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Title	**W-OFDM Submission to IEEE 802.16.3 PHY, Rev. 2.0**
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Re:	This document is based on: W-OFDM Submission to IEEE 802.16.3 PHY http://ieee802.org/16/tg3/contrib/802163c-00_29.pdf This is a response to the IEEE 802.16.3 Task Group, INVITATION TO CONTRIBUTE PHY PROPOSALS: Session #11, dated 2000-12-02. http://ieee802.org/16/tg3/docs/802163-00_24.pdf
Abstract	This document contains a proposal to the IEEE 802.16.3 Task Group for the PHY protocols for a broadband wireless access network standard for licensed bands from 2-11 GHz. This standard is also suitable for unlicensed bands in the 2.4 GHz ISM and 5.7 GHz U-NII unlicensed bands. It is based upon Wideband-Orthogonal Frequency Division Multiplexing (W-OFDM) technology.
Purpose	This document forms the basis and source of a proposed presentation to the IEEE 802.16.3 Task Group at the Working Group Session #11 (22-26 January 2001 in Ottawa, Ontario, CANADA).
Notice	
Release	
Patent Policy and Procedures	

Acknowledgements

The following people have contributed to this document:

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Revision History

Release Date	Document Number	Author	Change summary
2000-09-29	TBD	Adrian Boyer	First Draft.
2000-10-18	TBD	Bob Heise	Second Draft.
2000-10-30	TBD	Bob Heise	Third Draft
2001-01-16	Rev 2.0	Bob Heise	Rev 2

W-OFDM Submission to IEEE 802.16.3 PHY

Bob Heise and Shawn Taylor

Table of Contents

Introduction

This document contains a proposal to the IEEE 802.16.3 Task Group for the PHY protocols for a broadband wireless access network standard for licensed bands from 2-11 GHz. This standard is also suitable for unlicensed bands in the 2.4 GHz ISM and 5.7 GHz U-NII unlicensed bands. It is based upon Wideband-Orthogonal Frequency Division Multiplexing (W-OFDM) technology.

References

The following references have been used during the preparation of this document:

[CALL] IEEE 802.16.3 Task Group, INVITATION TO CONTRIBUTE PHY PROPOSALS: Session #11, dated 2000-12-02, IEEE 602.16.3-00/14.

[FUNCREQ] IEEE 802.16.3 Broadband Wireless Access Working Group, Functional Requirements for the 802.16.3 Interoperability Standard, dated 2000-09-26, IEEE 802.16.3-00/02r4.

Physical Layer

Overview

The following physical layer specification was designed to meet the functional requirements that have been defined for Broadband Wireless Access (BWA) systems. This physical layer is designed with a high degree of flexibility in order to allow service providers the ability to optimize system deployments with respect to cell planning, cost considerations, radio capabilities, offered services, and capacity requirements.

Two modes of operation have been defined for the downstream channel, one targeted to support a continuous transmission stream and one targeted to support a burst transmission stream. Having this separation allows each to be optimized according to their respective design constraints, while resulting in a standard that supports various system requirements and deployment scenarios.

Reference Model

Below are two simple reference models that show the general functions of the transmitter and receiver for the OFDM PHY.

