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Title	**OFDM based 802.16.3 PHY Proposal**
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Source(s)	**Nico van Waes** OFDM Forum 300 801 Manning Rd NE Calgary, AB T2E8J5 Canada Voice: +1 650 625 2201 Fax: +1 650 625 2058 mailto: ofdmforum_chair_fwa@wi-lan.com
Re:	Re: IEEE 802.16.3-00/24 TG3 CFC on PHY proposals
Abstract	OFDM based 802.16.3 PHY Proposal
Purpose	Discussion
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OFDM based 802.16.3 PHY Proposal

OFDM Forum FWA-WG members

1. Introduction

This document contains the outline of an OFDM based PHY proposal to IEEE 802.16 TG3. It discusses the generic layout of the proposed PHY layer and evaluates the criteria set forth in [1] and [2] in as far as the proposal is specific enough at this point to make this evaluation possible.

2. References, Terminology and Abbreviations

2.1. References

[1] IEEE 602.16.3-00/24 Call for Contributions: Session #11

[2] IEEE 802.16.3-00/02r4 Functional Requirements for the 802.16.3 Interoperability Standard

[3] On the computation and reduction of the peak-to-average power ratio in multicarrier comm. Tarokh, V and Jafarkhani, H, IEEE Trans. On Comm. V48.1, pp. 37-44.

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[15] A. Gatherer and M. Polley Controlling Clipping Probability in DMT Transmission," Asilomar Conference on Signals, Systems, and Computers, pp. 578-584, 1997.

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

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

2.2. Terminology and Abbreviations

This proposal uses the same terminology and abbreviations as defined in [2]. Deviations and additions are listed below.

PAPR	Peak-to-Average Power Ratio

3. Motivation of OFDM choice

From a frequency band and channel characteristics stand points, FWA below 11 GHz has a much closer relationship to WLANs than to FWA at the LMDS bands. For the intended application, the channel characteristics favor OFDM, as it allows for more flexible deployments because it doesn t suffer from some of the restrictions of systems in the LMDS band, such as short link distances, LOS requirement and antenna limitations.

For the given target markets (single residents through SME s), the cost of engineering LOS links is relatively high and often not possible. To enable this market, especially in competition with DSL and cable-modems, both the hardware and deployment must be cheap. NLOS operation allows for easy installation and improves coverage.

OFDM is robust in adverse channel conditions and allows NLOS operation while maintaining a high level of spectral efficiency. It effectively mitigates performance degradations due to multipath and is capable of combating deep fades in part of the spectrum.

The OFDM waveform can be easily modified to adjust to the delay spread of the channel.
OFDM allows efficient operation in both FDD and TDD mode as very short or no pre-ambles are needed.
Unlike with the use of equalizers, there is no need to load channel coefficients, which requires knowledge of the transmitter and hence mandates polling or scheduling. OFDM therefore allows the ability to use contention time-slots, which increases MAC efficiency.

OFDM can handle large delay spreads easier to due the independence of the carriers and the flexibility of varying the cyclic prefix length.

The main drawback of pure OFDM is the high maximum PAPR, which places increased linearity requirements on the amplifier. However, various methods are available to reduce this ratio, for example:

- Phase optimization
  - Using a weighted combination of partial transmit sequences [6,7]
  - Using minimum distance decoding to identify codewords with high PAPR [3]
  - Algebraic techniques to cancel large peaks [8]
  - Differentially encoding data on pairs of subcarriers [9]
- Clustered OFDM using multiple power amplifiers and transmit antennas [10]
- Mapping Techniques such as random interleaving [11], scrambling using m-sequences [12], multiplying by a phase vector [13].
- Virtual sub-carrier techniques, where the virtual carriers do not carry data, but are used to create an additive cancellation signal [14,15]
- Block coding [3,5]
- Clipping

It should also be noticed, that the average PAPR requires only 2 dB more backoff than a single carrier QAM signal, whereas high values of the PAPR, while possible, are exceedingly unlikely. Using pseudo-random scrambling, whitening or similar methods, the backoff can hence be significantly limited by allowing for a small error ratio due to amplifier non-linearity/saturation. As there are various methods of PAPR Reduction, there are various places to introduce this into the transmit chain. The choice of the best methods needs to be investigated.

