MAP information
- Acquisition methods and beam scanning
- Cell to Cell interference and C/I issues
- Spatial mutiplexing.

5.3 Duplex Schemes

In order to comply with the IEEE802.16.3 fuctional requirement [1], we propose to support both TDD and FDD systems and leave the selection of each system to the vendors /operators decision on implementation complexity, traffic scenario, cost objectives and spectrum availability.

5.3.1 TDD:

In **Time division duplex** (TDD) systems, the radio frame is divided into a downlink and an uplink section, offering flexibleand dynamic allocation of the upstream and downstream capacity. TDD enables the use of simpler antennas. In BWA system, where the delay between transmission and reception can consist of a few time slots, a guard time between the downlink and uplink sections of the frames has to be introduced in order to avoid collision between time slots. However, the guard time reduces system throughput, especially if the system is designed for low latency.

5.3.2 FDD:

In **Frequency division duplex** (FDD) systems, on the other hand, allocate a fixed proportion between uplink and downlink capacity. Residential users are likely to request asymmetrical uplink and downlink capacity, while in a business-user scenario, more symmetrical traffic behavior is likely to be the rule. FDD system can have full flexibility for instantaneous capacity allocation in the uplink and downlink for each access terminal and connection and it can address the business market segment easily.

5.4 Downstream Channel

5.4.1 Downstream Multiple Access Scheme

Each downstream RF channel (e.g., 6 MHz wide) is subdivided into fixed frames with which the RF carrier is suitability modulated (e.g., QPSK, 16 QAM or 64 QAM) to provide a digital bit stream (e.g., 30 to 40 Mbps). Within each RF channel a frame structure is used to organize and schedule the transmission of voice, video and data traffic.

5.4.2 Downstream Randomization, Channel Coding & Interleaving, Symbol Mapping and Baseband Shaping

ser data portion of the
frame. Different modulation formats and FEC groups can be defined on a subscriber level basis. In this way the
. Note that each frame contains control portion
odulation (QPSK) and FEC scheme. The details are described in Framing Section.

5.4.2.1 Randomization for Spectrum Shaping

clock recovery and to minimize occurrence of unmodulated carrier frequency. This process is done by modulo–2 addition (XORing) the data with the output of Linear-Feedback Shift Register (LFSR) with characteristic polynomial $1 + X^{14} + X^{15}$. The LFSR is cleared and preset at the beginning of each burst to a known value–100101010000000.

The preambles are not randomized and only information bits are randomized. The LFSR sequence generator pauses while parity bits are being transmitted.

5.4.2.2 Downstream Channel FEC definitions

Consistent with the structure of the 802.16 MAC, forward error correction code schemes which support both Block Turbo Coding and Concatenated Reed-Solomon+Convolutional coding will be employed. In addition, the provision of suppressing all FEC and operating using the ARQ mechanism in the 802.16 MAC for error control will be included.

Following is the summary of these coding schemes:

Block Turbo Code: This type of coding is based on the product of two or more simple component codes (also called Turbo Product code, TPC). The decoding is based on the concept of Soft-in/Soft-out (SISO) iterative decoding (i.e, "Turbo decoding"). The component codes recommended for this proposal are binary extended Hamming codes or Parity check codes. The schemes supported follow the recommendation of the IEEE802.16.1 mode B. However, more flexibility in block size and code rates is enabled. The main benefits of using BTC mode, are typically 2 dB better performance over the Concatenated RS, and shorter decoding delays. A detailed description of **Block Turbo Coding** is included as Appendix C.

Concatenated Reed-Solomon+Convolutional code: This case is based on concatenation of outer coding RS (204,188, t=8) and inner rate ½ Convolutional code with constraint length K=7. The Convolutional code is able to be configured to code rates 2/3, ¾, 5/6 and 7/8 using puncturing Convolutional interleaving with depth I=12 shall be implied as described in DVB-S spec [13]. The detailed description of Concatenated Reed-Solomon Coding is included as Appendix C.

5.4.2.3 Symbol Mapping

-coded and for Reed Solomon codes is pragmatic that are described in Ref [26] for all constellations.

5.5 UpStream Channel

5.5.1 Upstream Multiple Access

The upstream multiple access method shall be TDMA.

The upstream channel bandwidth for MMDS channel allocation would be 6MHz. In TDD mode this 6MHz

bandwidth and hence is capable of efficiently allocating the available traffic transport capacity for applications

FDD can be used by applications that require fixed asymmetric allocation between their upstream and ownstream traffic transport demand. In FDD mode upstream traffic would typically be allocated 3MHz. This is half of the 6MHz bandwidth assuming symmetrical traffic requirements.

5.5.2 Upstream Modulation Format

The upstream modulation types can be the same as those available for downstream transmission; e.g., QPSK,

for a particular Subscriber Station (SS) such that these parameters can be the same as in the downstream burst

MAC decides on the best modulation and error correction to use for the channel conditions. This information is passed back up to the Access Point (AP) in the corresponding upstream burst, and the AP MAC uses this information to assign the modulation type and error correction to the next burst of data to be transmitted.

5.5.3 Upstream Randomization, Channel Coding & Interleaving, Symbol Mapping And Baseband Shaping

The upstream channel has processing units similar to those described for the downstream. However, greater flexibility in packet transmission is allowed. The subscriber stations are transmitting only after receiving some configuration information from the base station through MAC messages. Several different configurations can be adjusted on the upstream channel on a burst-to-burst basis. The upstream payload is segmented into blocks of data designed to fit into the proper codeword size (including Transmission Convergence sublayer, TC, header). Note that payload length may vary from burst to burst.

5.5.3.1 Randomization for Spectrum Shaping

The upstream modulator uses a randomizer using LFSR with connection polynomial $X^{15} + X^{14} + 1$, with a 15-bits programmable seed. At the beginning of each burst, the register is cleared and the seed value is loaded. The seed value is used to calculate the scrambler output bit, obtained as the XOR of the seed with first bit of DATA of each burst (which is the MSB of the first symbol following the last symbol of the preamble).

5.5.3.2 FEC schemes for the upstream channel

Consistent with the structure of the 802.16 MAC forward error correction code schemes which support both **Block Turbo Coding** (TPC) and Concatenated Reed-Solomon+Convolutional coding will be employed. In addition, the provision of suppressing all FEC and operating using the ARQ mechanism in the 802.16 MAC for error control will be included.

5.5.3.3 Interleaving for the upstream channel

Interleaving is applied for the upstream channel only with BTC FEC scheme.

6 PERFORMANCE

6.1 Throughput

System throughput will vary with the operating modes. For single-carrier systems, the throughput is

$$T = R \frac{N - U}{N} r \log_2 M .$$

For multi-carrier systems, the throughput is

$$T = R \frac{N - L - G}{N + C - w} r \log_2 M .$$

Table 6 1are typical results using the above formulae, and assuming

Channel Width $W = 1.75$ MHz

$U = C = 2 \bullet R \bullet d$, rounded to the next highest power of 2

for MC: $L + G = C$ and $w = \frac{C}{4}$

Like the formulae in Table 3.3 and Table 3.6, these are guidelines for the selection of practical values that would be used in an actual standard.

Typical results for Channel Widths other than 1.75 MHz will be proportionately larger or smaller.

