Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**OFDM-based 802.16.3 sub-11 GHz BWA Air Interface Physical Layer proposal**
Date Submitted	**2000-10-30**
Source	Naftali Chayat and Tal Kaitz　　　　　　　　Voice:　+972-3-6456262 BreezeCOM　　　　　　　　　　　　　　　　Fax:　　+972-3-6456222 Atidim Tech Park, Bldg. 1　　　　　　　　　　E-mail: naftalic,talk@breezecom.co.il Tel Aviv 61131, ISRAEL
Re:	In response to Call for Initial Proposals for the 802.16.3 sub-11 BWA PHY layer from Sep 15, 2000.
Abstract	A Physical Layer based on OFDM modulation with parameters similar to 802.11a and HIPERLAN/2 is presented. The channel spacing is rescaled to address the 802.16.3 scenarios. The PHY covers data rates of 1.33 to 12 Mbit/s with 3.5 MHz channel spacing. The OFDM based PHY exhibits, in addition to good link budget, excellent multipath robustness. Aligning the 802.16.3 PHY with a contemporary packet data oriented PHY standards will result in widely available, cost effective and high-performance solution.
Purpose	To present a proposal which will serve as a baseline of the 802.16.3 BWA PHY layer.
Notice	This document has been prepared to assist IEEE 802.16. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.
Release	The contributor grants a free, irrevocable license to the IEEE to incorporate text contained in this contribution, and any modifications thereof, in the creation of an IEEE Standards publication; to copyright in the IEEE's name any IEEE Standards publication even though it may include portions of this contribution; and at the IEEE's sole discretion to permit others to reproduce in whole or in part the resulting IEEE Standards publication. The contributor also acknowledges and accepts that this contribution may be made public by IEEE 802.16.
Patent Policy and Procedures	The contributor is familiar with the IEEE 802.16 Patent Policy and Procedures (Version 1.0) <http://ieee802.org/16/ipr/patents/policy.html>, including the statement "IEEE standards may include the known use of patent(s), including patent applications, if there is technical justification in the opinion of the standards-developing committee and provided the IEEE receives assurance from the patent holder that it will license applicants under reasonable terms and conditions for the purpose of implementing the standard." Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <mailto:r.b.marks@ieee.org> as early as possible, in written or electronic form, of any patents (granted or under application) that may cover technology that is under consideration by or has been approved by IEEE 802.16. The Chair will disclose this notification via the IEEE 802.16 web site <http://ieee802.org/16/ipr/patents/notices>.

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

Naftali Chayat and Tal Kaitz

BreezeCOM

Table of Contents

Table of Figures

Table of Tables

1 General

1.1 Background

The PHY proposal for 802.16.3 brought below is based on OFDM modulation. It draws on the 802.11a Physical Layer and on the PHY of the HIPERLAN/2 project, with an appropriate rescaling due to bandwidth restrictions. Relative to those standards, there are some modifications, including a fast polling mechanism based on subcarrier allocation.

The 802.16.3 calls for an extremely robust PHY. This requirement stems from the deployment scenarios targeted towards residential customers - obstructions by buildings, less directional antennas for self installation and even indoor stations communicating with nondirectional antennas through the building's walls. This scenarios call for a Physical Layer which is highly tolerant both to multipath and to signal level variations. The PHY proposed in this proposal addresses these issues at several layers:

- OFDM based PHY addresses the anticipated multipath problems
- An adaptive modulation enables providing each user with a data rate according to his link quality. In particular, station experiencing a fade will reduce its data rate but will avoid the need to send an installer to deal with connection loss.
- An optional Frequency Hopping sublayer deals with wideband (low delay spread) frequency selective fading situations.

The OFDM modulation enables a fast polling capability based on subcarrier allocation. The orthogonality of the subcarriers is utilized to gather polling requests from multiple stations in parallel, even in heavy multipath environment. This capability is unique to OFDM and enables fast and efficient resource allocation in packet oriented environment.

The parameters of the OFDM modulation in this proposal follow closely the parameters of 802.11a and HIPERLAN/2 standards. This is done for several reasons:

- The 802.11a and HIPERLAN/2 standards are drawing many chip vendors to develop applicable ASICs. By keeping the main parameters aligned with those standards we envision availability of low cost solutions drawing on the economy-of-scale of the WLAN and consumer markets
- The parameters of those standards (number of subcarriers, preamble structures) are optimized towards packet data in terms of burst operation, packet size granularity, overhead and operation is uncertain propagation environment.
- The 802.11a and H/2 standards are capable of transmitting broadcast data, however they are optimized towards a situation typical in data networks in which each station communicates it's own individual data.
- The packet operation with a per-packet preamble facilitates a switched-antenna receive diversity

The proposed OFDM based PHY integrates naturally with the 802.16. MAC, and in particular with the packet oriented TDD and SFDD modes of operation.