Another perceived drawback is the required accurate frequency offset estimation. However, the baud timing accuracy required in single carrier approaches is equally difficult. Just as single carrier systems will be less sensitive to carrier offset errors than OFDM systems, OFDM systems are less sensitive to timing errors than single carrier systems. So the two problems are equivalent.

4 Transmit and Receive Chains

The transmit and receive chain model is shown in Figure 1.

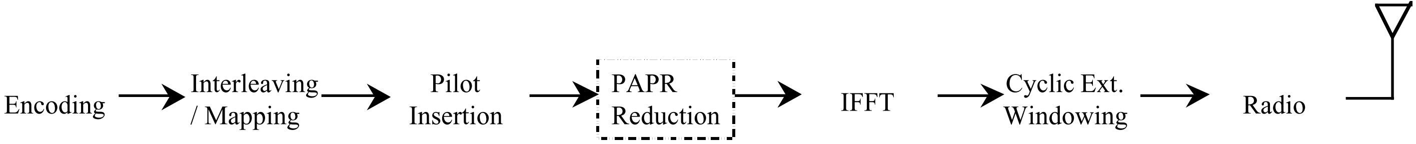

Figure 1 PHY Transmit chain model

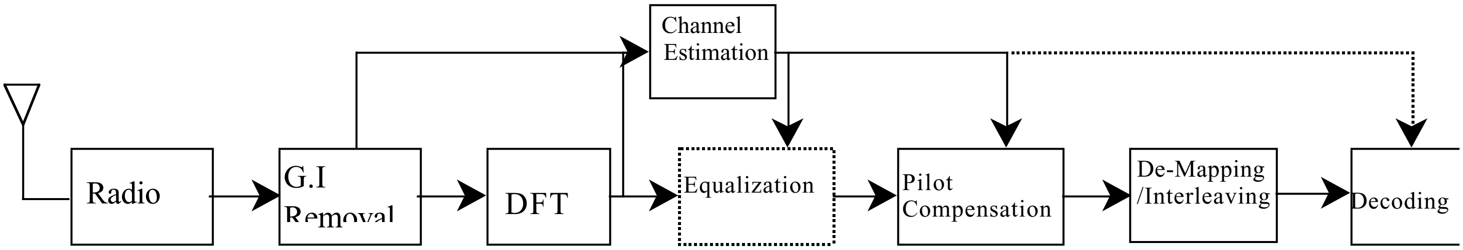

Figure 2 Receive Chain

4.1. Channel Estimation

Channel estimation may be performed on preambles, pilot-carriers, training symbols and even the carried data. Its implementation will however not be specified in the standard as different algorithms do not prohibit devices being interoperable.

4.2. Equalization

The equalizer is used to boost the performance of the delay spread resilience and frequency selective fading. This equalizer should not be confused with equalizers used in single carrier implementations, as it consists only of one independent tap per carrier. Hence, the adaptation of this equalizer, even though the overall number of taps may be larger than in a single-carrier equalizer, is simple and fast. Implementing the Equalizer will be optional.

4.3. Pilot Compensation

The pilots are extracted from the signal to reconstruct the transmitted constellation. The output from the Channel Estimator is used to determine what weight (if any) to attach to each of the pilots. In other words, a pilot in a deep fade will be unreliable and contribute little to the constellation reconstruction.

4.4. PAPR Reduction

See chapter 3.

5. DFT size

5.1 Introduction

A basic question is what the size of the DFT should be. A higher value of DFT size allows for higher throughputs for a given delay spread tolerance. On the other hand, reducing the carrier spacing to fit more carriers in the same bandwidth, increases the sensitivity to things such as carrier offset and phase noise. Additionally, increasing the DFT size also increases the max PAPR, even though the average PAPR changes insignificantly.

