Project	**IEEE 802.16 Broadband Wireless Access Working Group**
Title	**Proposal for an OFDM-based 802.16 BWA Air Interface Physical Layer**
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Re:	In response to Call for Proposals for the BWA PHY layer from Sep 22, 1999.
Abstract	A Physical Layer based on OFDM modulation with parameters similar to 802.11a, HIPERLAN/2 and MMAC is presented. The PHY covers data rates of 6.7 to 60 Mbit/s with 20 MHz channel spacing. The OFDM based PHY exhibits, in addition to good link budget, excellent multipath robustness. Aligning the BWA PHY with a contemporary high-speed wireless LAN PHY standard will result in widely available, cost effective and high-performance solution.
Purpose	To present a proposal which will serve as a baseline of the BWA PHY layer.
Notice	
Release	
IEEE Patent Policy	

Proposal for an OFDM-based 802.16 BWA Air Interface Physical Layer

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1 General

1.1 Background

The author of this proposal chairs the Task Group *a* of 802.11, which recently completed the development and the approval of a high speed Physical Layer in the 5 GHz band for 802.11 wireless LANs. The group has chosen, after thorough technical comparison, the OFDM as the preferred modulation method. The PHY developed by the Task Group covers data-rate range of 6 to 54 Mbit/s. The Task Group has tightly collaborated with two other standards bodies, ETSI BRAN project HIPERLAN type 2 and the Japanese MMAC (Mobile Multimedia Advisory Council) in aligning the Physical Layer parameters of the respective projects. As a result of this collaboration, the author envisions availability of OFDM-based Physical Layer components from several vendors, which will reduce in price due to economy of scale.

By adopting the 802.11a/HIPERLAN/MMAC-related OFDM-based Physical Layer the 802.16 BWA will have a high performance, multipath-robust and cost-efficient solution. The author intends to bring this proposal also for consideration by the BRAN HIPERACCESS project. Adoption of an OFDM based PHY by these bodies will improve further the economy of scale.

1.2 Introduction

The purpose of this paper is to propose a Physical Layer for the 802.16 BWA based on Orthogonal Frequency Division Modulation (OFDM). The parameters of the proposed Physical Layer are close to those of the 802.11a high speed PHY in the 5 GHz band for Wireless LANs.

The OFDM parameters of the proposed PHY are:

- Channel spacing of 20 MHz, signal bandwidth of approximately 16.6 MHz.
- Data rates rates ranging from 6.67 Mbit/s to 60 Mbit/s
- 52 subcarriers with 20 MHz / 64 = 312.5 KHz spacing
- 48 data carrying subcarriers and 4 pilot subcarriers for carrier phase reference.
- BPSK, QPSK, 16-QAM or 64QAM modulation on each subcarrier with Gray-coded constellation mapping
- Binary convolutional coding with bit interleaving.
- K=7, R=1/2 industry standard convolutional code with puncturing to rates of R=3/4 and R=2/3.
- Block interleaver with block size equal to a single OFDM symbol.
- OFDM symbol duration of 3.6 microseconds, composed of 3.2 microsecond Fourier period and 0.4 microsecond Guard Interval (GI). Note the proposed GI duration is shorter than in the 802.11a (0.8 usec)

The rest of the paper will discuss the performance of the proposed PHY, it's commonality and differences relative to 802.11a and HIPERLAN. At the end we will address the BWA comparison criteria.

1.3 Abbreviations and Acronyms

OFDM	Orthogonal Frequency Division Multiplex
BPSK	Binary Phase Shift Keying
QPSK	Quaternary Phase Shift Keying
QAM	Quadrature Amplitude Modulation
BER	Bit Error Rate
PER	Packet Error Rate

2 Reference documents

[Ref1] P802.11aD7.0. - Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High Speed Physical Layer in the 5 GHz Band.

[Ref2] ETSI Broadband Radio Access Networks (BRAN); HIPERLAN Type 2 Technical Specification; Physical (PHY) layer

3 Main parameters of the proposed OFDM Physical Layer

3.1 Number of Subcarriers

The OFDM PHY is based on using 52 subcarriers, of which 4 are designated as pilots. The use of pilot subcarriers facilitates the use of coherent modulations on the data subcarriers. In addition, it facilitates the use of advanced coding techniques, because the carrier tracking loop does not rely on unreliable tentative decisions.