System-Dependent Parameters		Link-Dependent Parameters		Traffic-Dependent Parameter							
Symbol [Sample] Rate (MS/sec)	Design Max Delay Spread (microsec)	Number of QAM States	Convolutional Code Rate	FFT Size							
				256		512		1024		2048	
				SC	MC	SC	MC	SC	MC	SC	MC
1.5	4	4	1/2	1.41	1.34	1.45	1.42	1.48	1.46	1.49	1.48
			2/3	1.88	1.79	1.94	1.89	1.97	1.95	1.98	1.97
			3/4	2.11	2.01	2.18	2.13	2.21	2.19	2.23	2.22
			7/8	2.46	2.35	2.54	2.48	2.58	2.55	2.60	2.59
		16	1/2	2.81	2.69	2.91	2.84	2.95	2.92	2.98	2.96
			2/3	3.75	3.58	3.88	3.79	3.94	3.89	3.97	3.95
			3/4	4.22	4.03	4.36	4.26	4.43	4.38	4.46	4.44
			7/8	4.92	4.70	5.09	4.97	5.17	5.11	5.21	5.18
		64	1/2	4.22	4.03	4.36	4.26	4.43	4.38	4.46	4.44
			2/3	5.63	5.37	5.81	5.68	5.91	5.84	5.95	5.92
			3/4	6.33	6.04	6.54	6.39	6.64	6.57	6.70	6.66
			7/8	7.38	7.05	7.63	7.45	7.75	7.66	7.81	7.77
	10	4	1/2	1.31	1.20	1.41	1.34	1.45	1.42	1.48	1.46
			2/3	1.75	1.60	1.88	1.79	1.94	1.89	1.97	1.95
			3/4	1.97	1.80	2.11	2.01	2.18	2.13	2.21	2.19
			7/8	2.30	2.10	2.46	2.35	2.54	2.48	2.58	2.55
		16	1/2	2.63	2.40	2.81	2.69	2.91	2.84	2.95	2.92
			2/3	3.50	3.20	3.75	3.58	3.88	3.79	3.94	3.89
			3/4	3.94	3.60	4.22	4.03	4.36	4.26	4.43	4.38
			7/8	4.59	4.20	4.92	4.70	5.09	4.97	5.17	5.11
		64	1/2	3.94	3.60	4.22	4.03	4.36	4.26	4.43	4.38
			2/3	5.25	4.80	5.63	5.37	5.81	5.68	5.91	5.84
			3/4	5.91	5.40	6.33	6.04	6.54	6.39	6.64	6.57
			7/8	6.89	6.30	7.38	7.05	7.63	7.45	7.75	7.66
	20	4	1/2	1.13	0.95	1.31	1.20	1.41	1.34	1.45	1.42
			2/3	1.50	1.26	1.75	1.60	1.88	1.79	1.94	1.89
			3/4	1.69	1.42	1.97	1.80	2.11	2.01	2.18	2.13
			7/8	1.97	1.66	2.30	2.10	2.46	2.35	2.54	2.48
		16	1/2	2.25	1.89	2.63	2.40	2.81	2.69	2.91	2.84
			2/3	3.00	2.53	3.50	3.20	3.75	3.58	3.88	3.79
			3/4	3.38	2.84	3.94	3.60	4.22	4.03	4.36	4.26
			7/8	3.94	3.32	4.59	4.20	4.92	4.70	5.09	4.97
		64	1/2	3.38	2.84	3.94	3.60	4.22	4.03	4.36	4.26
			2/3	4.50	3.79	5.25	4.80	5.63	5.37	5.81	5.68
			3/4	5.06	4.26	5.91	5.40	6.33	6.04	6.54	6.39
			7/8	5.91	4.97	6.89	6.30	7.38	7.05	7.63	7.45

Table 6.1 Throughput for Various Modes in 1.75 MHz Channel

6.2 Fading Immunity

The performance of both the SC and MC modes of this proposal has been evaluated via extensive Monte Carlo simulation. Figs.6.1 through 6.4 present some typical results over the SUI Channels 2 and 5, both with and without antenna diversity. It can be seen from these curves that, at low to moderate BERs, both the SC and MC perform within 2-4 dB of the theoretically optimal Matched Filter bound (MFB) over these channels. The FD-DFE achieves a universally superior performance, with substantial gains evident by using even a few (1-2) feedback taps (Fig 6.5, 6.6). The (coded) OFDM performance is seen to lie between the FD-LE and FD-DFE curves. Details regarding training requirements are available in contribution [4].

The results presented in this Section enable us to conclude that Frequency Domain Processing (Fig. 3.1) is, in general, an extremely robust technique to counter the frequency-selective fading effects of channels with severe delay spread.

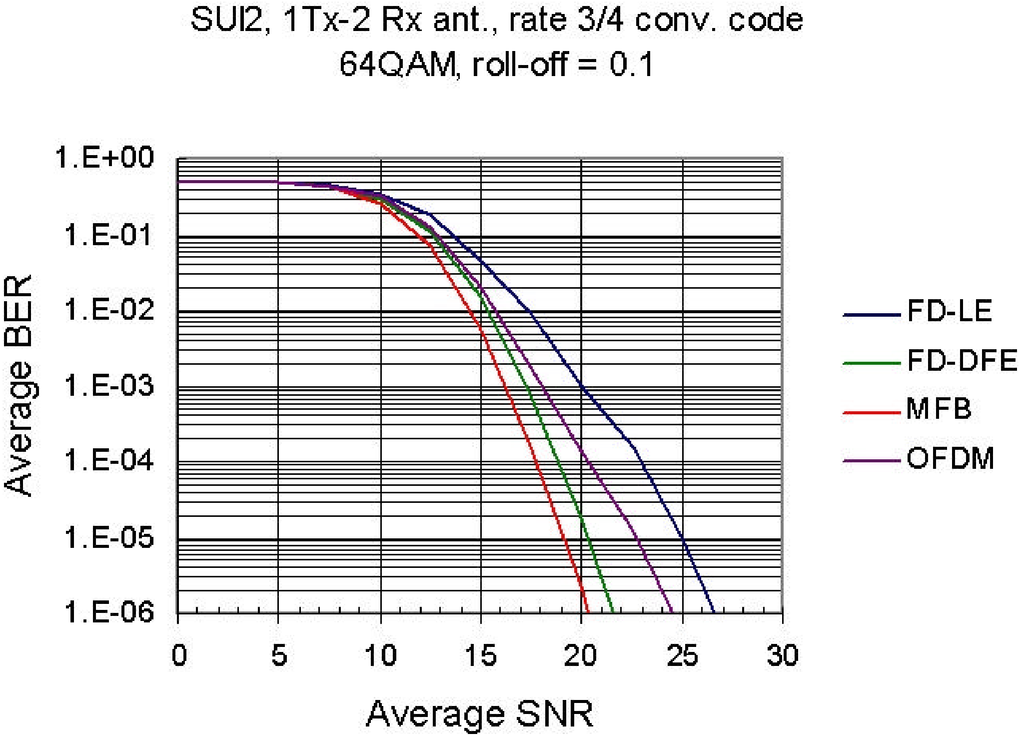


Figure 6.1 SC, MC Performance over SUI Channel #2 (Without Antenna Diversity)

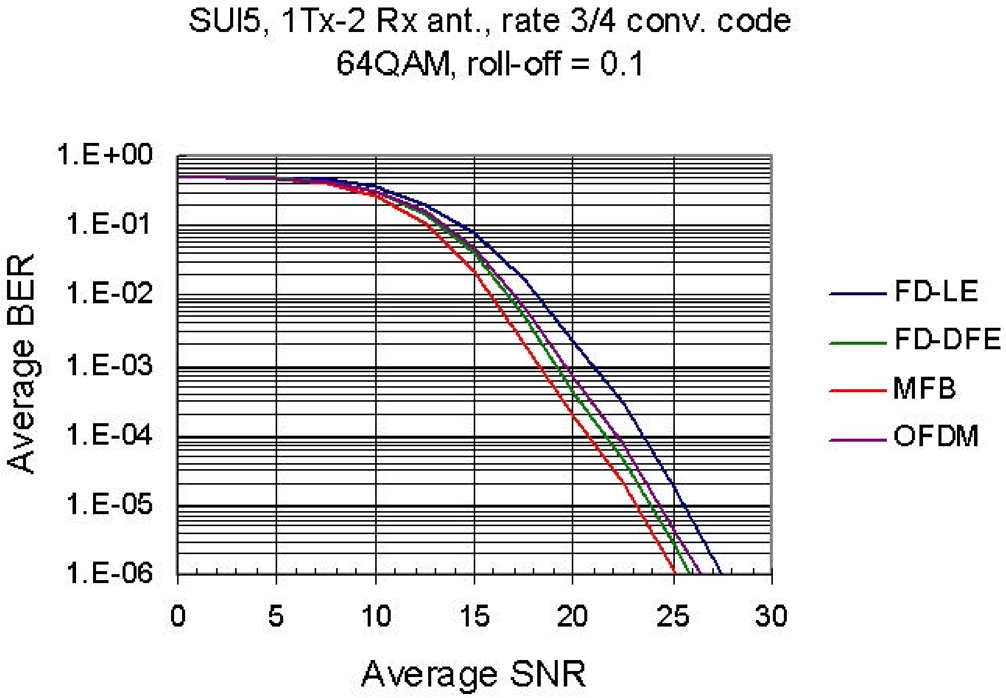


Figure 6.2. SC, MC Performance Over SUI Channel #5

(without Transmit antenna diversity)