At the end, we would like to discuss the negative sides of OFDM. The main one is the Peak-to-Average Ratio (PAR) disadvantage. On the average, OFDM requires about 2 dB higher backoff in power amplifiers than a single carrier QAM signal (worst-case PAR is much higher but it is an extremely rare event). Another disadvantage attributed to of OFDM is its sensitivity to phase noise. This issue was studied in the 802.11a committee and in the case of 52 subcarriers the OFDM system compared favorably with the single carrier systems.

1.2 Introduction

The purpose of this paper is to propose a Physical Layer for the 802.16.3 sub-11 GHz BWA Task Group, based on Orthogonal Frequency Division Modulation (OFDM). The parameters of the proposed Physical Layer draw on those of the 802.11a and HIPERLAN/2 standards for Wireless LANs in the 5 GHz band. Some of the parameters are different, however, due to the smaller bandwidth available typically to the operators in the sub-11 licensed frequency bands. Let us focus at an example of channel width of 3.5 MHz (the parameters can be easily rescaled to other channels widths). The parameters of the proposed OFDM PHY are then:

- Channel spacing of 3.5 MHz, signal bandwidth of approximately 3.2 MHz.
- Data rates ranging from 1.33 Mbit/s to 12 Mbit/s
- 52 subcarriers with 4 MHz / 64 = 62.5 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 18 microseconds, composed of 16 microsecond Fourier period and 2 microsecond Guard Interval (GI). Note the proposed GI overhead is smaller than in the 802.11a (1/8 instead of 1/4 of the Fourier period)

In terms of integrating the PHY layer with the MAC we propose an approach which incorporates elements of both 802.11a and of HIPERLAN/2.

- The data payload granularity is a single byte as in 802.11a, rather than 54 bytes as in HIPERLAN/2
- The coarse/fine acquisition sections of the 802.11a preamble are used.
- The concept of several preamble and mid-amble types which are used according to the amount of prior knowledge on the receiving side is similar to HIPERLAN/2
- An entirely new component which draws on OFDM technology but is not part of 802.11a or HIPERLAN/2 is the concept of subcarrier-based polling.

1.3 Abbreviations and Acronyms

OFDM   Orthogonal Frequency Division Multiplex
BPSK   Binary Phase Shift Keying
QPSK   Quaternary Phase Shift Keying
M-QAM   Quadrature Amplitude Modulation with **M** constellation points
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.
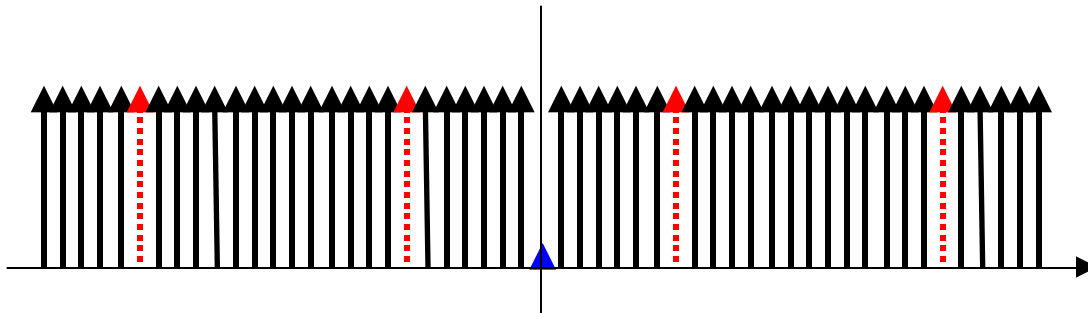
Figure 1   Frequency plan of the data and pilot subcarriers

The use of 62.5 KHz (4 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 located 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/duration 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 16 microsecond periodicity (1/62.5 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.

