Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**RM Wavelet Based (WOFDM) PHY Proposal for 802.16.3, Rev.0.0**
Date Submitted	**2001-1-16**
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Re:	IEEE802.16.3-00/14/Call for contributions on:INITIAL PHY PROPOSAL
Abstract	RM Wavelet Based (WOFDM) 802.16.3 PHY Proposal
Purpose	Discussion for a possible PHY layer standard for 802.16.3 Air Interface Standard
Notice	
Release	
Patent Policy and Procedures	

RM Wavelet Based PHY Proposal for 802.16.3

Rainmaker Technologies, Inc.

1.0 Introduction to Modulation Scheme

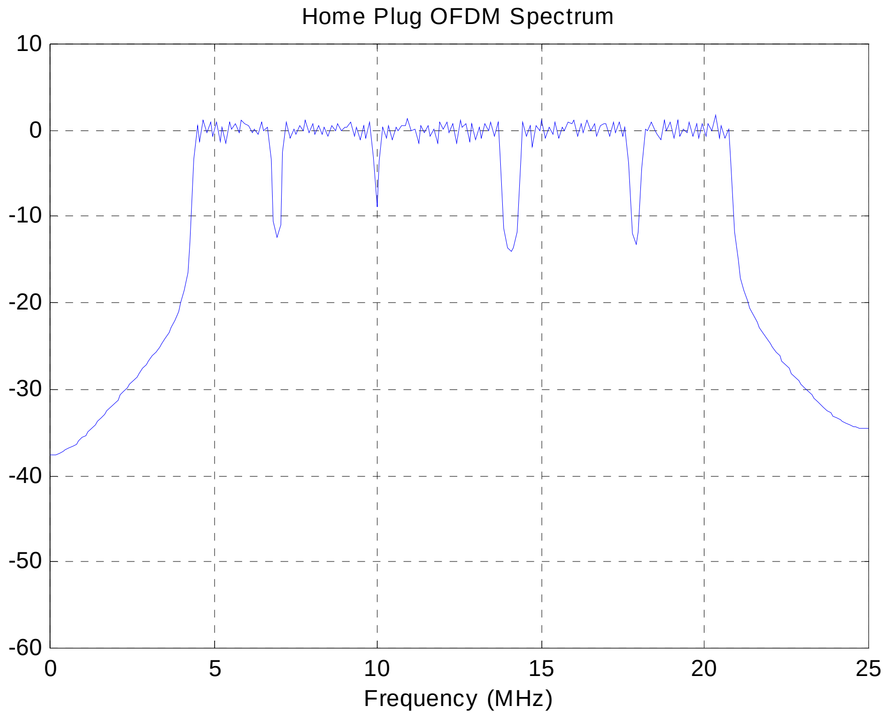
Multi-Carrier Modulation schemes divide the input data into bands upon which modulation is performed and multiplexed into the channel at different carrier frequencies. In general rectangular windowed sinusoids are used and the large sidelobes of the frequency response lead to substantial inter-band interference.

Fundamental to the theory of MCM, the power spectrum of the transmitted signal can be shaped to match the channel characteristics and achieve more optimized performance.