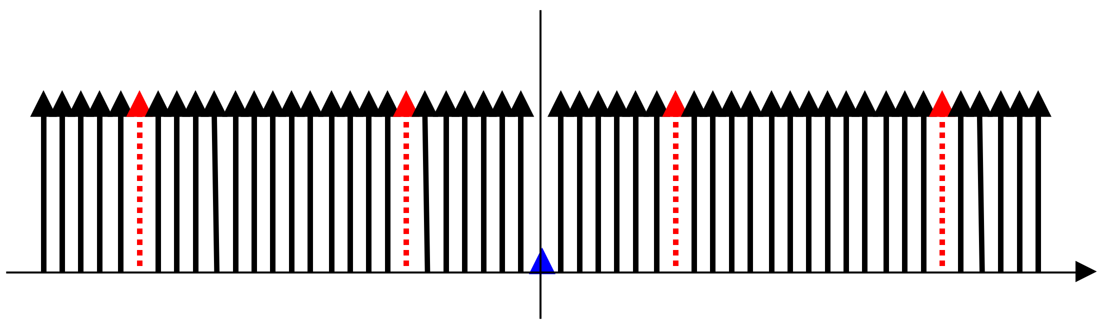


Figure 1 Frequency plan of the data and pilot subcarriers

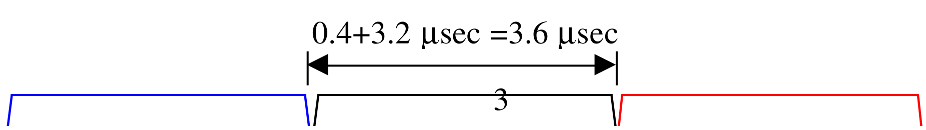
The use of 312.5 KHz (20 MHz/64) carrier spacing implies a 64 point FFT in the implementation. Using 52 out of 64 subcarriers leaves guard bands on the edges, which facilitate anti-aliasing filtering.

The center subcarrier is not utilized. This small sacrifice in bandwidth is paid for an important implementation consideration. The quadrature modulators used to impose the I/Q information onto the carrier frequency exhibit some carrier leakage, which degrades the subcarrier locarted at the center.

The number of subcarriers is a compromise of several factors. Increasing the number of subcarriers improves the multipath robustness and reduces the "guard interval" overhead. On the other hand, it increases the phase noise sensitivity and makes the granularity of the packet size/dutation coarse.

3.2 Guard Interval

The data is imposed onto the subcarriers, which are subsequently transformed into time domain by an inverse Fourier transform (IFFT). The resulting waveform is periodic with 3.2 microsecond periodicity (1/312.5 KHz). One period of the waveform is sufficient for conveying the data imposed on that group of subcarriers, however it is common practice to extend the transmitted waveform by the so-called Guard Interval (GI). The Guard interval prevents the adjacent symbol echoes from leaking into the symbol being currently demodulated, as illustrated in Figure 2.



FFT interval

Figure 2 The robustness of OFDM to multipath due to Guard Interval

The length of the Guard Interval is directly related to the duration of the anticipated multipath. The 802.11a and HIPERLAN standards recommend 0.8 microsecond GI. HIPERLAN/2 in the "direct link" mode enables an optional 0.4 microsecond GI mode, since in the home environment the multipath is expected to be shorter in time.

Our recommendation for the 802.16 BWA project is to use GI of 0.4 microseconds. The multipath expected with directional antennae in millimeter-wave frequencies is relatively short, and it does not justify the 0.8 microsecond GI. On the other hand, it should not be excessively shortened, because some of the "multipath" comes from the analog filters in the transmitter and the receiver, irrespectively from the medium.

By shortening the Guard interval the data rates are increased by the factor of 4.0/3.6 = 1.111. Therefore, instead of data rates of 6 to 54 Mbit/s of 802.11a and HIPERLAN data rates of 6.67 to 60 Mbit/s are achieved.

3.3 Preamble Structure

Receiving an OFDM packet requires an acquisition of several parameters. In 802.11a a preamble was designed which facilitates the reception of a packet without any prior knowledge about its timing, frequency offset, phase and channel response. The 802.11a preamble is divided into three parts:

- The "short training sequence" part, used for signal detection, AGC convergence, antenna diversity selection, coarse timing and frequency estimation. This part is composed of 10 periods of 0.8 microsecond long waveform.
- The "long training sequence" part, used for fine timing and frequency estimation and for channel estimation. This part is composed of two repetitions of a 3.2 microsecond long sequence, with an increased guard interval. The frequency estimation may be accomplished by comparing the phases of two repetitions of the training sequence.
- The SIGNAL field is a single OFDM symbol, which conveys 18 bits of data containing the packet data rate and length.