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. Our recommendation for the 802.16.3 sub-11 GHz BWA project is to use GI of 2 microseconds (for the case of 3.5 MHs channels).
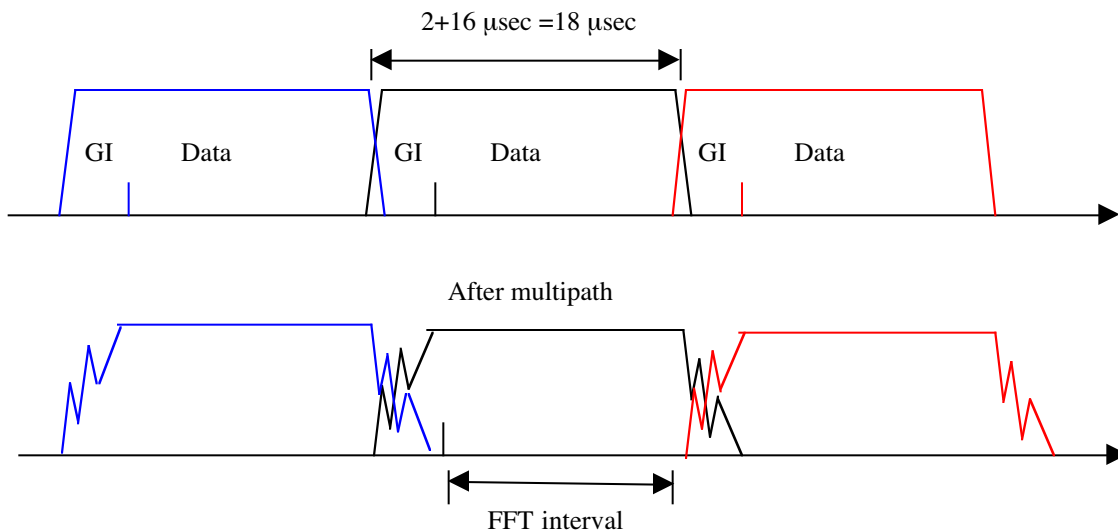
3.3 Frame Types and Formats

The proposed PHY supports several frame types, each type optimized to a specific MAC layer functions. The frame types differ in structure, format and synchronization method.

Most frame types are composed of a synchronization section (preamble and midamble) and optional SIGNAL field and a data section. An exception is the polling frame which is described in section 3.4.

 In the following sections, an overview of the frame components is given. An illustration of several frame types is given in section 3.3.4.

3.3.1 Synchronization Sections

The synchronization section is composed of preambles and mid-ambles.

The preamble section is used for initial gain timing, frequency and channel response estimation. The preamble is also used to resolve antenna diversity, where applicable. The preamble is composed of an optional coarse estimation section and a fine estimation section. The use of the coarse estimation section is dictated by several factors:

*   The time since previous transmission of same station. If the previous transmission occurred too long ago, then receiver settings will be mismatched to the incoming signal. This applies especially to gain and antenna settings. In this case a coarse estimation section should be used to allow the receiver to adjust the gain and antenna settings.
*   If no a-priori information is available on timing frequency and gain settings then a coarse estimation section should be used. An example of such situation is the transmission of registration requests.

A synchronization section which contains only the fine estimation section is termed a *short preamble*, while a synchronization section which contains both a coarse and a fine synchronization sections is termed a *long preamble*.

The midamble is used to allow a station to regain synchronization when reception was interrupted. This may be required in the case of SFDD operation, when a station may stop listening to the media while transmitting up-stream information, or a multibeam system in which previous section was sent to a different beam.

The synchronization sections are described in detail in section 3.3.5.

3.3.2 Data Section

The data section contains the up-stream and down-stream information. The data section is OFDM modulated as described in section 3.1. The data section conveys information either to a single station, or to several stations. In the latter case, which is applicable in the down-stream channel, the data section is composed of several data fragments. Each data fragment is a completely terminated data unit, which can be decoded independently of other data fragments. To assist independent decoding, mid-ambles may be inserted between adjacent fragments. Data fragments may have different data rates, thereby optimizing throughput for far and near stations.

3.3.3 Signal field

The signal field is used to convey information on the rate and length of the subsequent data fragment. The signal field is a fully terminated data fragment, always transmitted at the lowest most reliable rate.

3.3.4 Illustration of frame types.

In this section the structure of some frame types is illustrated. The polling request frame is discussed in section 3.4. In the following, all timing and rate related information pertains to the 3.5MHz example.