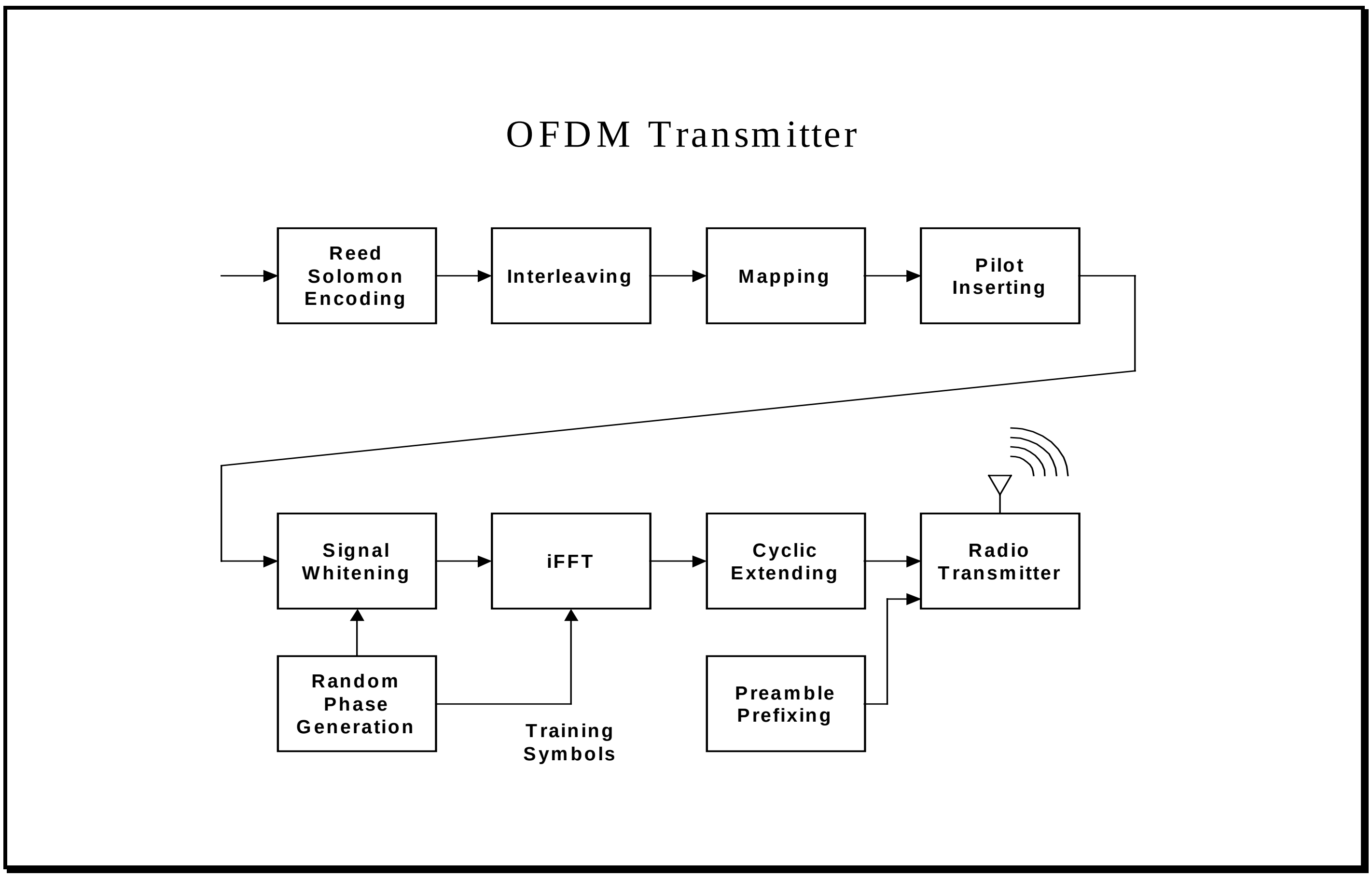

Figure 1: Transmitter Reference Configuration

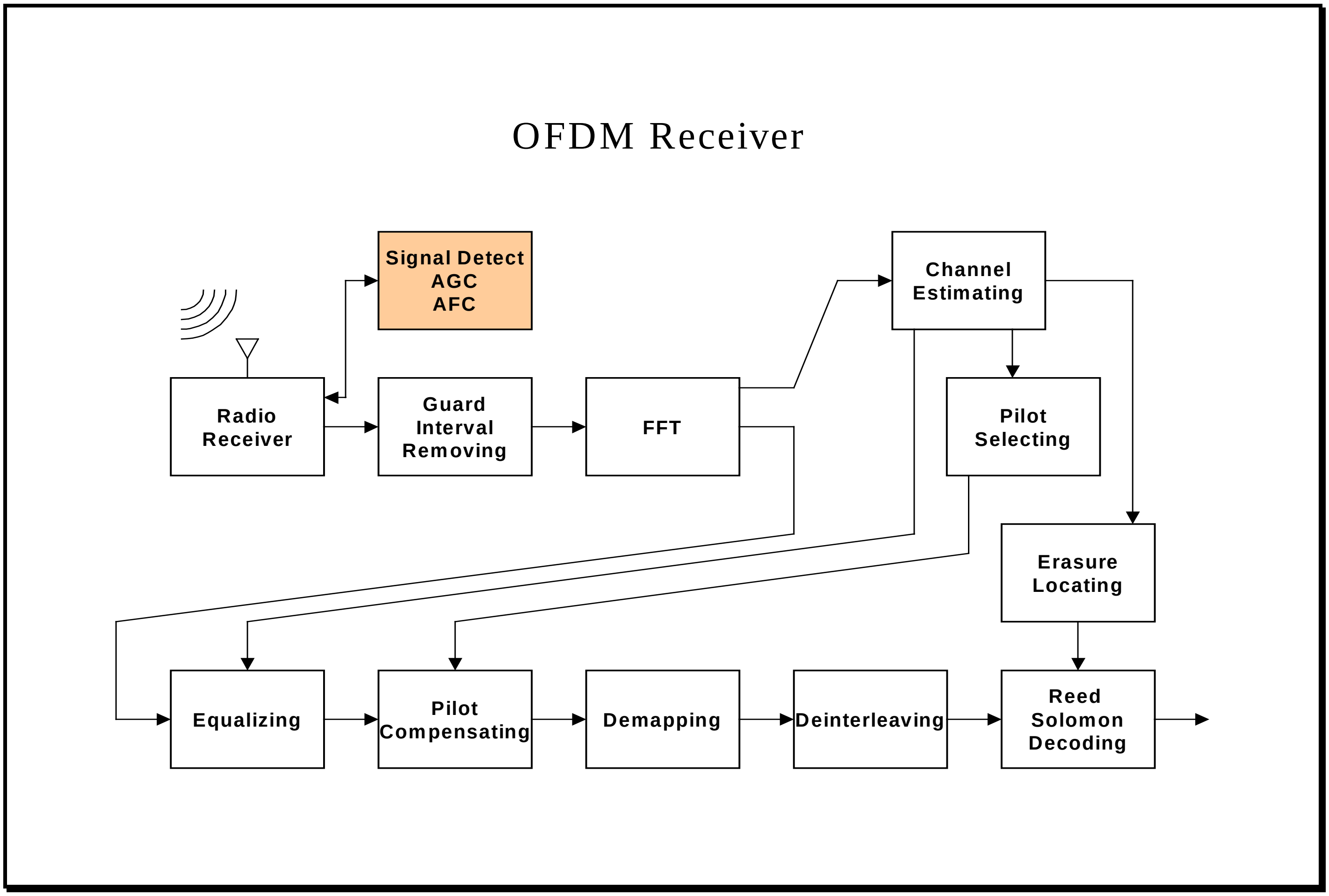

Figure 2: Receiver Reference Configuration

Reed-Solomon Encoding

The forward error correction (FEC) scheme used in this model is Reed-Solomon (RS). Block coding was chosen specifically to address errors due to multipath fading and subcarrier jamming. The OFDM channel estimation provides useful information, which can be used to determine which RS symbols are likely to be in error. This information can be passed on to the RS decoder to improve the RS correction power.

Interleaving

The interleaver maps one RS codeword to one or more OFDM data symbols according to the RS symbol size and the mapping scheme. Ideally, each RS symbol is split such that all of its bits are transmitted on one OFDM subcarrier frequency. This is done to take advantage of the block correcting nature of the RS decoder in the presence of multipath fading or subcarrier jamming.

Mapping

The subcarrier modulation mapping will be BPSK, QPSK, 16QAM, or 64QAM. 256QAM should also be evaluated. A Gray coded constellation mapping is recommended.

Pilot Insertion

Each OFDM data symbol must contain pilot signals in order to recover the proper constellation magnitudes and the proper constellation phases. Constellation phase rotations are caused by carrier offsets.

Random Phase Generation

This function creates a set of Random Phase Vectors, which are used to whiten the transmitted signal.

Signal Whitening

Each mapped data point is multiplied by a random phase. This is done to reduce the peak-to-average power ratio of an OFDM data symbol.

iFFT

The inverse FFT transforms the data from the frequency domain into the time domain for transmission over the RF channel. Two FFT sizes are proposed and will be selectable depending upon the channel characteristics. The proposed FFT sizes are 64 points, and 256 points.

Training Symbols

The random phase vectors are used as training symbols. The same training symbol is sent several times to provide a measure of noise immunity to the channel estimation. The receiver uses these training symbols to perform the channel estimation.