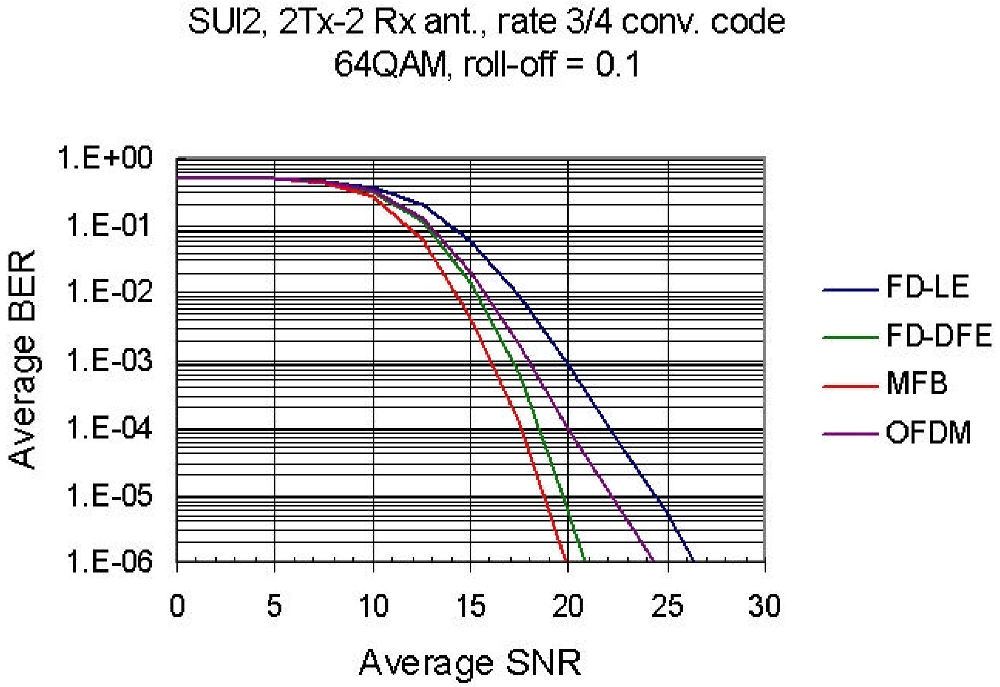


Figure 6.3 SC, MC Performance Over SUI Channel #2

(with Transmit antenna diversity)

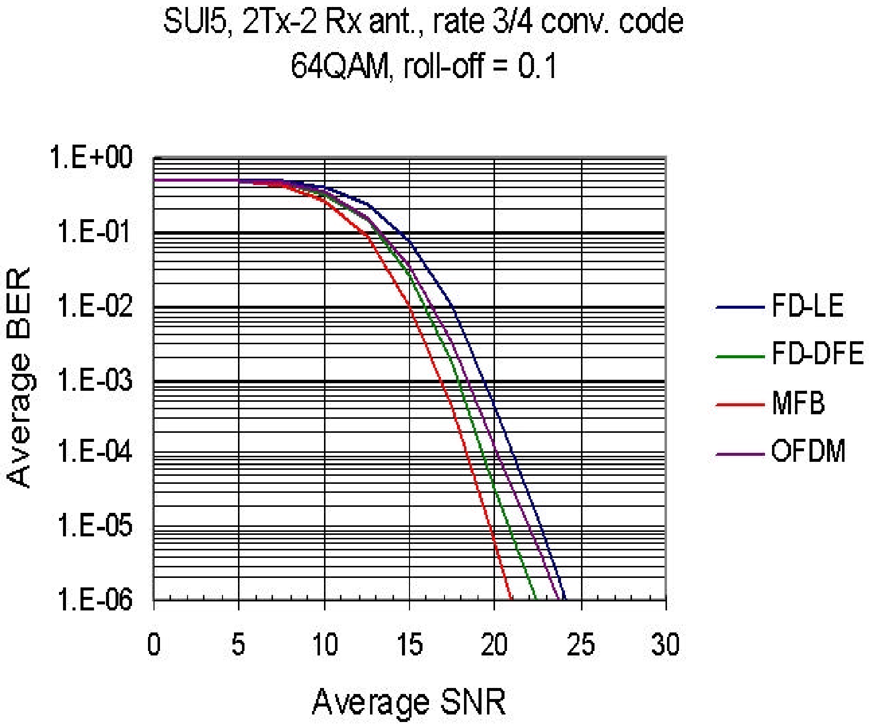


Figure 6.4 SC, MC Performance Over SUI Channel # 5

(with Transmit antenna diversity)

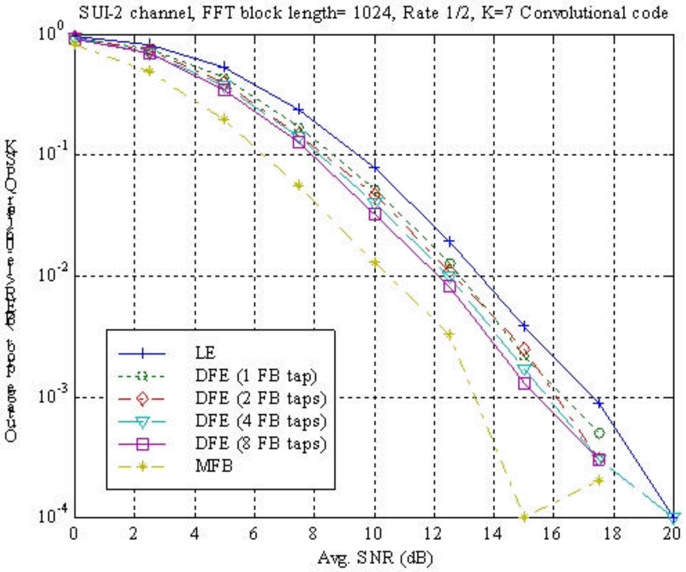


Figure 6.5. Effect of Number of Feedback taps in SC-FD-DFE (SUI #2)

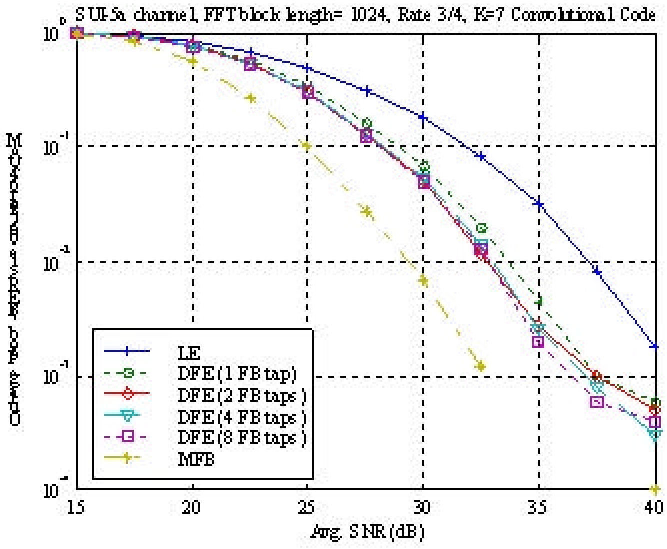


Figure 6.6. Effect of Number of Feedback taps in SC-FD-DFE (SUI #5)

6.3 *System Capacity and Modulation Efficiency*

Table 6.2 shows the BWA PHY with Downstream and Upstream modulation schemes and the corresponding system capacity and Bits per sec./ Hz. The aggregate transmission bit rate is optimized based on several constraints. These are:

- The allocated channel bandwidth;
- The modulation level;
- The spectrum shaping filter bandwidth with roll factor of á = %0.15 to %0.25;
- The FEC coding scheme (Reed-Solomon (n, k) over GF(2^8));
- The requirement of upstream time tick for the Mini-slots burst duration; and
- Processing power limitation of available chips to be used. Table 6.2 presents an example of achievable system capacity where all coding and FDE overhead budget is being included.

Table 6.2: An Example Of System Capacity Objectives.

Channel Spacing	**Downstream Transmission**		**Upstream Transmission**	
	Rate (Mb/s)		**Rate (Mb/s)**	
	(16 QAM) **3.38 bps/Hz**	**(64 QAM)** **5.07 bps/Hz**	**(QPSK)** **1.46 bps/Hz**	**(16 QAM)** **2.92 bps/Hz**
3.5 MHz	11.02	16.54	4.77	9.54
5 MHz	15.72	23.57	7.44	14.88
6 MHz	18.82	28.21	8.93	17.86
7 MHz	22.03	33.03	9.52	19,05

7 RF System Requirements

7.1 Phase Noise

RF local oscillator phase noise may degrade the residual bit error rate and receiver sensitivity of QAM systems. Multi-carrier OFDM systems are more susceptible to this degradation than single-carrier systems; therefore, only the MC systems were considered.

To verify that the proposed multi-carrier system is feasible, a simulation model of an OFDM transmitter and receiver were built, using equivalent complex baseband signals. A low-cost phase-locked oscillator in the MMDS band, with 0.22 degrees rms phase noise, was simulated to obtain its power spectral density, and applied to the model. The SUI-6 channel was also introduced into the model, with the fading held constant during each OFDM symbol, and also the channel coefficients were uncorrelated among OFDM symbols (block-stationary, uncorrelated fades). Perfect channel and timing estimates were assumed in the receiver, but other algorithms reflected the operation of an actual OFDM receiver. Simulations were run using several representative sets of multicarrier system parameters from Table 3.7, including those with the closest subcarrier spacings.

As expected, the oscillator phase noise introduced residual noise into the equalized receiver FFT outputs. The ratio of signal to residual noise power (SINR) was averaged over several tens of symbols and found to be better than 44 dB in all cases. This noise level will cause negligible sensitivity degradation of a 64QAM receiver. Thus, it is concluded that low-cost RF local oscillators may be used in any implementation of the proposed PHY, either SC or MC.