3.3.4.1 Long preamble + signal field + data

An example of a frame composed of long preamble a Signal field and a data section is shown in figure 3. This frame type is used whenever the transmitting has been inactive for a prolonged period of time, e.g. in registration requests. The inclusion of a signal field enables the use of any data rate and length.
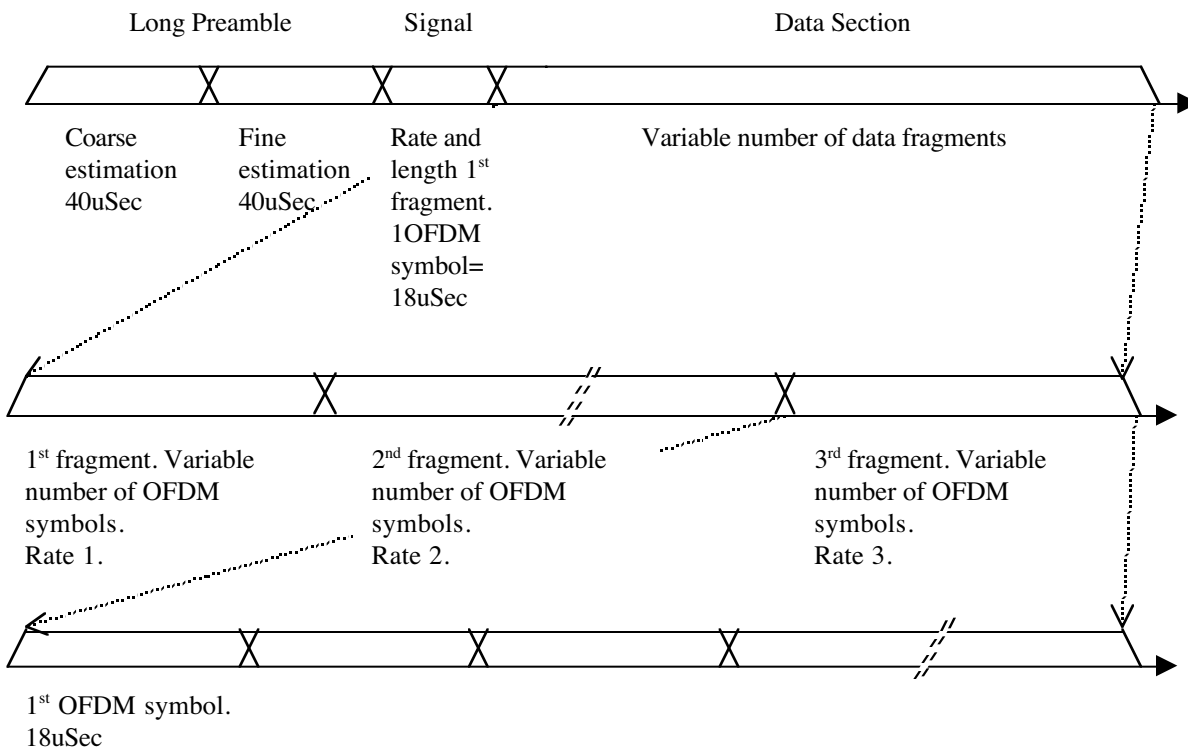
Figure 3   Structure of a packet with a long preamble, SIGNAL field and multiple datafragments with mid-ambles

3.3.4.2 Long preamble + data

A frame with a long preamble and a data section is shown in figure 4.

Long Preamble   Data Section

Coarse   Fine   Variable number of data fragments
estimation   estimation   Variable number of OFDM symbols
40uSec   40uSec   18*N uSec, N=1,2,3…
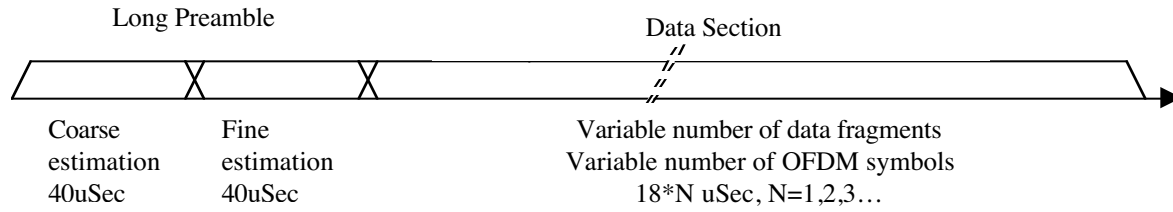
Figure 4   Structure of a packet with a long preamble and data

3.3.4.3 Short preamble + data

A frame with a short preamble and a data section is shown in figure 5.

Short Preamble   Data Section

Fine   Variable number of OFDM symbols
estimation   18*N uSec, N=1,2,3…
40uSec
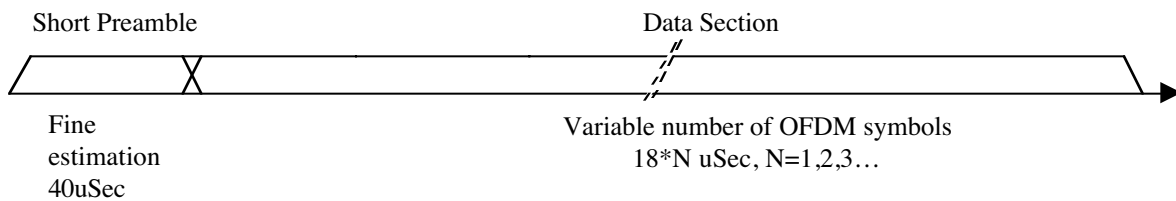
Figure 5   Structure of a packet with a short preamble and data

3.3.4.4 Long preamble + signal field data +mid-ambles

The use of mid-ambles to separate data fragments is shown in figure 6.