Cyclic Extending

Each time-domain OFDM data symbol is extended, by copying a portion from one end of the symbol to the other. This is done to make the OFDM data robust against multipath delays. The length of the extension will be selectable over a range of samples.

Preamble Prefixing

A preamble must be added to each OFDM packet. The receiver uses the preamble for:

- Packet synchronization
- Automatic Gain Control (AGC)
- Carrier Frequency Offset Compensation

It can also be used for signaling certain PHY parameters such as the FFT size.

Channel Estimating

This function creates an equalization vector by taking the complex reciprocal of each subcarrier in the average OFDM training symbol. It also creates a subcarrier magnitudes vector, which can be used by the Pilot Selecting function and the Erasure Locating Function.

Pilot Selecting

The magnitudes vector created by the channel estimator is used to determine which pilot symbols should be used in the pilot compensation. If some pilots are in deep fades while others are not, then the pilots in deep fades should not be used in the pilot compensation algorithm.

Erasure Locating

The magnitudes vector created by the channel estimator is used to determine which RS symbols within an RS codeword are likely to be in error. If some RS symbols are deemed much more likely to be in error, they can be erased, and if they are in fact in error, then the correction power of the RS decoder can be increased.

Equalizing

Each OFDM data symbol is equalized, in an attempt to restore the relative position of each constellation point with respect to the pilot symbols. This process will compensate each subcarrier on an individual basis as well as undo the phase randomization.

Pilot Compensating

Pilot compensation attempts to recover the transmitted constellation on the receiver.

OFDM Frame Format

The format of the OFDM frame is depicted below.