To adapt to the large number of bandwidths the standard should service, OFDM offers various possible approaches. The clock rate can be changed to accommodate the different bandwidths while the DFT size remains constant. This would cause the sub carrier separation to vary strongly. Alternatively, the sampling rate can remain fixed and sub carriers nulled from the fixed size DFT. This would result in a constant sub carrier spacing, but would result in increased cost and complexity by require the maximum clock rate to be implemented in all systems irrespective of their target bandwidth. A third option, which we are proposing here, is to combine sampling clock changes with variable DFT sizes. The goal is to maintain nearly constant sub carrier spacing over the various channels.

5.2 DFT sizes vs bandwidth

In Table 1, the essential bandwidths and the selected DFT sizes are shown. It can be seen that the subcarrier spacing remains nearly constant. In effect, by selecting the maximum bandwidth a vendor wants to cover, a choice of the maximum clock rate (and hence the cost of chips) can be made. To comply with the standard, a device hence does not have to implement every DFT size, but only that for which bandwidths the device is intended, hence allowing for savings in cost for low bandwidth, low-performance units.

MHz	DFT size	pilots	Data subcarriers	subcarrier spacing(kHz)	symbol duration (µs)	raw data rate (Mbps)	
						BPSK-1/2, ~4µs guard	64QAM-3/4, ~1µs guard
1.5	64	4	48	23.44	42.67	0.51	4.95
1.75	64	4	48	27.34	36.57	0.59	5.75
3	128	6	106	23.44	42.67	1.14	10.92
3.5	128	6	106	27.34	36.57	1.31	12.70
6	256	8	216	23.44	42.67	2.31	22.26
7	256	8	216	27.34	36.57	2.66	25.87

12	512	16	432	23.44	42.67	4.63	44.52
14	512	16	432	27.34	36.57	5.32	51.74
24	1024	24	872	23.44	42.67	9.34	89.86
28	1024	24	872	27.34	36.57	10.75	104.44

Table 1 Bandwidth, DFT and raw performance

5.3 Guard Interval

Taking into consideration the current channel models, it is expected that in most cases, the delay spread will be less than 2µs. However, by allowing for a configurable guard-interval, the provider can select a guard-interval that fits with the type of deployment. We hence propose to allow for several guard intervals, in the order of 1, 2, 4, 8 and 16µs.

The raw data rate, as shown in Table 1, is computed using 4µs guard-interval and lowest modulation (BPSK, _-rate code) as well as with smallest guard-interval and highest modulation (64-QAM _ rate code), to indicate to some extent the range of data rates that can be achieved.

5.4 Band-edge considerations

Pure OFDM has an out-of-band spectrum that decreases rather slowly. To meet stringent spectral mask and band-edge requirements, either windowing in time-domain or filtering in the frequency domain is required, which reduces the effectiveness of the guard interval by a few percent.

A number of carriers on either side of the DFT is nulled to ease the requirements on the filter. With exception of the 64-DFT mode, where 12.5% (i.e. 5 subcarriers) are nulled for legacy reasons (i.e. to make this mode similar to 802.11a), and because lower DFT sizes have a less steep roll-off, 6.25% of carriers are nulled in the other modes. To alleviate the requirements on the anti-aliasing filter, it is also possible to increase the sampling rate and cut slightly more sub-carriers on either side.

5.5 Modulation & FEC

The modulation shall provide for BPSK, QPSK and 16-QAM. 64-QAM is optional.

The encoding could be both of block and convolutional coding type. The advantage of block-coding over convolutional coding here is that no trailing bits (or reduced performance due to the lack of these) are required. On the other hand, the number of tail bits required for short constraint-length convolutional codes is small.

Which specific type of codes should be used is left open until channel models are selected for fair comparative studies. Various coding rates should be implemented to accommodate a trade-off between throughput and robustness (in addition to modulation-adaptation).