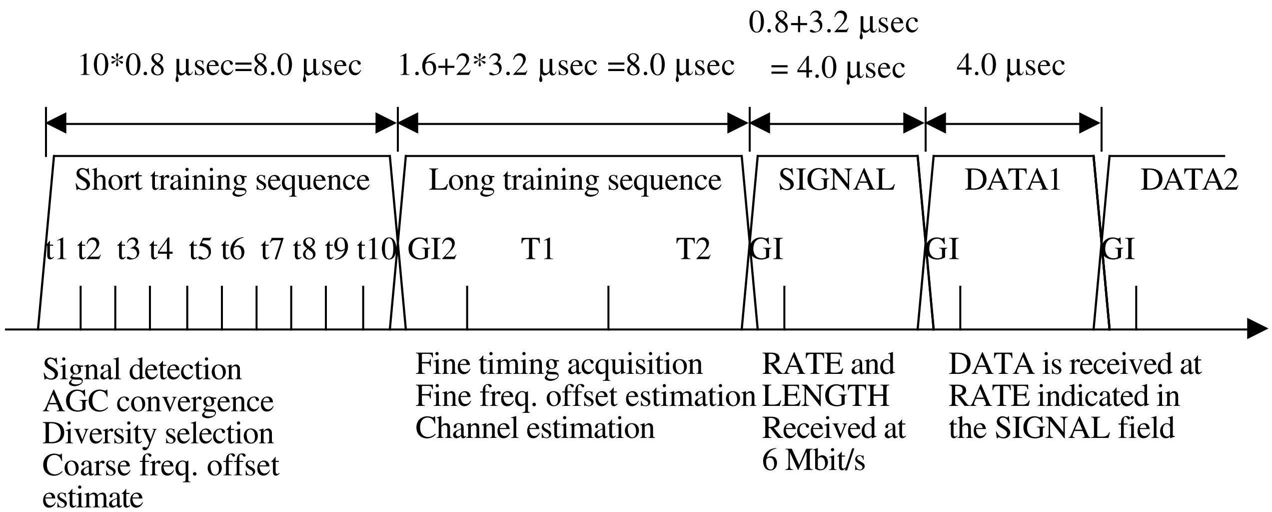


Figure 3 The 802.11a preamble and packet structure

In HIPERLAN there are several variations on the same theme.

- In the short training sequence not all the short sequences are identical.
- There are several type of preamble. For example, 4 microsecond long "short training sequence" can be used, or it can be omitted entirely, depending on the amount of prior knowledge about the AGC setting, timing offset etc.
- The SIGNAL field is omitted. The PHY is instructed from the DLC (MAC) layer what the anticipated data rate and length of the arriving packet are.

Our recommendation to the 802.16 BWA is to use 802.11a-like preamble with the following parameter changes:

- Use short training sequence with 9 identical 0.8 usec long sequences, 9*0.8=7.2 microseconds.
- Use long training sequence with two repetitions and 0.8 usec long GI, 2*3.2+0.8 = 7.2 microseconds.
- Define shortened training sequences for packets with prior knowledge, as in HIPERLAN. This is especially beneficial in short packets such as reservations.
- The SIGNAL field may be omitted, as in HIPERLAN. The PHY can be instructed from the DLC (MAC) layer what the anticipated data rate and length of the arriving packet are.

3.4 Error Correction Coding

The error correction coding used in 802.11a and HIPERLAN is based on binary convolutional codes. The industry veteran K=7, R=1/2 convolutional code is used, with R=2/3 and R=3/4 coding rates derived by puncturing (omitting coded bits on the Tx side and inserting "zero metric" on the Rx side).

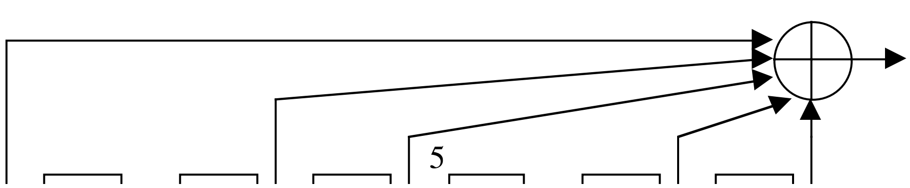


Figure 4 Convolutional encoder with K=7, R=1/2, g1=133_8 , g2=171_8

The encoded bits are interleaved (reordered), divided into groups of 1, 2, 4 or 6 bits, depending on the constellation, mapped onto the constellation values and then OFDM-modulated.