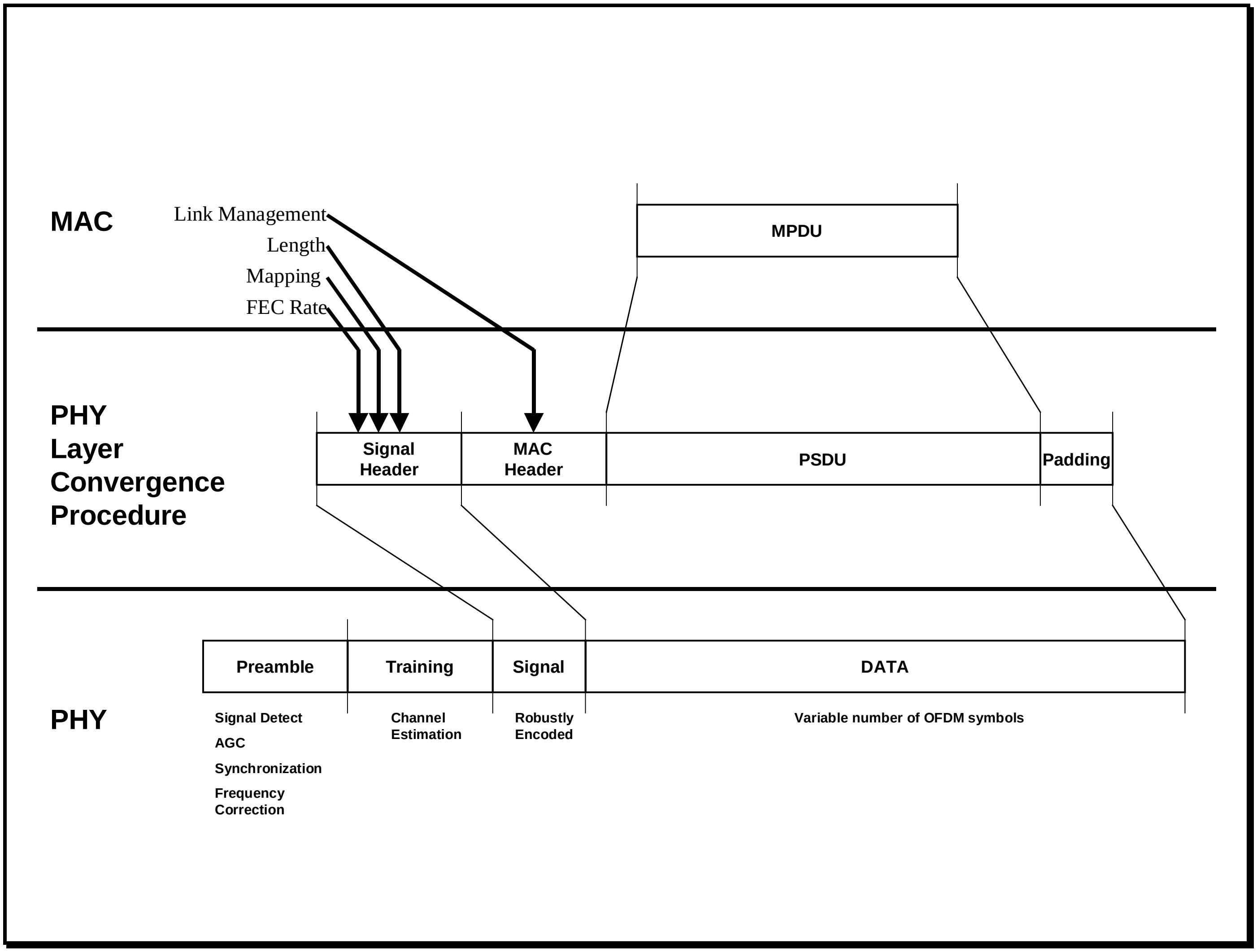

Figure 3: OFDM Frame Format

Upper Layer Interfaces

The MAC should send the following information to the PHY:

- Data Length
- Data
- Modulation (Mapping) Rate
- FEC Rate
- Tx Power
- Tx Time
- Tx Center frequency
- Rx Center frequency

The PHY should send the following information to the MAC

- Data Length
- Data
- RSSI
- BER
- Rx Time

Channel and Data Rate Analysis

The PHY supports various channel sizes. The supported channels are 1.75, 3.5, and 7MHz, and 1.5 to 25MHz. The channel size is selected by adjusting the system clock.

A performance analysis for a 3MHz channel, of the two FFT sizes, with the various recommended modulation and coding rates is presented in the table below. The performance of channel sizes will almost be proportional to channel size. Only the guard interval prevents the data rate from being directly proportional to the channel size.

Channel Size (MHz)	OFDM FFT Size	Data Subcarriers	Pilots per Symbol	Coding Rate	Mapping	Coded Bits per Subcarrier	Coded Bits per OFDM symbol	Guard Interval (µs)	Data Rate (Mbit/s)
3.00	64	48	4	3/4	BPSK	1	48	2.00	1.542857
3.00	64	48	4	3/4	QPSK	2	96	2.00	3.085714
3.00	64	48	4	3/4	16QAM	4	192	2.00	6.171429
3.00	64	48	4	3/4	64QAM	6	288	2.00	9.257143
3.00	256	216	8	23/27	BPSK	1	216	2.00	2.106870
3.00	256	216	8	23/27	QPSK	2	432	2.00	4.213740
3.00	256	216	8	23/27	16QAM	4	864	2.00	8.427481
3.00	256	216	8	23/27	64QAM	6	1296	2.00	12.641221

Figure 4: Performance Analysis of 3MHz Channel

Evaluation Criteria

1 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)?

This OFDM-based PHY can meet the 802.16.3 FRD requirements. Not all of the requirements are addressed in this proposal, as this is still a fairly high-level document. This PHY must be properly combined with a compatible MAC to ensure that all requirements are met.

2 Channel spectrum efficiency

Channel spectrum efficiency -defined in terms of single channel capacity (TDD or FDD) assuming all available spectrum is being utilized (in terms of bits/sec/Hz). Supply details of PHY overhead.

- ***Modulation Scheme***
- ***Gross Transmission Bit Rate***
- ***User information bit rate at PHY-to-MAC Interface***
- ***Occupied Bandwidth***

The modulation technique is OFDM. There are many factors to consider for channel spectrum efficiency. Some of them are:

- Cyclic extension (based on channel delay spread)
- FFT size
- QAM constellation mapping size
- Coding Rate

With these parameters the OFDM PHY has many possible configurations. Quality of Service, Latency, Channel Delay, Data Rate, and Packet Size must all be considered when choosing the parameters.

For the 3.0 MHz channel spacing used earlier in this proposal the spectrum efficiency can easily vary between 0.51 bit/sec/Hz to 4.21 bits/sec/Hz, and the data rates range between 1.54 Mbit/sec and 12.64 Mbit/sec.