Depending on the FEC chosen, interleaving may be required. If interleaving is required, then unless turbo-codes are selected, one OFDM symbol would be the interleaving size. When using turbo-codes, the number of OFDM symbols per block would be dependent on the DFT size.

5.6 Preambles & Midamble

5.6.1 Preamble & midamble structures

The preambles will have a similar structure as in 802.11a[19] and HiPerLAN/2 [20]. Coarse and Fine training sequences will be used in order to provide proper detection, AGC, synchronization and channel estimation. To reduce the amount of overhead, a number of different preambles are defined.

1) Long preamble

The long preamble is defined to be used when a new CPE enters the network, and when a timer, counting the time since the previous communications with the addressed device, times out. This timeout needs to be based on the time-variance of the channels.

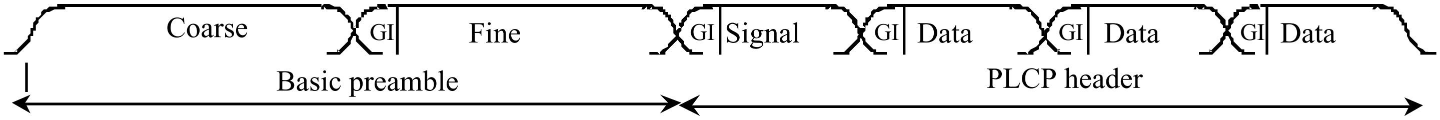

Figure 2 Long preamble

The Coarse symbols are used to do the initial detection, select any diversity and adjust the AGC, as well as perform an initial frequency offset and timing sychronization. Once the AGC has been adjusted, there is no need to re-adjust it unless the channel changes very significantly. Also, once the initial coarse timing and frequency offset has been acquired, the Fine training sequences are sufficient to maintain frequency offset and timing accuracy to allow the detection of the next burst from the Guard Interval (GI). Alternatively, it allows acquisition of the next burst from system synchronization (MAC dependent).

2) Short preamble

When the frequency offset and timing inaccuracy are known (within certain limits due to clock drift etc..), it is sufficient to adjust both from the Fine Sequence. The Fine Sequence is further used to improve the channel estimation, such that slow channel changes are corrected for.

Figure 3 Short preable

3) Midamble

The midamble is used in long streams of OFDM symbols to refine the channel estimation. It contains one symbol from the Fine estimation sequence.

Figure 4 Midamble

5.6.2 Coarse estimation (64-DFT)

The coarse estimation, derived from [19], 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 coarse estimation section is generated by taking the inverse Fourier transform of the frequency domain sequence shown in Table 2 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.

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

Table 2 Coarse estimation sequence (Short sequence) for 64-DFT

5.6.3 Fine estimation (64-DFT)

The fine estimation section, derived from [19], 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 9. The fine estimation section can be generated by taking the inverse Fourier transform of the frequency domain sequence shown in Table 3 and cyclically extending to the required length.

The structure of the fine estimation section allows:

- Fine frequency estimation, by comparing the phases of the two repetitions.
- Channel estimation.
- 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.

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

Table 3 Fine estimation sequence

5.6.4 Coarse and Fine sequences for data-DFT sizes above 64

For DFT sizes above 64, there are two possibilities. The choice between the two heavily depends on the behavior of the channel, hence a definitive choice will be made based on the channel models.

Option 1: The DFT size for the Coarse and Fine sequences can remain 64 for all data-DFT sizes. This would allow using the same sequences for all DFT-sizes, and keep the matched filter the same as well. Channel estimation would be performed by interpolating from the 64-DFT to the appropriate DFT size. This would give the advantage of a reduction in the duration of the preamble, but it may reduce the accuracy of the channel estimation.

Option 2: The DFT size for the Coarse and Fine sequences are the same as the data-DFT size. This provides accurate channel estimation, but results in a larger overhead due to the preamble. The matched filter would need to be matched to the appropriate sequences for each DFT size as well.