Long Preamble   Signal   Data Section

Coarse   Fine   Variable number of data fragments
estimation   estimation
40uSec   40uSec

1st fragment.   Midamble   2nd fragment   Midamble
                    18uSec   18uSec

Figure 6   Structure of a packet with a long preamble and multiple data fragments with mid-ambles

3.3.5 Preamble and midamble Sections

Receiving an OFDM packet requires acquisitions of several parameters, among them are:

- Exact time of packet start.
- Frequency offset.
- Channel response.

In addition both the analog gain setting and the antenna diversity needs to be resolved prior to decoding the data sections.

The preamble section was designed to estimate the above parameters. The preamble section is divided into two subsections, the coarse estimation section and the fine estimation section.

The coarse estimation section allows coarse parameters estimation without any prior knowledge of timing and frequency offset. The analog gain setting and antenna diversity can be resolved using this section.

The fine estimation section is used for accurate parameter estimation, while relying on some a-priori knowledge.

The midamble section is used to aid the re-synchronization of the receiver when continuous reception was not possible, such as in the cases of full-duplex operation or in the case very long frames.
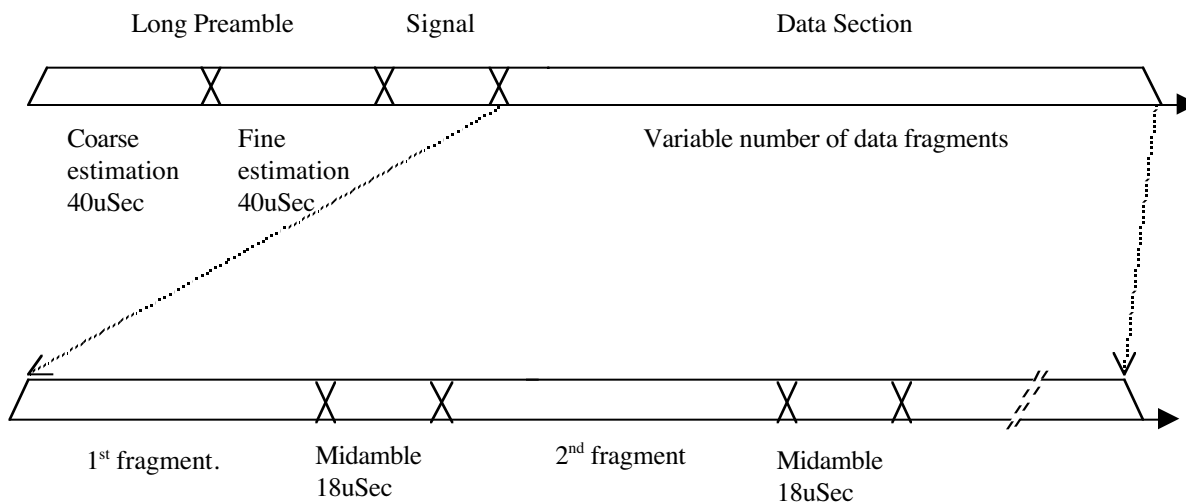
A short preamble is composed only of the fine estimation section.

A long preamble is composed of coarse estimation section followed by a fine estimation section.

3.3.5.1   Coarse estimation Section

The coarse estimation is composed of 10 repetitions of a short sequence pattern. Each sequence is 1/4 of the length of an OFDM symbol (prior to cyclic extension). The time domain depicted in figure 7 for the case of the 3.5MHz bandwidth.

The coarse estimation section is generated by taking the inverse Fourier transform of the frequency domain sequence shown in table 1 and cyclically extending to the required length. The sequence is normalized so that the RMS power is equal to that of data section.

Note that only subcarriers the index of which is multiple of 4 are utilized. This agrees with the periodicity of the sequence, which is _ of the OFDM symbol.

 The relative phases of the active subcarriers are chosen such the overall peak to average power ratio is extremely low. Thus the estimation section is not distorted by power amplifier non-linearities.