7.2 Linearity

One of the most significant contributors to the cost of a BWA radio is the **power amplifier** (PA). Its cost is related to its maximum power output, which is related to the backoff required for a given signal, which is related to the signal's distribution of amplitude peaks.

7.2.1 Distribution of Amplitude Peaks

Figure 7.1 shows the CCDF (complementary cumulative distribution function) of the instantaneous power of the input signal to the PA, for some of the proposed signals.

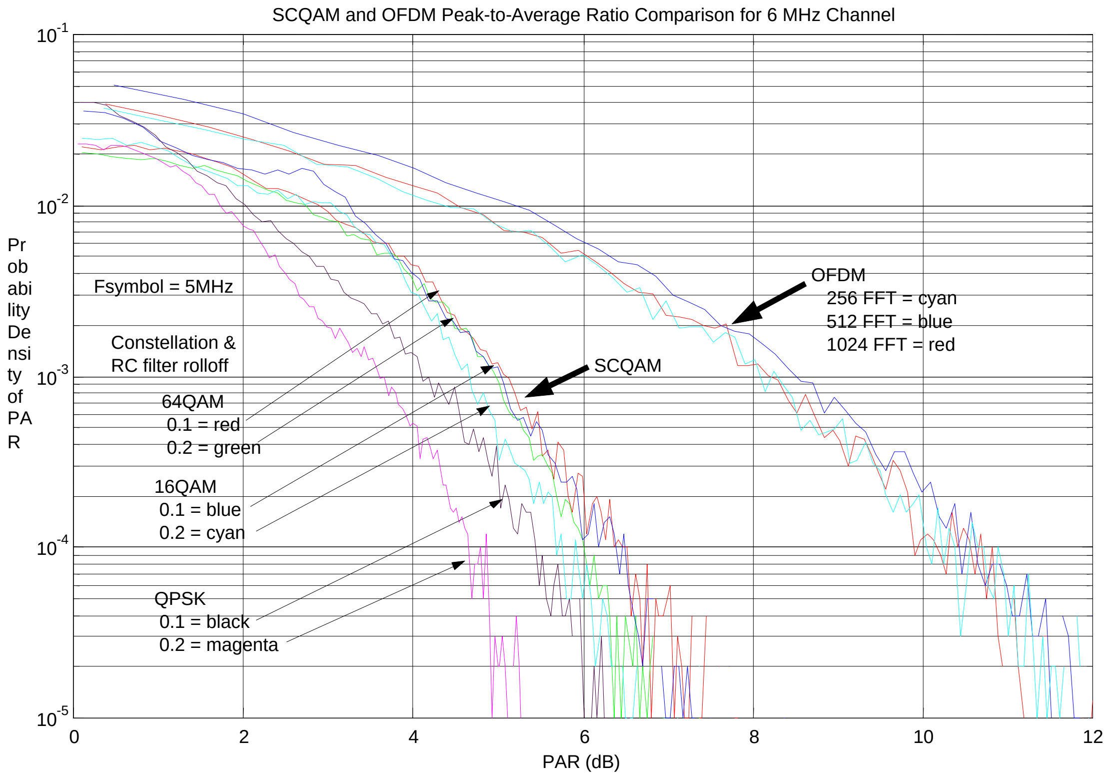


Figure 7.1. Peak CCDF for various signals.

7.2.2 Simulations of Transmitter Output Spectra

Simulations were run to see the effect of a typical PA on some of the proposed signals**.**

7.2.2.1 Power Amplifier Model

Measurements of AM-AM distortion and AM-PM distortion were made on a +32 dBm P1dB, GaAs Power Amplifier operating at 2.5GHz. These measurements were then used to construct a behavioral model of the PA, used in the simulations described below.

7.2.2.2 Results

Figure 7.2 through Figure 7.10 show the resulting simulated transmitter output spectra for various scenarios.

The compliance masks in the figures are drawn from USA FCC Regulations, 47CFR21.908, for MMDS transmitters in the 2.5 GHz band.

The depicted scenarios of 1.25 Ms/sec signal in a 6 MHz or 3 MHz-wide channel would be typical of an upstream transmitter where the operator has split the channel into 4 or 2 subchannels.

All of the simulated signals are seen to meet the FCC specification at backoff values that are indicated in the provided data. Note that the effects of windowing and the choice of number of guard tones (G) are critical in meeting out-of-band requirements in multicarrier systems.

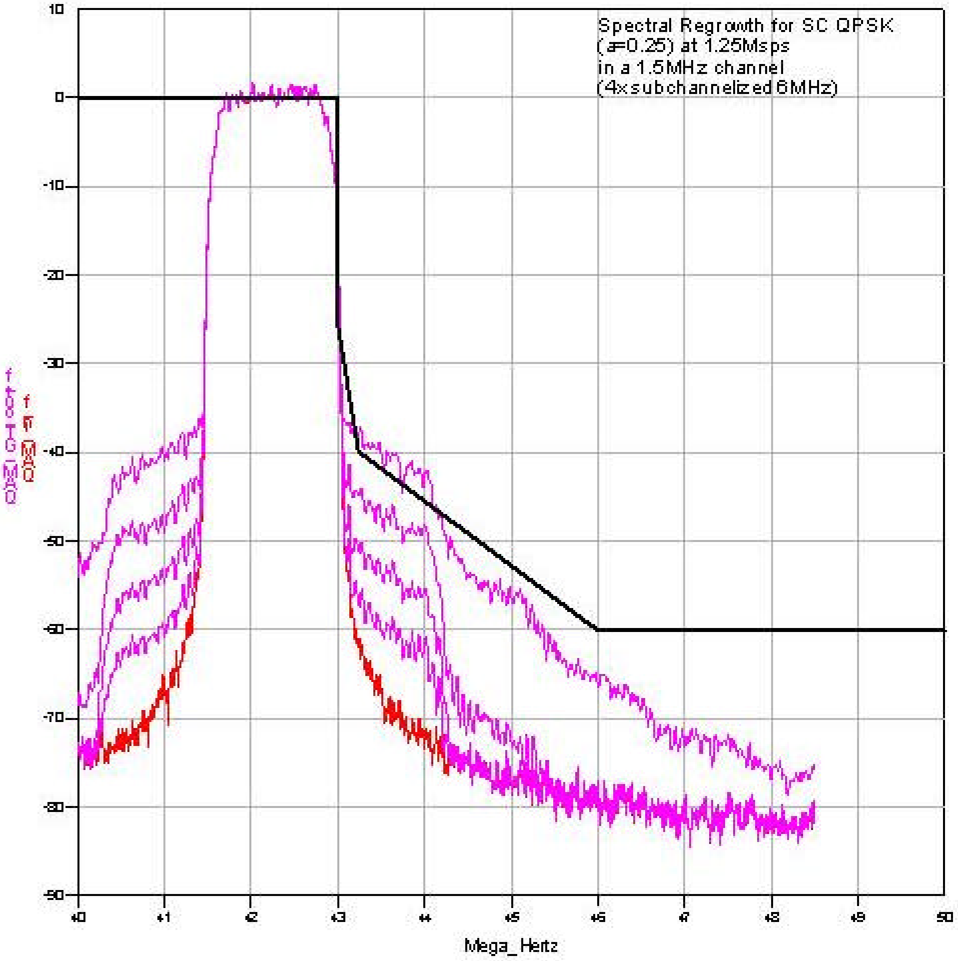


Figure 7.2. Simulated PA output for SC QPSK, á=.25, 1.25 Msym/sec, centered in the highest 1.5 MHz quarter of an FCC 6 MHz Channel. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 3, 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