6 FDD and TDD mode

The suggested structure of chapter 4 applies equally to FDD as to TDD. To reduce the interference in a multi-cellular multi-sector network, a continuous mode type of transmission would create unneccessary interference. Also, when using continuous transmission with embedded training sequences, the acquisition will take longer than one with the preamble structure suggested above. Especially for CPEs that use H-FDD, the re-acquisition time is critical.

6.1 FDD mode

In FDD mode, we propose in the downstream to start each MAC frame with a long preamble, followed by a downlink map, containing the number of symbols for each modulation (in increasing order of modulation). The data for all CPE s with the same modulation is concatenated in OFDM symbols. The map will also contain designations of OFDM symbols in the uplink for new nodes to enter the system

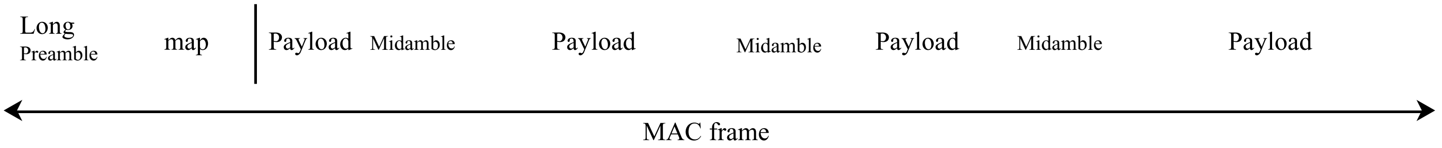

Figure 5 FDD downlink

In the uplink, the frame starts with a number of polling symbols, in which each station has the opportunity to send one designated subcarrier. The number of polling symbols times the total number of subcarriers will equal the max. number of CPE s a BS can support. As long as the CPEs send within the symbol time, a simply FFT and threshold detection by the BS suffices. The frequency, timing and AGC tolerance are hence much larger during these symbols.

To keep the delay between polling and transmissions low, down and up-link frames could be shifted in time from eachother with half a frame.

System access is easily facilitated by leaving a number of consequtive OFDM symbols (for example 3 with a maximum cell-radius of 5 km) empty in the uplink for random access.

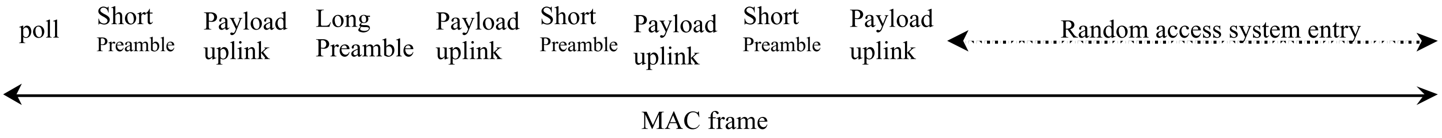

Figure 6 FDD uplink

6.2 TDD mode

In the TDD mode, it is possible to concatenate all downstream traffic after issueing the schedule, which reduces the number of preambles needed. The need to insert midambles in the downlink direction depends on the number of downstream data symbols. The number of data symbols between midambles can be configurable.

Scheduled CPE transmissions may start with either a long or short preamble, depending on the time since the most recent activity of the CPE and the channel characteristics.

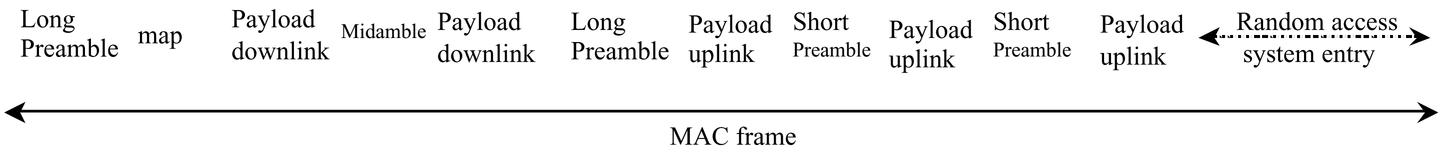

Figure 7 TDD Frame

System access is easily facilitated by leaving a number of consequtive OFDM symbols empty for random access (for example 3, allowing a maximum cell-radius of 5 km). This number should be configurable.