The relatively short periodicity of the coarse estimation section enables low-ambiguity frequency estimation. Also antenna diversity and analog gain setting are supported.
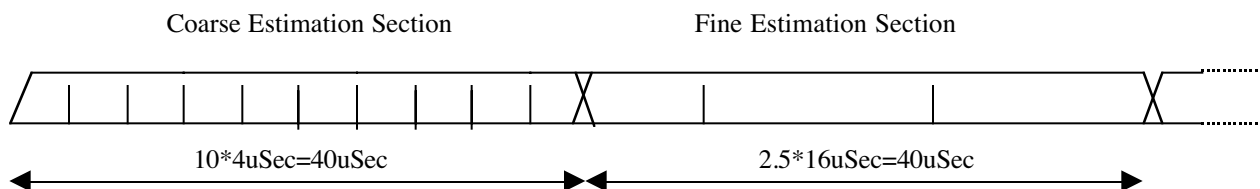

Figure 7   Coarse and fine estimation sections of the preambles

Table 1   Values of the coarse estimation section subcarriers

Subcarrier location	Subcarrier value	Subcarrier location	Subcarrier value
-24	1+j	4	-1-j
-20	-1-j	8	-1-j
-16	1+j	12	1+j
-12	-1-j	16	1+j
-8	-1-j	20	1+j
-4	1+j	24	1+j

3.3.5.2   Fine estimation Section

The fine estimation section is composed of 2.5 repetitions of a basic sequence. each sequence is of the length of 1 OFDM symbol (prior to cyclic extension). The time domain presentation is depicted in figure 7. The fine estimation section can be generated by taking the inverse Fourier transform of the frequency domain sequence shown in table 2 and cyclically extending to the required length.

The structure of the fine estimation section allows:

1. Fine frequency estimation, by comparing the phases of the two repetitions.
2. Channel estimation.
3. Fine timing estimation.

As with the coarse estimation section, the relative phases of the active subcarriers are chosen such the overall peak to average power ratio is minimized.

Table 2   Values of the fine estimation section subcarriers

Subcarrier location	Subcarrier value	Subcarrier location	Subcarrier value
-26	1	1	1
-25	1	2	-1
-24	-1	3	-1
-23	-1	4	1
-22	1	5	1
-21	1	6	-1
-20	-1	7	1
-19	1	8	-1
-18	-1	9	1
-17	1	10	-1
-16	1	11	-1
-15	1	12	-1
-14	1	13	-1
-13	1	14	-1
-12	1	15	1
-11	-1	16	-1
-10	-1	17	1
-9	1	18	-1
-8	1	19	1
-7	-1	20	-1
-6	1	21	1
-5	-1	22	-1
-4	1	23	1
-3	1	24	1
-2	1	25	1
-1	1	26	1

3.3.5.3   Midamble

The midamble is composed of a cyclic extension of the basic sequence of the fine estimation section. The sequence is extended to the length of a single OFDM symbol.

3.4 Subcarrier based polling

The polling packets allows for a very efficient polling process. This is achieved by assigning each SU a combination of subcarrier and time slot. Whenever a SU needs to be polled, it transmits a continuous wave signal at the assigned time and frequency slot. Thus a form of sub-carriers based multiple accesses mechanism is established. Using this mechanism, the AU can poll simultaneously a large number of SUs. The polling packet is composed of a predefined number of OFDM symbols which is transmitted once per up-stream period. The subcarrier-time assignment may span several such periods, and ensures that all stations are polled. At each polling period the subcarrier-time allocations to SUs are permuted, so the polling process is immune to selective fading, avoiding the situation in which a station tries repeatedly to transmit on a faded frequency.

 Additionally, during the polling packet, each SU transmits only at a single subcarrier, and the transmit power density can be much higher than in regular transmissions.

Figure 8 shows an example of two instances of a polling process. Each polling packet contains 3 OFDM symbols, allowing thus polling of 156 stations. Two sets of sub-carrier assignments are shown. In the first, shown in red the SU transmits the subcarrier 24 in the first symbol of first polling period and the subcarrier –25 in the second symbol of the second polling period.