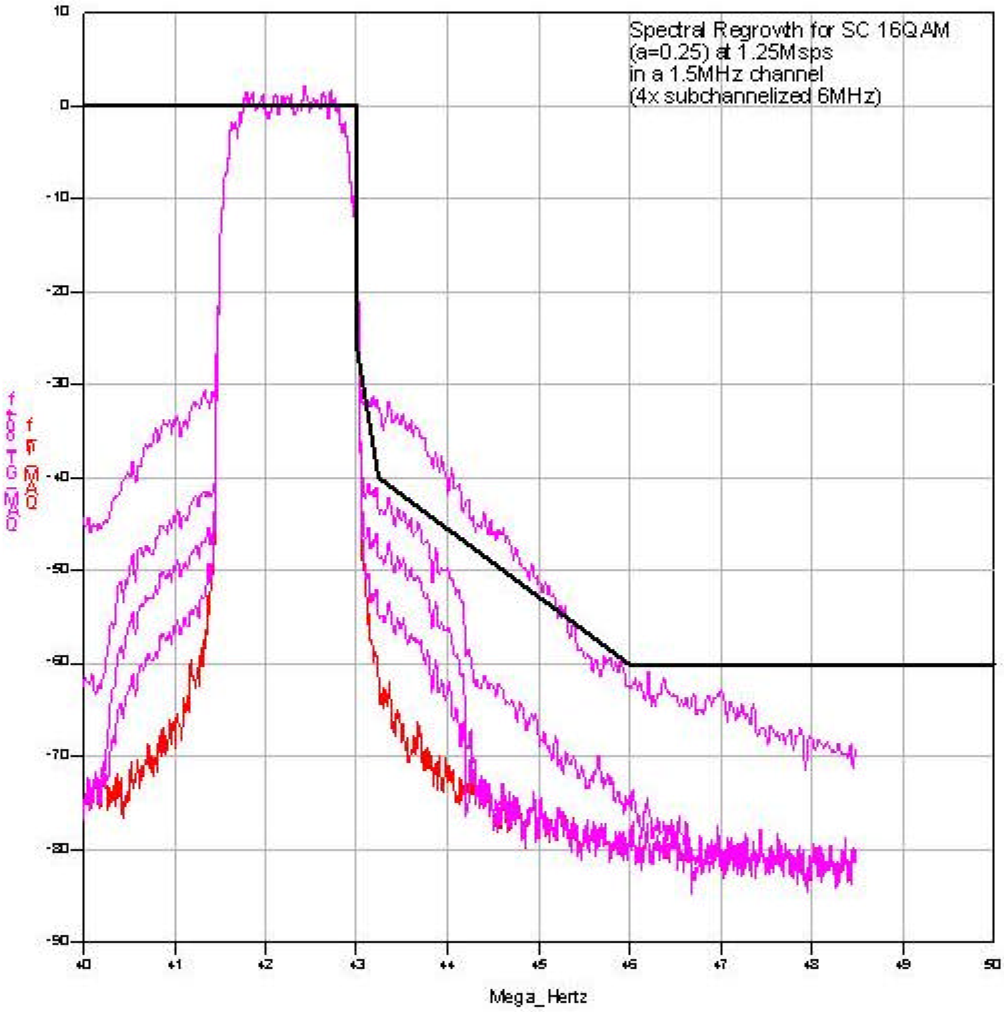


Figure 7.3. Simulated PA output for SC 16QAM, á=.25, 1.25 Msym/sec, centered in the highest 1.5 MHz quarter of an FCC 6 MHz Channel. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 3, 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

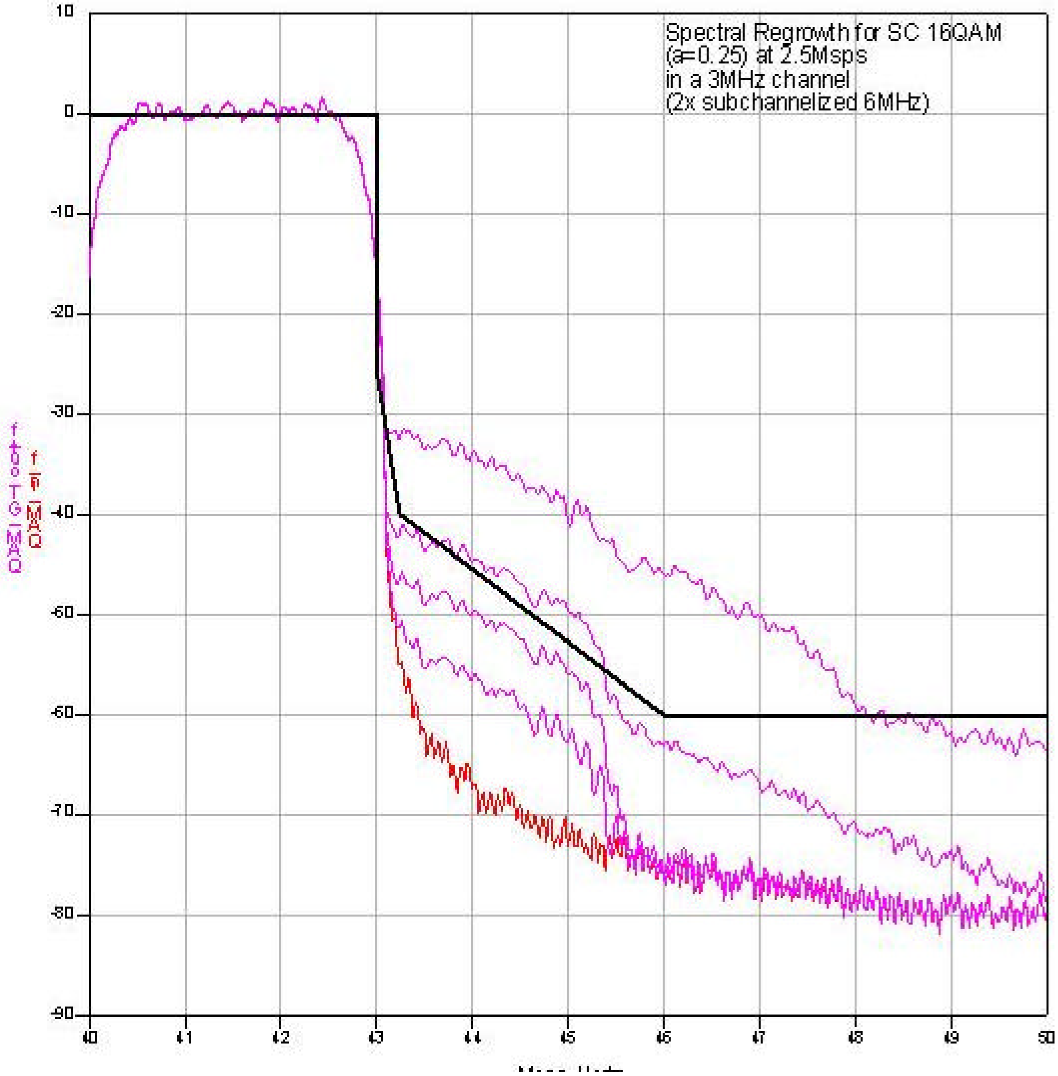


Figure 7.4. Simulated PA output for SC 16QAM, á=.25, 1.25 Msym/sec, centered in the higher 3.0 MHz half of an FCC 6 MHz Channel. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 3, 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

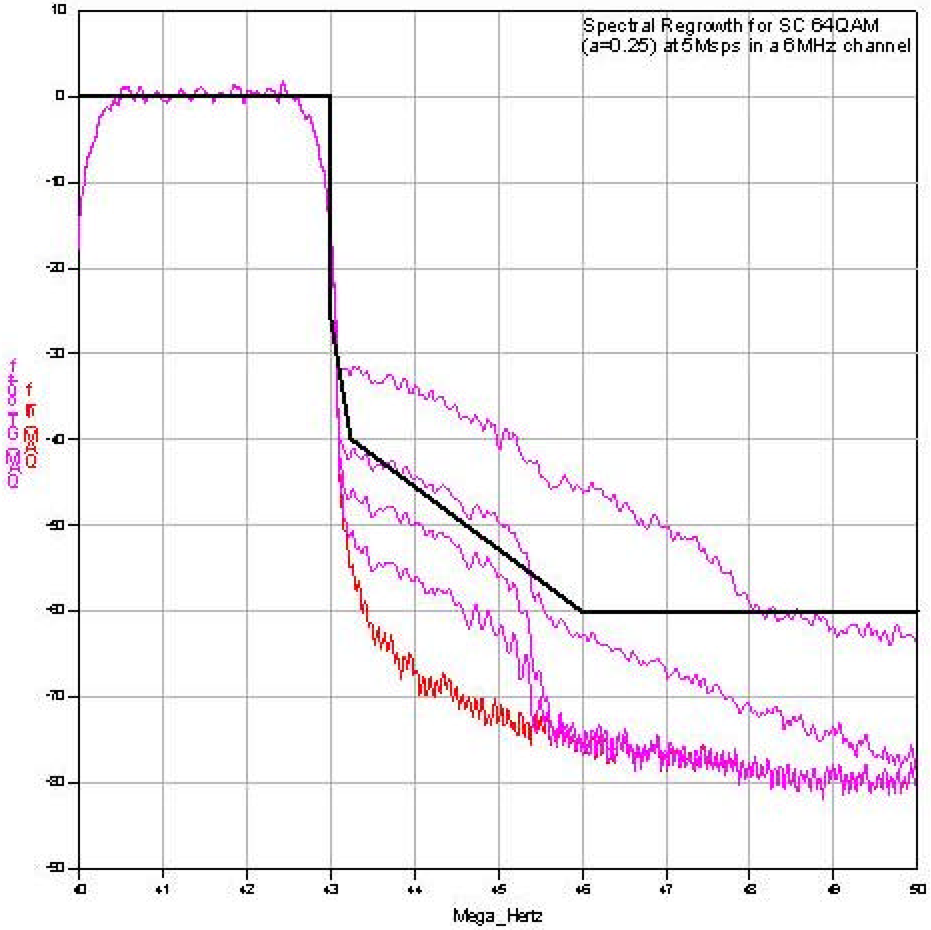


Figure 7.5. Simulated PA output for SC 64QAM, á=.25, 5.0 Msym/sec, in an FCC 6 MHz Channel. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 3, 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