7 Uplink OFDMA

Using OFDMA requires tighter specification of frequency offset, AGC variation and sampling clock offset errors. However, for high DFT sizes, it reduces the large granularity. Therefor, it is proposed to implement OFDMA in the uplink, but with the addition, that a mandatory option to assign all subcarriers to each user be available, whereas the ability to divide the the subcarriers amongst CPE s is optional.

In this fashion, each vendor has the ability to trade off complexity vs. performance (i.e by reducing granularity), without loss of compatibility. Vendors who will build products for high bandwidth channels will undoubtable implement the carrier division feature, as this makes makes cost-performance(in terms of throughput) wise. Vendors who cater to the low bandwidth channels likely won t, as the granularity problem there does not exist, and the cost-performance(in terms of throughput) is entirely different.

In chosing the subcarrier assignment method, it is bad practice to assign adjacent carriers to a single user, as this defeats the frequency-selective fading mitigation inherent in OFDM. However, transmitting long sequences of sub-carriers to use is a waste of bandwidth.

It is therefor suggested, that a number of non-adjacent sequences of various length be designed for each DFT size. If both the BS and the CPE s have knowledge of these sequences, it suffices to merely indicate the sequence number in the mapping table. Different lengths of sequences mean that different amounts of sub-carriers are assigned to a CPE, which hence dictates the throughput for that user. The amount of memory required for such a table, or the computational power for generating a sequence (should an appropriate algorithm be found) will be relatively small.

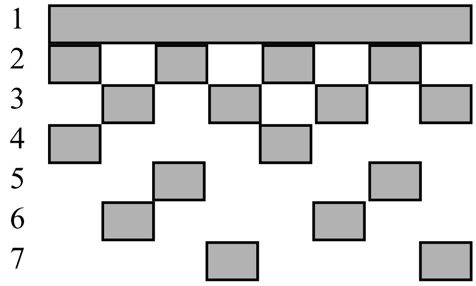

Figure 8 Trivial 8-DFT example of 7 (plus 8 individual carrier) sequence codes

The assigned subcarriers should be permutated according to the frame number, such that in adjacent frames, a CPEs using the same sequence number will use different sub-carriers. Doing so, intercell-interference would be distributed.

From the sequence number, a deterministic algorithm to compute the sub-carrier and time slot to insert a pilot-symbol should be introduced as well.

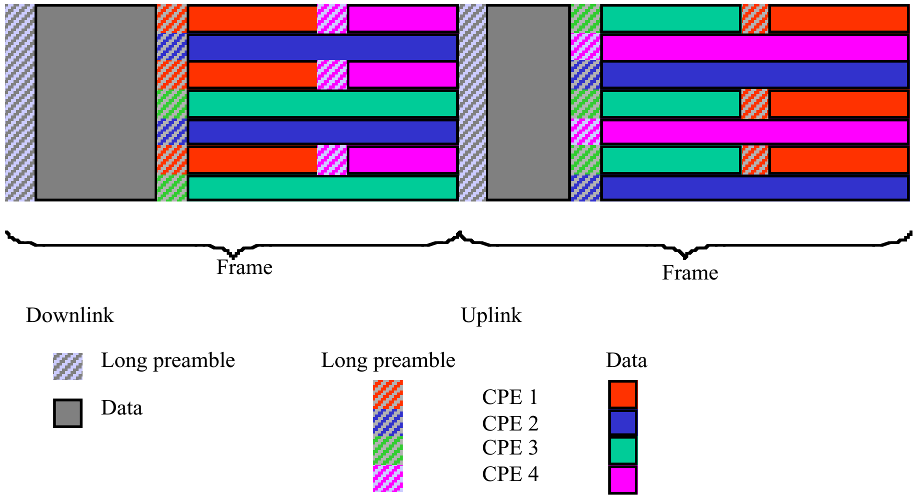

Figure 9 TDD Example of downlink frame with OFDMA (6 carriers for simplicity)

6. Antenna Diversity support

It is well known that antenna-diversity provides a significant improvement in throughput and link-budget, and that transmit antenna diversity can reduce overall interference. The cost of this is however fairly significant. It is therefore the aim of this proposal to make this feature supported but optional.