3 Simplicity of Implementation

How well does the proposed PHY allow for simple implementation or how does it leverage on existing technologies? For example:

- ***SS cost optimization. How does the proposed PHY affect SS cost.***
- ***BS cost optimization. How does the proposed PHY affect BS cost.***
- ***Installation cost***

OFDM is quickly gaining widespread acceptance for wireless communications. The basic building blocks for OFDM are now well known and readily available individually or as complete systems. OFDM chipsets are already available.

Installation costs should be relatively low because of OFDM's robustness to multipath. It is not necessary to spend a lot of time aligning antennas.

4 Spectrum Resource Flexibility

- ***a) Flexibility in the use of the frequency band (i.e. channelization, modularity, band pairing ,and Upstream/Downstream data asymmetry)***
- ***b) Channel rate Flexibility. Data rate adjustment capability at PHY to accommodate the channel quality variations.***

The proposed PHY is very flexible and can be scaled to almost any channel size and channel spacing. The various configuration parameters defining the PHY make it very modular. Upstream and Downstream parameters can be defined independently for asymmetric Upstream/Downstream operation.

The data rate can be adjusted according to channel quality variations by using various combinations of constellation mapping and coding rates.

5 System Spectral Efficiency

Defined in terms of available capacity, availability and coverage (in bits/sec/Hz/cell.)

Takes into account re-use factor, and interference rejection capability. Tested with the number of cells needed to cover a predefined scenario.

For the 3.0 MHz channel spacing used earlier in this proposal the spectrum efficiency can easily vary between 0.51 bit/sec/Hz to 4.21 bits/sec/Hz on a per sector basis. Deployments include options for 3, 4 or 6 sectors per cell. There are also options for TDD, FDD and time division sector interleaving (TDSI).

6 System Service Flexibility

How flexible is the proposed PHY to support FRD optional services and potential future services?

The proposed PHY can be made as flexible as need be for optional services and potential future services.

7 Protocol Interfacing complexity

Interaction with other layers of the protocol, specifically MAC and Network Management. Provide the PHY delay.

The proposed PHY requires a compatible MAC. Data movement will be optimized for IP traffic. The MAC will also have the capability to control the various adaptable parameters within the PHY.
The PHY delay varies greatly depending on the chosen adaptable parameters. For example the latency when using a 64 point FFT with 64-QAM will be less than a 256 point FFT with BPSK. It is foreseen that problems with PHY latency will be mitigated by the MAC's multiple access protocol.

8 Reference System Gain

Sector coverage performance for a typical BWA deployment scenario (supply reference system gain). Provide practical link budget analysis. (Refer to Gain definition within FRD).

Transmit Power (dBm)	23
Transmit Antenna Gain (dBi)	16
Receive Antenna Gain (dBi)	18
Receive Sensitivity (dBm)	-75
Cable/Connector Loss (dB)	1
Overall System Gain (dB)	131

Table 1. Link budget of downlink deployment

Table 1 shows a link budget of a realistic deployment using 16-QAM. The transmit power is at a sufficient level so that there is no amplifier saturation. The receive sensitivity takes into account the coding gain, noise figure of the amplifier, implementation loss and required signal to noise ratio (SNR) for 16-QAM.

9 Robustness to interference

Resistance to intra-system interference (i.e. frequency re-use) and external interference cause by other systems.

Provide co-channel, adjacent channel interference levels and spectral spillage resulting from modulation.

The forward error correction scheme used in this PHY make it robust to interferers both within the system and without.

10 Robustness to channel impairments

Small and large scale fading (Rain fading, multipath, N(non or near) LOS, Foliage effect, Frequency Selective fading, atmospheric effects.)

One of the biggest advantages of OFDM is its robustness to multipath. OFDM uses a frequency-domain equalizer together with FEC to combat multipath problems. Various coding rates are supported to combat other channel impairments. It will be up to the MAC to negotiate a new data rate based on link degradation information obtained from the PHY.

11 Robustness to radio impairments

Specify the degradation due to radio impairments such as phase noise group delay of filters, amplifier nonlinearities, etc.

OFDM is sensitive to amplifier non-linearities. However, pre-distortion techniques and PA back-off can be used to minimize these effects. Phase noise should not be a problem with FFT sizes of 64 and 256.

All but the most excessive group delay can easily be handled by the channel estimation.

12 Support of advanced antenna techniques

Specify how the system would support advanced techniques, such as smart antennas, diversity, or space-time coding.