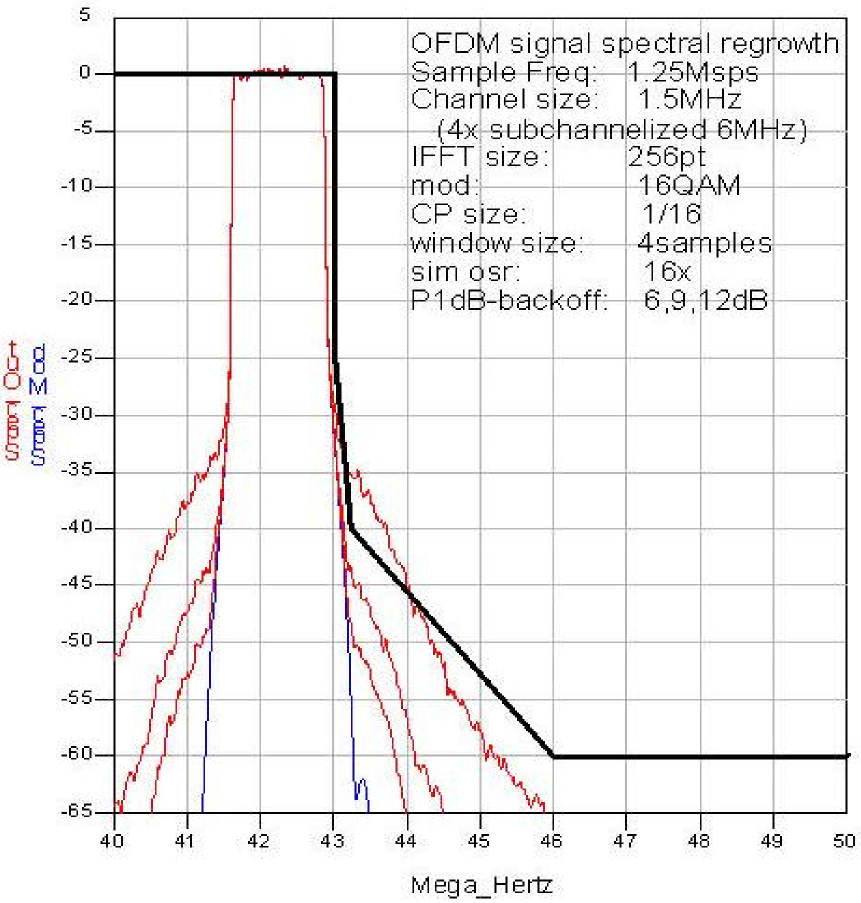


Figure 7.6. Simulated PA output for MC. Blue spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 6, 9 and 12 dB from the 1-dB gain compression point of the PA. The modulation scheme here is 16-QAM.

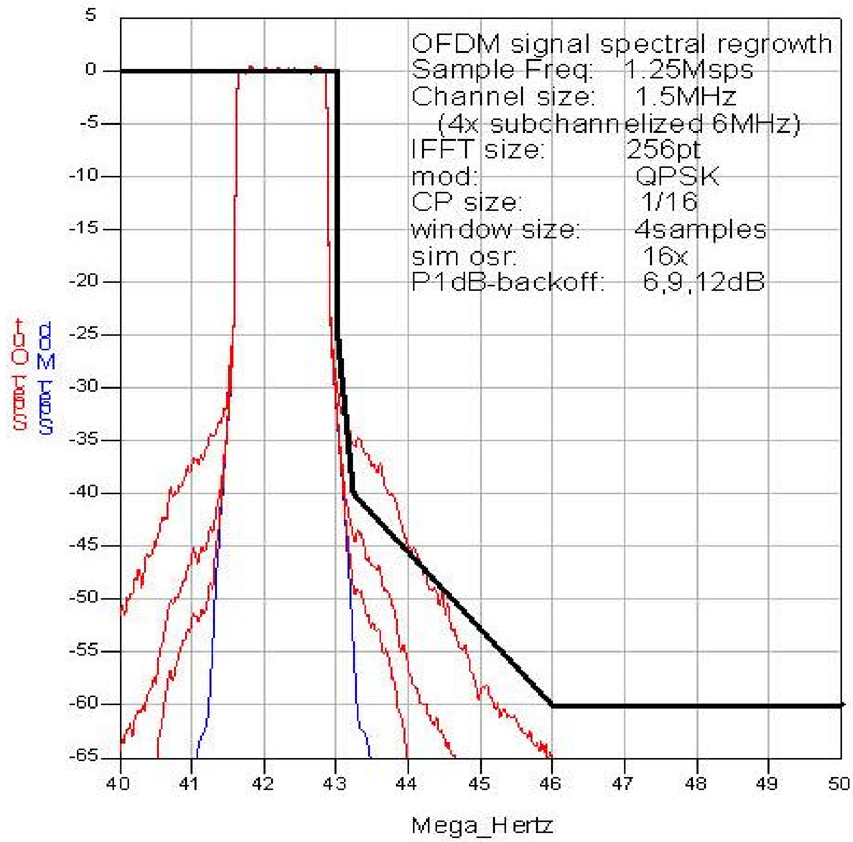


Figure 7.7. Simulated PA output for MC. Blue spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 6, 9 and 12 dB from the 1-dB gain compression point of the PA. The modulation scheme here is QPSK.

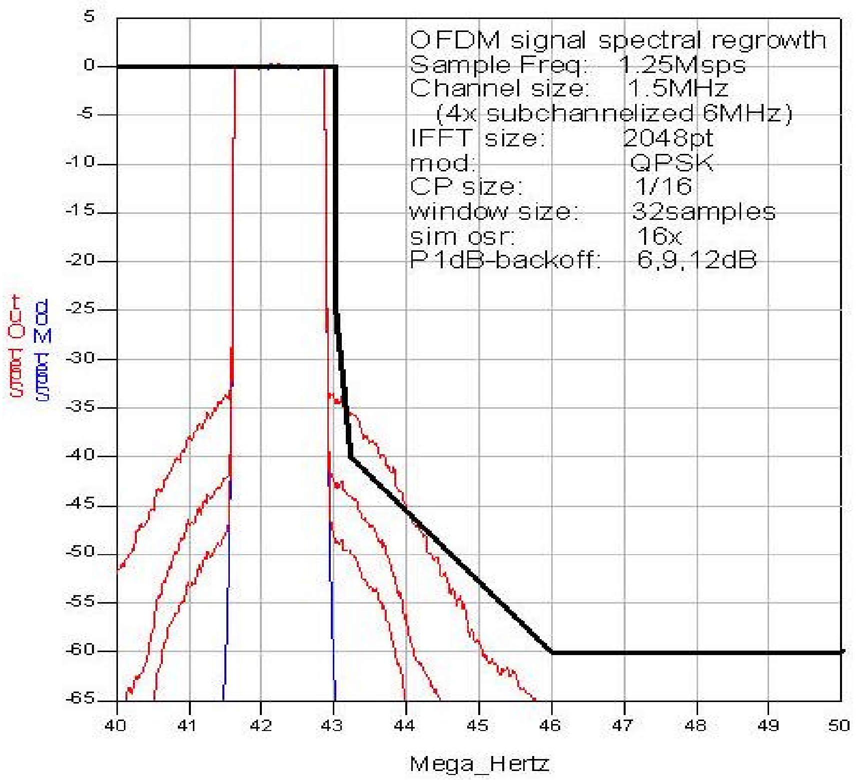


Figure 7.8. Simulated PA output for MC. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

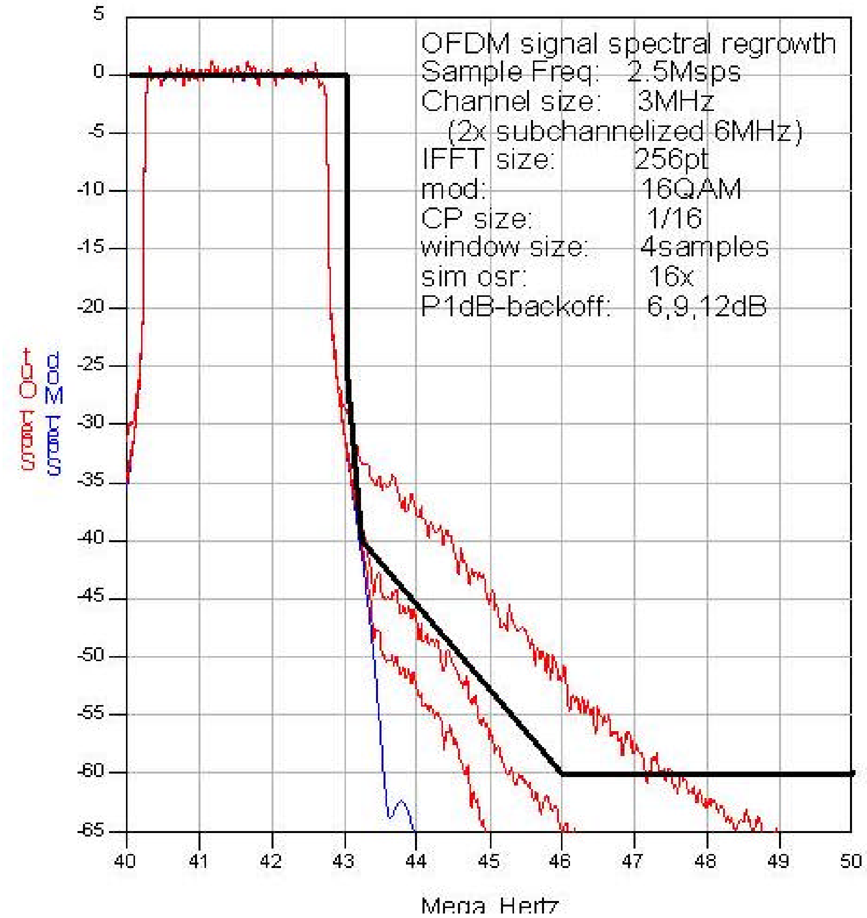


Figure 7.9. Simulated PA output for MC. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