Another station, marked in gray, transmits subcarrier 26 in the 3rd symbol of first polling period and subcarrier –24 in the 1st symbol of the 2nd polling period.
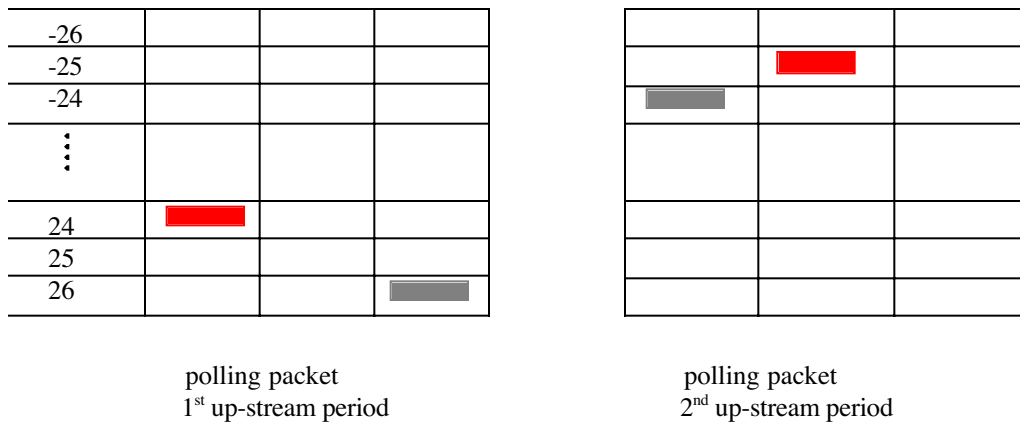

polling packet
1st up-stream period

polling packet
2nd up-stream period

Figure 8   Illustration of subcarrier based polling

3.5 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).
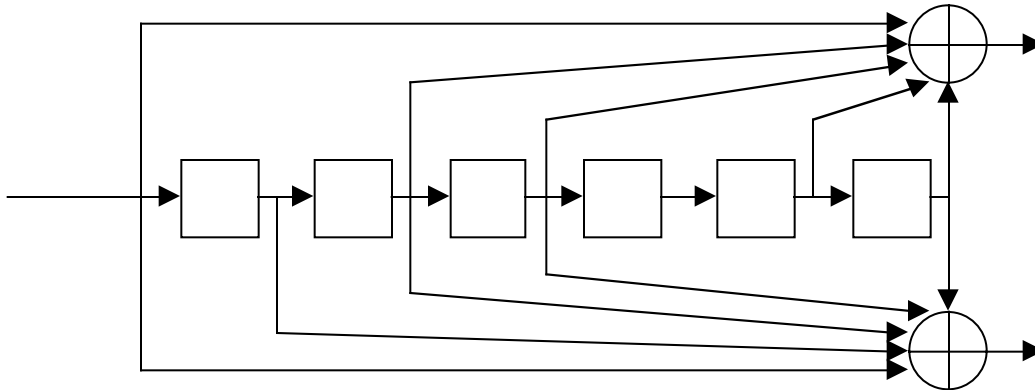
Figure 9   Convolutional encoder with K=7, R=1/2, g1=133$_8$, g2=171$_8$

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.

3.5.1 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.

3.5.2 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 3   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	1.33 Mbit/s	48	24
BPSK	R=3/4	2 Mbit/s	48	36
QPSK	R=1/2	2.66 Mbit/s	96	48
QPSK	R=3/4	4 Mbit/s	96	72
16QAM	R=1/2	5.33 Mbit/s	192	96
16QAM	R=3/4	8 Mbit/s	192	144
64QAM	R=2/3	10.67 Mbit/s	288	192
64QAM	R=3/4	12 Mbit/s	288	216

3.5.3 Turbo Coding option

The OFDM modulation may gain from usage of stronger Error Correction Code options, such as Turbo Codes. In particular, the BTC as defined in 802.16.1 may be used for this purpose.

3.6 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 4   Data rates versus constellation and coding rate

Coding rate Constellation	R=1/2	R=2/3	R=3/4
BPSK	1.33 Mbit/s		2 Mbit/s
QPSK	2.66 Mbit/s		4 Mbit/s
16QAM	5.33 Mbit/s		8 Mbit/s
64QAM		10.66 Mbit/s	12 Mbit/s

3.7 Flexibilities

The basic ideas presented above can be applied 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.

3.7.1 Switching Antenna Diversity

The OFDM is optimized for operation in multipath with long delay spreads. In low delay-spread (nearly flat fading), however, additional measures are needed, since the energy of the signal may nearly vanish. One such measure is switching antenna diversity, taking advantage of the fact that two antennas at sufficient spacing seldom experience deep fades at the same time. In the switching diversity case there's no need to have double RF chains, as needed with combining diversity, while obtaining most of the gain. This requires, however sufficiently long preambles which allow examination if the signal at both antennas and selection of the best. Current proposal incorporates 802.11a-like preambles which were designed with this application in mind.