7. Convergence Layer Interface

The Convergence Layer should pass the following data to the PHY.

- Data Length
- Pointer to Data or data itself
- TX start time
- FEC Rate
- Modulation Type
- TX Power
- TX Channel
- RX Channel

The PHY Layer should pass the following data to the Convergence Layer

- Data Length
- Pointer to Data or data itself
- Modulation Type
- TX Power
- FEC Rate
- RX Time
- RSSI value
- BER value
- PHY busy signal

8. Evaluation Criteria

Meets system requirements?	Yes (so far)
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.	Capable of over 2 bits/sec/Hz.
-Modulation Scheme	BPSK, QPSK, 16- QAM mandatory 64 QAM optional.
-Gross Transmission Bit Rate	Between 0.5 and 80 Mbps depending on bandwidth and modulation
-User information bit rate at PHY-to-MAC Interface	TBD
-Occupied Bandwidth	~ 88% of selected channel
Simplicity of implementation -How well does the proposed PHY allow for simple implementation or how does it leverage on existing technologies?	OFDM is well understood from WLAN and DVB implementations. No blind copying of these standards is proposed, however, as channel and application conditions are different. No stringent requirements are made to support exotic scheduling algorithms.
SS cost optimization	Allows for an SS with reduced component cost as compared to the BS. Turn up cost is reduced due to the high delay spread tolerance allowing NLOS installation (i.e. no pointing and placing of highly directional antennas in LOS position is required).
BS cost optimization	Digital and analog baseband can be performed in one chip each. OFDM does not preclude direct conversion. PAPR reduction reduces the PA cost. Hence no big cost issues are noted between OFDM and single carrier methods.
Spectrum resource flexibility -Flexibility in the use of the frequency band (i.e.channelization,modularity,band pairing,and Upstream/Downstream data asymmetry)	All channelization and duplexing modes mentioned in the Functional Requirements document are supported. Channelization and band-pairing are extremely flexible. Full data-asymmetry is supported. Very high channel bandwidth will suffer more from data granularity. Switching between channels in the modem solely involves changing the sampling rate.

System service flexibility -How flexible is the proposed PHY to support FRD optional services and potential future services?	No restrictions are evident. Especially allowing for antenna diversity support allows potentially for very high throughput, creating ample bandwidth for future and optional services.
Protocol interfacing complexity -Interaction with other layers of the protocol,specifically MAC and Network Management. Provide the PHY delay.	TBD TBD, Fully mitigatable by the MAC
Reference system gain -Sector coverage performance for a typical BWA deployment scenario (supply reference system gain). Provide practical link budget analysis.	Gain expected to be in the order of between 100 to 120 dB for the various modulations (9 dB backoff, 30 dBm max power.
Robustness to interference -Resistance to intra-system interference (i.e.,frequency re-use)and external interference caused by other systems. -Provide co-channel,adjacent channel interference levels and spectral spillage resulting from modulation.	Very robust to narrowband interference. Rest TBD
.Robustness to channel impairments -Small and large scale fading (Rain fading,multipath,N (non or near)LOS,LOS, Foliage effects,frequency-selective fading,atmospheric effects,etc.)	Very robust to frequency selective fading and delay spread.
Robustness to radio impairments -Specify the degradation due to radio impairments such as phase noise,group delay of filters,amplifier non-linearities,etc.	The DFT size is such that the phase noise is low enough to allow for oscillators of reasonable cost. Group delay is neglegible. OFDM is the best transmission scheme for avoiding group delay problems. For the amplifier, a number of dB s of backoff will be required. PAPR reducing algorithms will be investigated to reduce the backoff requirements.