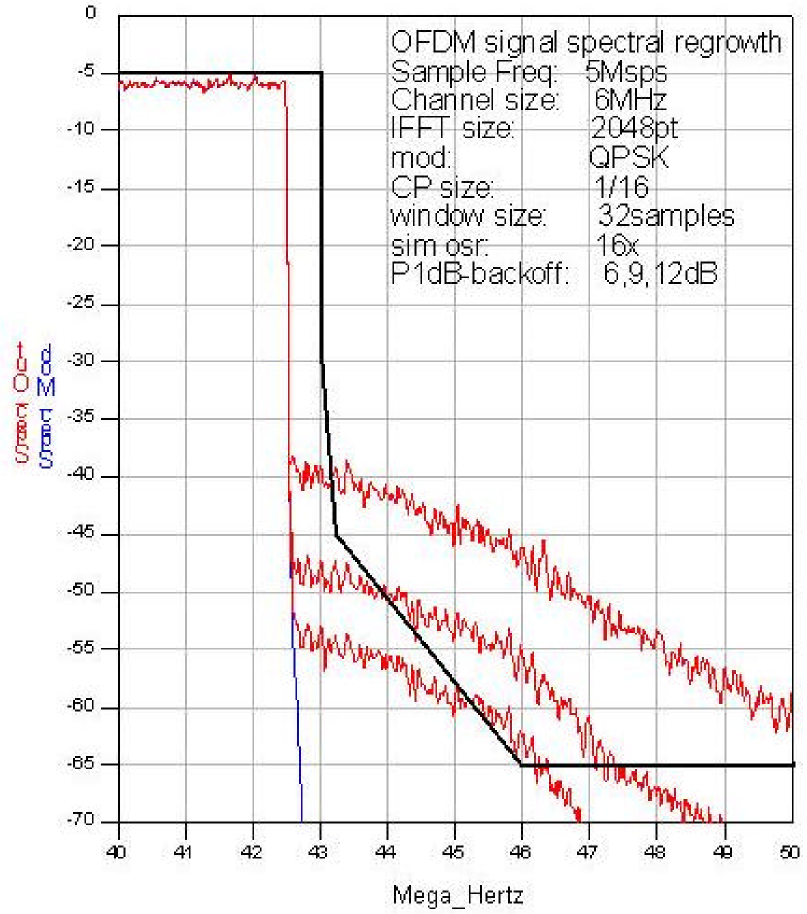


Figure 7.10. Simulated PA output for MC. Bottom spectrum is simulated PA input. Succeedingly higher spectra show simulated PA output for output power levels backed off 6, 9 and 12 dB from the 1-dB gain compression point of the PA.

7.3 Frequency Ranges

The frequency range and the required downstream and upstream channel bandwidths of the Proposed PHY system are given in Table 3.5.

Frequency Bands	**Channel Bandwidth Options**	**Reference**
2.15- 2.162 GHz, **2.50- 2.690 GHz**	**2 to 6 MHz downstream,** **200 kHz to 6 MHz upstream**	**FCC 47 CFR 21.901 (MDS)** **FCC 47 CFR 74.902 (ITFS, MMDS)** **Industry Canada SRSP-302.5 (Fixed Services operating in the 2500 to 2686 MHz band)**
b) 3.5 GHz	**1.75- 7 MHz downstream,** **250 KHz to 7 MHz upstream**	**EN 301 021,** **CEPT/ERC Rec. 14-03 E, CEPT/ERC Rec. 12-08 E, Others (TBD)**
c) 10.5 GHz	**3.5, 5 and 7 MHz**	**EN 301 021, CEPT/ERC Rec. 12-05 E**

Table 7.1 Frequency Bands and Channel Bandwidth

7.4 Antenna Systems

7.4.1.1 Application of Smart Antenna

The PHY layer shall support future application of smart antenna for primary feature of providing the ability to track the line of sight target within a predetermined angle of uncertainty. Typically, one would expect 3 or more degrees of tracking. This active tracking capability of smart antenna will potentially provide better coexistence and will optimize the antenna pattern (transmit where the subscriber is located)

7.4.2 Antenna Diversity

Multiple antennas can be used at the transmitter and/or receiver to provide added dimension to the model.

When multiple antenna diversity (so called Multiple-Input/Multiple-Output; MIMO) is compared with a Single-Input/Single-Output (called SISO) technique, it is shown in performance that it can improve the capacity of the fading wireless channel regardless of the modulation techniques utilized. It is applicable to Single Carrier (SC) modulation. The benefits, however, of using space diversity should be examined against its implementation complexity and economic factors.

8 Summary and Conclusions:

- For channels exhibiting severe multipath spread, Single Carrier QAM with simplified frequency-domain equalization, as well as OFDM perform comparably well, and form viable solutions (Section 6.2).
- Frequency domain linear equalization has essentially the same complexity as OFDM (Section 3.1.2), without OFDM's inherent backoff power penalty. A "Compatible" frequency domain receiver structure can be programmed to handle either OFDM or Single Carrier.
- Operators deploying MMDS systems in different parts of the world may choose the Single or the Multi-carrier implementation, depending on their considerations of cost, environment, market, backward compatibility, etc.

Advantages of SC and OFDM	
Single Carrier	**Multi-carrier (OFDM)**
Sensitivity (margin): Less Affected by Freq Selective Fading (spectrum notches averaged) Reduced overhead Less pilots & No guard interval 'Lighter' coding possible	Simple Equalization Tx diversity ostensibly easier
IC Complexity--Less Memory (data buffering)	Robustness at low SNR Avoid DFE (use pilots) PAPR unaffected by modulation order
Reduced RF expense: Reduced Phase noise sensitivity Reduced Freq Regist Reqments Reduced PA Backoff 64QAM: 1e-3 env prob 3 dB less QPSK: 1e-3 env prob 4-4.5 dB less Important at edge of cell Single Carrier can use Freq domain equalizer	IC Complexity--Less logic
Smaller packet granularities	Automatically integrates multipath -- but not coherently
FIFO Advantages Throughput (Queueing Theory)	Single Frequency Networks (OFDMA)

Reduced MAC complexity (vs OFDMA)	

9 Main Features and Benefits of the Proposal

This PHY proposal for the IEEE802.16.3 air interface standard presents basic features that meet all the requirements identified in [1], under the critical constraint of low-cost solution to the target markets. A migration approach that will enable an exploitation of current industry standards and systems is indicated. Further advanced features are recommended to improve the performance in a number of ways. Benefits of the proposed PHY and its unique features are outlined below:

1) borrowing key features from **well-established wireless standards**

2) **Adaptive Modulation and Coding -** allowing flexible bandwidth allocation to maximize spectral

3) **Mature and well-proved technology** - build on the footprint of the evolving cable modem technology and efficiency and overall system capacity. For example, near SS can use higher modulation scheme with high coding rate, while far SS or other SS experiencing severe interference profile can use more robust QPSK modulation. AMC exhibits more than 20dB gain relative to non-adaptive schemes (see 2000-10-30 IEEE 802.16.3c-00/39).

4) **Flexible Asymmetry –** supporting high degree of flexibility between deliver upstream and downstream via duplexing schemes; e.g., FDD and TDD.

5) **Scalability -** supporting IP, ATM and MPEG-2 packets with variable-length Packet Data Units (PDU). High immunity to RF impairments and radio equipment impairment. The proposal is based on Single Carrier M-QAM that is less sensitive than OFDM to RF impairments such as: linearity of power amplifier, frequency instability, phase noise, synchronization errors, Doppler spread etc.

6) **Advanced Coding Schemes** – based on Reed-Solomon concatenated with Convolutional codes or Block Turbo Coding (BTC). Both coding techniques provide a good solution for variable packet length with high code rates.