This proposed OFDM system would be able to support advanced antenna techniques such as smart antennas, beam forming, beam switching, diversity, or space-time coding. These techniques can be implemented either in time domain (before the FFT) or in frequency domain (after the FFT). Time domain implementation is relatively easy. It requires a module before the OFDM processor, and some corresponding hardware changes for the RF part. Frequency domain implementation requires an additional module after OFDM processor. This module would perform functions such as channel estimation, smart antenna algorithm, etc.

13 Compatibility with existing relevant standards and regulations

There are no existing standards that satisfy all the requirements for this standard. This OFDM based proposal has the same benefits as other OFDM based standards (IEEE 802.11a, HIPERLAN/2) with the additional benefit of being optimized for the targeted channels.   This PHY will be compatible with any regulations for BWA frequencies.

Summary

Benefits of PHY

- OFDM is very spectrally efficient. This is very important with the RF spectrum becoming increasing crowded.
- OFDM can be used in TDD or FDD modes of operation.
- OFDM can be easily configured for various channel characteristics.
- OFDM is robust to channel impairments caused by multipath.
- Reed-Solomon with erasures complements OFDM very well, especially when the RF channel is non-ideal. Occurrences of errors due to multipath nulls or jammers may be predictable and erasable.
- Reed-Solomon provides quality of service information based on the occurrence of correctable errors. This may allow the link data rates to be adjusted and optimized without any uncorrectable errors occurring.
- OFDM is already used in other standards. Ultimately this will result in low cost implementation alternatives.

Drawbacks of PHY

The nature of the orthogonal encoding gives rise to high peak-to-average signals; or in other words, signals with a large dynamic range. This means that only highly linear, low-efficiency RF amplifiers can be used.

Comparison to Existing Standards

This proposed standard is similar to IEEE 802.11a and ETSI HIPERLAN Type 2, in that it is based on OFDM. The main difference is that the proposed system is optimized for the types of channels which will be encountered by the IEEE 802.16.3 standard.

Intellectual Property Rights

Wi-LAN offered to license its W-OFDM technology in July 1998 to all interested parties on fair, reasonable and non-discriminatory terms. See US patent number 5,282,222.

Appendix A: Acronyms and Abbreviations

ATDD	Adaptive Time Division Duplexing
BR	Bandwidth Request
BS	Base Station
CG	Continuous Grant
CID	Connection Identifier.
CPE	Customer Premises Equipment (equivalent to SS)
CS	Convergence Subprocess
CSI	Convergence Subprocess Indicator
CTG	CPE Transition Gap
DAMA	Demand Assign Multiple Access
DES	Data Encryption Standard
DL	Down Link
DSA	Dynamic Service Addition
DSC	Dynamic Service Change
DSD	Dynamic Service Deletion
EC	Encryption Control
EKS	Encryption Key Sequence
FC	Fragment Control
FDD	Frequency Division Duplex
FSN	Fragment Sequence Number
GM	Grant Management
GPC	Grant Per Connection
GPT	Grant Per Terminal
HCS	Header Check Sequence
H-FDD	Half-duplex FDD
HL-MAA	High Level Media Access Arbitration
HT	Header Type
IE	Information Element
IUC	Interval Usage Code
LL-MAA	Low Level Media Access Arbitration

MAC	Medium Access Control
MIC	Message Integrity Check
MPDU	MAC Protocol Data Unit
MTG	Modulation Transition Gap
OFDM	Orthogonal Frequency Division Multiplexing
PCD	Physical Channel Descriptor
PBR	Piggy-Back Request
PDU	Protocol Data Unit
PHY	Physical layer
PI PHY	PHY Information element
PKM	Privacy Key Management
PM	Poll Me bit
PS	Physical Slot
PSDU	Physical sublayer Service Data Unit
QoS	Quality of Service
RS	Reed-Solomon
SAP	Service Access Point
SI	Slip Indicator
SDU	Service Data Unit
SS	Subscriber Station
TC	Transmission Convergence
TDD	Time Division Duplex
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TDU	TC Data Unit
TLV	Type-Length-Value
TRGT	Tx/Rx Transmission Gap
UGS	Unsolicited Grant Service
UGS-AD	Unsolicited Grant Service with Activity Detection
UL	Link
W-OFDM	Wideband - Orthogonal Frequency Division Multiplexing