3.4.1 Packet termination

The convolutional codes are designed for continuous streams of data. When used for packet data, care is needed in handling the beginning and the end of the packet. The common practice, implemented in 802.11a and in HIPERLAN is to zero the contents of the shift register in the beginning and to feed extra 6 zero-value “tail bits” at the end of the packet until the contents of the shift register is flushed. This process is called “trellis termination” and it assists the Viterbi decoder to decode correctly the last bits of the packet.

In HIPERLAN the data “atoms” are 54 bytes long and they accommodate an integral number of OFDM symbols. In order to avoid loosing this property due to the 6 extra tail bits, an extra “puncturing” process is used, omitting 12 coded bits. In 802.11a the extra puncturing is not used, because anyway the packet sizes are variable with a granularity of a single byte. BWA can choose either to implement this procedure or not, depending on the approach taken to fragmenting the data.

3.4.2 Interleaving

The interleaving used in the 802.11a and HIPERLAN/2 serves the purpose of spreading adjacent coded bits among distant subcarriers. In addition, adjacent bits are assigned different significance in the constellation (MSB, LSB) in order to avoid clusters of less reliable bits. Interleaving over longer blocks improves the reliability, but incurs penalty on the encoding and decoding latency and the block size granularity. Both 802.11a and HIPERLAN/2 agreed to perform the interleaving over blocks of bits constituting one OFDM symbol. The number of bits per OFDM symbol depends on the data rate, and is summarized in the following table.

Table 1 Number of bits per OFDM symbol

Modulation	Coding rate	Data Rate	Number of coded bits per symbol	Number of data bits per symbol
BPSK	R=1/2	6.67 Mbit/s	48	24
BPSK	R=3/4	10 Mbit/s	48	36
QPSK	R=1/2	13.22 Mbit/s	96	48
QPSK	R=3/4	20 Mbit/s	96	72
16QAM	R=1/2	27.77 Mbit/s	192	96
16QAM	R=3/4	40 Mbit/s	192	144
64QAM	R=2/3	53.33 Mbit/s	288	192
64QAM	R=3/4	60 Mbit/s	288	216

3.5 Data Rates

The data rates are based on the use of BPSK, QPSK, 16QAM or 64QAM constellations. In conjunction with coding rates of R=1/2, 2/3 or 3/4, the following data rates are obtained:

Table 2 Data rates versus constellation and coding rate

Coding rate Constellation	R=1/2	R=2/3	R=3/4
BPSK	6.67 Mbit/s	8.89 Mbit/s	10 Mbit/s
QPSK	13.22 Mbit/s	17.77 Mbit/s	20 Mbit/s
16QAM	27.77 Mbit/s	35.55 Mbit/s	40 Mbit/s
64QAM	(40 Mbit/s)	53.33 Mbit/s	60 Mbit/s

3.6 Flexibilities

The basic ideas presented above can be aplied in many ways. For example, multiple payloads, each with its own data rate and with its own code termination and CRC can be concatenated into a single packet. Preambles can be shortened whenever prior information exists. HIPERLAN is a good example of a standard which took advantage of such flexibilities and which can be incorporated into BWA.

4 Summary

The OFDM based Physical Layer has numerous advantages for BWA systems. In addition to its good link gain performance, it excels in multipath robustness, it’s scalable due to it’s variable rate support, its phase noise requirements are comparable to single carrier systems.

Chip-sets implementing this Physical Layer will become available due to the implementation efforts of 802.11a and HIPERLAN device developers. These chipsets will be available from several vendors and will be competitively priced.

For all those reasons we see in 802.11a/HIPERLAN2-like PHY an excelent candidate for the 802.16 BWA Physical Layer.

5 Addressing the Evaluation Criteria

5.1 Meets system requirements

How well does the proposed PHY protocol meet the requirements described in the current version of the 802.16 System Requirements (Document IEEE 802.16s0-99/n)?

The proposed OFDM-based PHY was already chosen by projects of similar scope, both by 802.11a, which is connectionless by nature, and by HIPERLAN/2 which is tightly managed and is ATM-oriented. We are confident that by coupling the proposed PHY with an appropriate MAC and by exploiting the flexibilities inherent in it (data rates, preamble overheads etc.) the proposed PHY can meet the 802.16 system requirements.

5.2 Spectrum efficiency

Defined in terms of single sector capacity assuming all available spectrum is being utilized (either in terms of Gbps/Available Spectrum or in terms of Mbps/MHz)

The specific proposal covers data rates of 6.7 Mbit/s up to 60 Mbit/s with 20 MHz channel spacing. This translates to a single-sector capacity of 0.33 bit/sec/Hz up to 3 bits/sec/Hz.