3.7.2 Frequency Hopping option

Another measure designed to cope with low delay-spread (nearly flat fading) situation is Frequency Hopping (FH). The FH exploits higher bandwidth, spread over time, than a single channel and enjoys the frequency domain diversity even at relatively short multipath. We suggest incorporating an optional support of FH within 802.16.3. This capability integrates naturally with the SuperFrame-based nature of the 802.16 MAC. The technology of low cost, fast settling time frequency hoppers is readily available, for example in 802.11FH and Bluetooth networks. Not related to 802.16.3, FH is also a valuable addition to WirelessHUMAN networks, which must withstand uncoordinated interference.

3.7.3 Smart Antenna support option

Additional means for throughput improvement is the possibility to point several beams to different users simultaneously, improving thus the frequency reuse. Beamforming in presence of multipath poses an extreme challenge for single carrier systems, but fits naturally in the context of OFDM systems. In OFDM systems the beamforming can be performed per subcarrier, hiding thus the "matrix equalization" complexity.

Applying this concept requires monitoring the channel responses from all the antenna elements in the base station to the users. On the uplink side the channel estimation can be done by the base station autonomously. In the downlink direction this calls for issuing appropriate training beacons and gathering the response data from the stations (the channel estimation beacons for multiple antennas can be shared for all the subscribers). An exception is a TDD system, in which due to reciprocity the uplink training can be applied for downlink beamforming. Introduction of smart antenna capability calls for appropriate hooks in the MAC and in the PHY

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 its 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 excellent 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 802.16.3 Functional Requirements Document (FRD)?

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 the 802.16 MAC and by exploiting the flexibilities inherent in it (data rates, preamble overheads etc.) the proposed PHY can meet the 802.16.3 FRD requirements.

5.2 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 channel spectrum efficiency varies between 0.38 bit/sec/Hz up to 3.42 bits/sec/Hz. In the example of 3.5 MHz channel spacing used throughout the proposal the data rates range between 1.33 Mbit/sec and 12 Mbit/sec. The modulation is OFDM, with variable size QAM constellation and variable coding rate in order to trade data rate for link quality over wide range of channels conditions.

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 802.16.3 WBA Physical Layer with 802.11a and HIPERLAN technologies will facilitate availability of competitively priced chip-sets supporting this technology.

5.5 BS cost optimization

How does the proposed PHY affect Base Station cost?

We believe that aligning the 802.16.3 WBA Physical Layer with 802.11a and HIPERLAN technologies will facilitate availability of competitively priced chip-sets supporting this technology. The use of OFDM has some disadvantage with PA backoff, but on the other hand has considerable advantages for future introduction of smart antenna technology.

5.6 Spectrum resource flexibility

Flexibility in the use of the frequency band (i.e.channelization,modularity,band pairing,and Upstream/Downstream data asymmetry)

The proposal can be scaled to virtually any channel spacing. The inherent packet-based nature of the proposed PHY makes it particularly well suited to TDD with asymmetric Upstream/Downstream allocation.

5.7 System service flexibility

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

The new services are provided with the 802.16 MAC assistance. The proposed PHY supports the MAC's capabilities with providing the flexibilities in many respects: adapting data rates, providing the capability to shorten the preamble overhead by exploiting prior knowledge and by reducing the reservation overhead and latency using the fast polling capability.

5.8 Protocol Interfacing complexity

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

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 therefore 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.

The PHY delay for the modulation scheme based on OFDM is about one OFDM symbol of demodulation and couple hundred bit delay of ECC decoding. For the example of 3.5 MHz bandwidth and speed of 8 Mbit/s the delay is about 40 microseconds.

A particular strength of the proposed PHY is its capability to efficiently poll multiple stations in parallel, utilizing the inherent parallelism of the subcarrier transmission. In a time equivalent to a single reservation slot tens or hundreds of stations may be polled.

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 5   Link budget versus data rate

Data Rate	Sensitivity NF=0 dB degr.=2 dB	Backoff	Transmit power	System gain (link loss)
1.33 Mbit/s	-102dBm	7 dB	23 dBm	125 dB
2 Mbit/s	-101 dBm	7 dB	23 dBm	124 dB
2.66 Mbit/s	-99 dBm	7 dB	23 dBm	122 dB
4 Mbit/s	-97 dBm	7 dB	23 dBm	120 dB
5.33 Mbit/s	-94 dBm	7 dB	23 dBm	117 dB
8 Mbit/s	-90 dBm	7 dB	23 dBm	113 dB
10.67 Mbit/s	-86 dBm	9 dB	21 dBm	107 dB
12 Mbit/s	-85 dBm	9 dB	21 dBm	106 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.