7) **Reduced System Delay -** using advanced Block Turbo Coding that can eliminate the need for a large interleaving. **Reduction in cost, complexity and network architecture simplification**. Advanced single carrier modulation based on M-QAM combined with adequate equalizing techniques and BTC reduces the overall system complexity. Note that a system using SC in uplink and OFDM in downlink is a possible avenue and might reduce subscriber unit complexity and also its power amplifier cost.

8) Easy Migration from simple SC to SC –FDE: that meet more demanding channel impairments and interference at increased spectrum efficiency.

9) An easy migration path to diversity receiver and multiple-input/multiple-output (MIMO): Improving the robustness to interference, channel impairments and radio equipment impairment for applications requiring additional link margin.

10 Similarity to other standards:

The proposed PHY is similar to some extend with TG1 PHY (supporting TDMA multiple access, both TDD and FDD, QPSK/m-QAM, and FEC coding), to some degree with DOCSIS (supporting TDMA multiple access, QPSK/m-QAM, and FEC coding).

11 Statement on Intellectual Property Rights:

All team member companies have read this document and the IEEE patent policy and agree to abide by its terms.

12 References:

[1] IEEE802.16.3-00/02r4, "Functional Requirements for the 802.16.3 Interoperability Standard", dated 2000-09-22.

[2] A. Bolle, O, Eriksson and A. Nascimbene, "Competitive broadband access via microwave technology", Ericsson Review, No. 4, 1998.

[3] R. Van Nee and R. Prasad, "OFDM for Wireless Multimedia Communications", Artech House Publisher, year 2000.

[4] Falconer and S.L Ariyavisitakul, "Modulation and equalization Criteria for 2 11 GHz Fixed Broadband Wireless Systems," IEEE802.16c-00/13.

[5] V. Erceg et al., " A model for the multipath Delay Profile of Fixed wireless Channels," IEEE JSAC, vol. 17 no.3, March 1999, pp.399-410.

[6] V. Erceg et al., " An empirically Based Path Loss Model for the Wireless Channels in Suburban Environments," IEEE JSAC, vol. 17 no.7, July 1999, pp.1205-1211.

[7] H. Kuchibhotla, "Interim Channel Model for G2 MMDS Fixed Wireless Ap

[8] D. Forney, "Burst correcting codes for the classic bursty channel ," IEEE Trans. Comm. COM-19.

[9] IEEE802.16.1pc-00/35.

[10] ETSI EN301 210 V1.1.1 1999.

[11] Hewitt, E, "Turbo Product Codes for LMDS," IEEE Radio and Wireless Conference, August 1998

[12] A Viterbi Algorithm with Soft-Decision Outputs and its Applications, J. Hagenauer, P. Hocher, *IEEE Globecom '89*, Nov. 1989, pp. 1680-1685.

[13] Drury G., Markarian G., Pickavance K. "Coding and Modulation in Digital Tele
ACADEMIC Publishers, 2000, USA.

[14] J. Hagenhauer and E. Offer, "Iterative Decoding of Binary Block and Convolutional Codes," IEEE Trans. Inf. Theory IT-42, March 1996.

[15] J.W. Porter and J.A. Thweatt, “Microwave Propagation Characteristics in the MMDS FrequencyBand”, Proc. Int. Conf. On Commun., New Orleans, June, 2000.

[16] H. Sari, G. Karam, and I. Jeanclaude, "Channel Equalization and Carrier Synchronization in OFDM systems," in Audio and Video Digital Radio Broad- casting Systems and Techniques, R. de Gaudenzi and M. Luise (Editors), pp. 191-202, Elsevier Science Publishers, Amsterdam, The Netherlands, 1994. (Proceedings of the International Tirrenia Workshop in Digital Communications, September 1993, Tirrenia, Italy.)

[17] V. Tarokh and H. Jafarkhani, “On the Computation and Reduction of the Peak-to-Average Ratio in Multicarrier Communications”, IEEE Trans. Commun., Vol. 48, No. 1, Jan., 2000, p. 37-44.

[18] C. Van den Bos, M.H.L. Kouwenhoven and W.A. Serdijn, “The Influence of Nonlinear Distortion on OFDM Bit Error Rate”, Proc. Int. Conf. On Commun., New Orleans, June, 2000.

[19] M.V. Clark, “Adaptive Frequency-Domain Equalization and Diversity Combining for Broadband Wireless Communications”, IEEE JSAC, Vol. 16, No. 8, Oct. 1998, pp. 1385-1395.

[20] 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.

[21] 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. 753-757.

[22] A. Czylwik, “Comparison Between Adaptive OFDM and Single Carrier Modulation with Frequency Domain Equalization”, Proc. VTC ’97, Phoenix , May 1997, p. 865-869.

[23] G. Kadel, “Diversity and Equalization in Frequency Domain A robust and Flexible Receiver Technology for Broadband Mobile Communications Systems”, Proc. VTC ’97, Phoenix.

[24] A. Gusmao, R. Dinis, J. Conceicao and N. Esteves, “Comparison of two Modulation Choices for Broadband Wireless Communications”, Proc. VTC ’00, Tokyo, Japan, vol. 2, June 2000, p. 1300-1305.

[25] IEEE802.16.3p-00/39.

[26] A. Milewski, “Periodic Sequences with Optimal Properties for Channel Estimation and Fast Start-up Equalization”, IEEE J. Research and Development, Sept. 1983, pp. 426-431.

[27] EN301-210, “Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for Digital Satellite News Gathering (DSNG) and other contribution applications by satellite, ETSI, 1998-12.

[28] H. Sari, G. Karam and I. Jeanclaude, “Transmission Techniques for Digital Terrestrial TV EE Comm. Mag., Vol. 33, No. 2, Feb. 1995, pp. 100-109.

[29] H. Sari, G. Karam, and I. Jeanclaude, "An Analysis of Orthogonal Frequency-Division Multiplexing for Mobile Radio Applications," VTC '94 Conf. Rec., vol. 3, pp. 1635-1639, June 1994, Stockholm, Sweden.

[30] H. Sari, G. Karam, and I. Jeanclaude, "Frequency-Domain Equalization of Mobile Radio and Terrestrial Broadcast Channels," GLOBECOM '94 Conf. Rec., vol. 1, pp. 1-5, Nov.-Dec. 1994, San Francisco, California.

[31] H. Sari, "Channel Equalization and Carrier Synchronization Issues in Multicarrier Transmission," Proc. IEEE Workshop on Synchronization and Equalization in Digital Communications, pp. 29-36, May 1995, Ghent, Belgium.

[32] Walzman and Schwartz, “Automatic Equalization Using the Discrete *IEEE Transactions on Information Theory*, Jan. 1973.

[33] R.L Frank and S.A. Zadoff, “Phase Shift Pulse Codes With Good Periodic Correlation Properties”, *IRE Trans. Info. Theory*, Oct. 1962, pp. 381-382.

APPENDIX A: Compliance with the Evaluation Criteria:

Criteria	Response
Meets system requirements	
How well does the proposed PHY protocol meet the requirements described in the current version of the 802.16.3 Functional Requirements Document (FRD)?	FRD Requirements.xls
FRD Compliance Table	
Support for TDD and/or FDD duplexing scheme	yes
Multi-rate support	yes
Support for optional repeater function	yes
Support for QoS	yes
Support for 1.75 to 14 MHz for ETSI mask, 1.5 to 25 Mhz for other masks	yes full compliance for ETSI, data supplied to support FCC mask up to 12 MHz
Channel and System Efficiency	
Gross bit rate at PHY to MAC interface for each mode	
Modulation scheme	adaptible between BPSK and 64QAM
Gross Transmission bit rate	adaptible between ~1 Mbps and 60 Mbps depending on channel mask and modulation format
Sensitivity and 5 dB SNR and PER=10e-2 for 400 Byte packet	See link budgets
Channel Efficiency; %(capacity-overhead/capacity)	varies by modulation format and FEC see sections see Table 9
Spectral Efficiency Bits/second/Hz	s
Simplicity of Realization	
SS cost optimazation	minimum cost of RF circuitry due to reduced back off required for upstream
BS cost optimazation	minimum cost of RF circuitry due to reduced back off required for downstream
Installation cost	minimal, single antenna

Spectrum Resource Flexibility	
Flexibility in use of the frequency band	All channel plans supported
Channel rate flexibility	adaptive modulation and coding used to adjust for channel quality
System Robustness to Channel Fading, Interference and Radio Impairments	
Small and large scale fading	See sections on adaptive modulation, coding and Frequency Domain Equalization
Co-channel and adjacent channel interference	Co-channel and adjacent channel leakage are minimized by reduced linearity requirements of single-carrier modulation
Dgradation due to phase noise, linearity, etc	Single carrier modulation systems have lower linearity and phase noise requirements than OFDM schemes
Compatibility with existing relevant standards and regulations	
Relevant FCC standard	fits spectral mask requirements of 47CFR21.907