5.3 Simplicity of implementation

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

The proposed PHY draws on recently adopted standards – 802.11a and HIPERLAN/2 PHY. These committees decided that the technology described here is implementable with a reasonable effort. OFDM based standards of even more ambitious scale, such as DVB-T and dTTb, are destined for consumer use. We believe that aligning the WBA Physical Layer with 802.11a and HIPERLAN technologies will facilitate availability of competitively priced chip-sets supporting this technology.

5.4 CPE cost optimization

How does the proposed PHY affect CPE cost?

We believe that aligning the WBA Physical Layer with 802.11a and HIPERLAN technologies will facilitate availability of competitively priced chip-sets supporting this technology.

5.5 Spectrum resource flexibility

Flexibility in the use of the frequency band (i.e., minimum frequency band required to operate and migration capabilities)

The minimum channel width in the current proposal is 20 MHz. This needs to be multiplied by the number of channels needed. This highly depends on sectorization and polarization planning. Assuming that 4 frequencies are sufficient, an operator will need 80 MHz.

5.6 System diversity flexibility

How flexible is the proposed PHY to any other system variations and future technology improvements or new services?

With an appropriate MAC layer, the PHY is capable of supporting both synchronous and asynchronous services. Future services can be accomodated by defining appropriate Convergence Layers in the MAC. One issue of concern in increasing data rates in the future. This can be accomplished, for example, by creating wider channels and increasing the number of subcarriers, while maintainint the OFDM symbol duration. The basic ideas presented contain flexibilities which can support multiple enhancements in the future.

5.7 Protocol Interfacing complexity

Interaction with other layers of the protocol, specifically MAC and NMS

The proposed PHY draws on recently adopted standards – 802.11a and HIPERLAN/2 PHY. In particular, HIPERLAN system is tightly managed and based on resource allocation and therefor is a good baseline for comparison with BWA. We believe that the MAC-PHY integration complexity of the WBA is commensurate with HIPERLAN/2 and 802.11a projects. Given that these projects approved the OFDM based PHY and successfully defined MAC/DLC layers for it indicates that it can be done for BWA as well.

5.8 Implication on other network interfaces

Intrinsic transport efficiency of telecomm and datacomm services

Again, the reader is referred to the HIPERLAN/2 example.

5.9 Reference system gain*

Sector coverage performance for a typical BWA deployment scenario (supply, reference system gain)

The table below summarizes the sensitivities, the transmit power and the system gain (link loss) for a hypothetical system at different data rates. The receive sensitivity assumes 0 dB noise figure and 2 dB implementation degradation. The receive sensitivity is derived from simulations conducted in 802.11a and those include the loss due to channel estimation inaccuracy and carrier phase error degradation. The transmit power assumes 0 dBW = 30 dBm saturated transmit power. The backoffs are taken relative to the saturated power. The backoffs at BPSK can be reduced even further, but that comes at expense of adjacent channel interference, and a more conservative value is taken.

Table 3 Link budget versus data rate

Data Rate	Sensitivity NF=0 dB degr.=2 dB	Backoff	Transmit power	System gain (link loss)
6.67 Mbit/s	-95 dBm	7 dB	23 dBm	118 dB
10 Mbit/s	-94 dBm	7 dB	23 dBm	117 dB
13.22 Mbit/s	-92 dBm	7 dB	23 dBm	115 dB
20 Mbit/s	-90 dBm	7 dB	23 dBm	113 dB
27.77 Mbit/s	-87 dBm	7 dB	23 dBm	110 dB
40 Mbit/s	-83 dBm	7 dB	23 dBm	106 dB
53.33 Mbit/s	-79 dBm	9 dB	21 dBm	100 dB
60 Mbit/s	-78 dBm	9 dB	21 dBm	99 dB

5.10 Robustness to interference

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

By the nature of the proposed PHY and the strong Error Correction Coding, the system has good interference rejection properties. Specific C/I data will be brought at later stage.

5.11 Robustness to channel impairments

Rain fading, multipath, atmospheric effects

The multipath robustness of OFDM is its main strength. It enables equalizing channels with multiple notches in frequency, and yet maintaining considerable coding gain. Regarding atmospheric effects and rain in particular, those mainly appear as a time-varying attenuation. The proposed PHY contains a support for multiple data rates, so that the system can fall back to lower rates in case of large attenuation. This requires the support of the MAC layer which will detect the link degradation, will negotiate new data rate and will prioritize the traffic according to the new system capacity. All this needs to be done at time scales commensurate with the evolution of the atmospheric phenomena related attenuation.