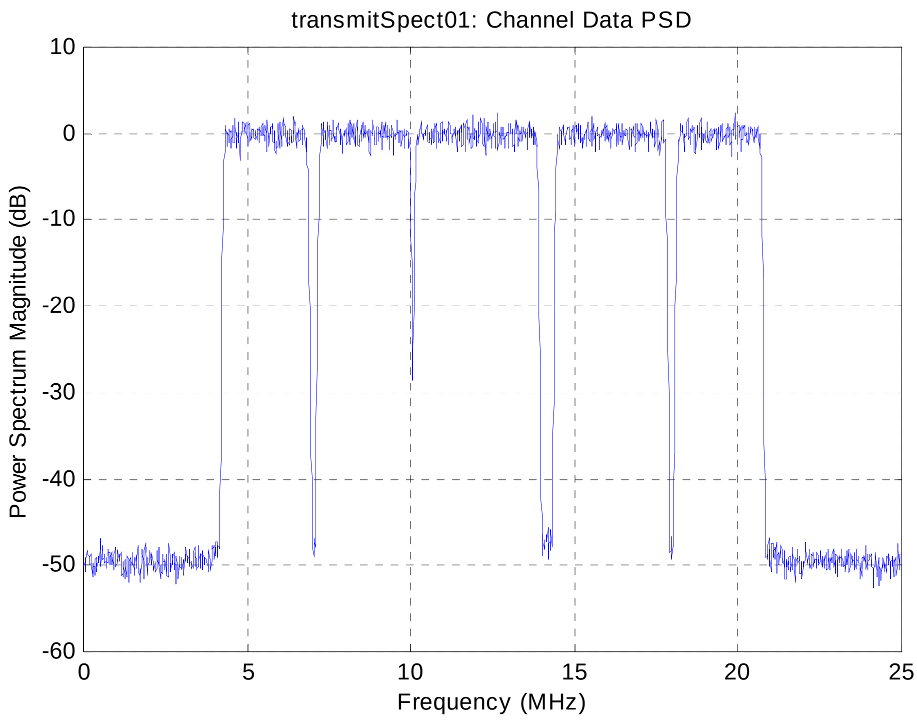
Wavelet transforms can be thought of as a generalized Fourier Transform while allowing design of a communication system with certain specific properties. In that respect it is similar to DMT and OFDM with certain additional benefits that can be designed in by carefully selecting the orthonormal basis functions.

For the following discussion, the proposed modulation scheme will be referred to as Wavelet-based OFDM (WOFDM).

The following figure shows the stop-band characteristics of an OFDM and a WOFDM implementation (Power Spectrum Magnitude in dB versus Frequency in MHz):



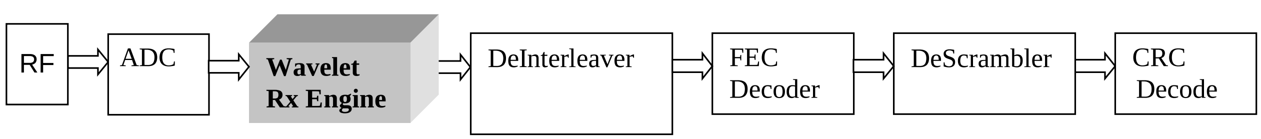
The following figure illustrates a comparable WOFDM power spectral density, illustrating the additional 35dB of stop-band, allowing much superior adjacent band rejection as compared to an OFDM PHY layer (Power Spectrum Magnitude in dB versus Frequency in MHz):



The following shows a top-level block diagram of a generic WOFDM based PHY:

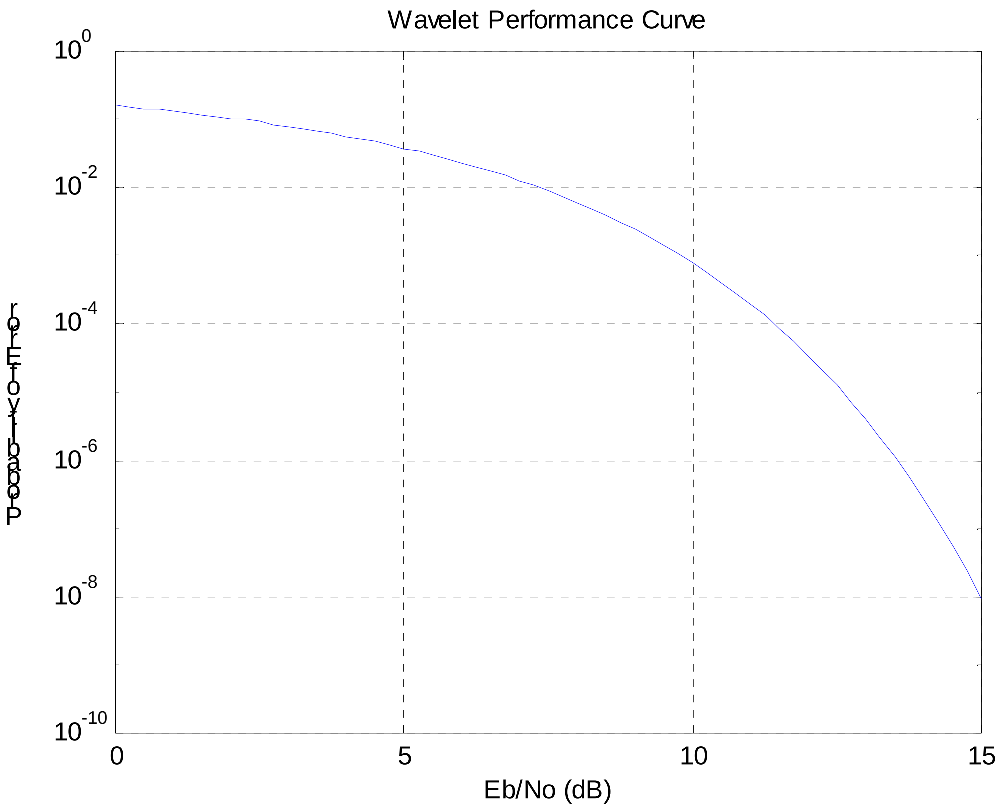
Transmit Side:

Receive Side:



2.0 Spectrum Efficiency

WOFDM is a Multi-Carrier modulation with a one-dimensional constellation. It does not use raised cosine filtering (excess bandwidth=0) and does not use a cyclic prefix (GI=0). The Eb/No requirements for a given BER are the same as for QAM. A Graph of Bit Error Rate (BER) versus Eb/No for WOFDM is shown below:



2.1 Channel Capacity

The following table shows the efficiency of a WOFDM system and the nominal equivalent for other comparable modulations:

Wavelets	**Bits/Sec/Hz**	**Equivalent**
2 Level	2	QPSK
4 Level	4	16QAM
8 Level	6	64QAM
16 Level	8	256QAM

2.2 PHY Overhead

The PHY overhead for WOFDM is less than that of Fourier based OFDM modulations. OFDM Guard Intervals of 20% or more are typical for wireless thus giving Wavelet OFDM an advantage of roughly 20% in BW efficiency.

In addition, pilot tones are not necessary for wavelets so that in comparison systems like 802.11a / HiperLan2 uses 4 out of 52 sub-bands for pilots which gives WOFDM another 8% advantage over typical OFDM implementations.

In other respects, W-OFDM and OFDM have equivalent PHY overhead.

2.3 Gross Tx Bit Rate

For the proposed channel bandwidths in column 1 the raw data rates are given for 2,4,8,and 16-level wavelet modulation with allowance for spectral masking.

Channel Bandwidth (MHz)	2-Level Wavelet Data Rate (Mbps)	4-Level Wavelet Data Rate (Mbps)	8-Level Wavelet Data Rate (Mbps)	16-Level Wavelet Data Rate (Mbps)
1.5	2.5	5.0	7.5	10.0
1.75	3.0	6.0	9.0	12.0
3.0	5.5	11.0	16.5	22.0
3.5	6.5	13.0	19.5	26.0
6.0	11.5	23.0	34.5	46.0
7.0	13.5	27.0	40.5	54.0
8.0	15.5	31.0	46.5	62.0
12.0	23.5	47.0	70.5	94.0
14.0	27.5	55.0	82.5	110.0
28.0	**55.5**	**111.0**	**166.5**	**220.0**

2.4 Bit Rate at MAC/PHY

The rate delivered to the MAC is TBD and depends on FEC rate and other overhead common to all other OFDM modulations.

3.0 Simplicity of Implementation

The proposed WOFDM base-band modulation uses a wavelet filter for both the transmitter and the receiver. The Tx and Rx filters have identical finite impulse responses and have been implemented digitally as multi-rate filter banks using poly-phase filtering techniques that reduce significantly the computational requirements.

The wavelet filters can be implemented as a Fast Wavelet Transform, wherein the poly-phase decomposition of the filter-bank can use a Fast Fourier Transform. The FFT is used differently than in conventional OFDM because the FFT is used to evaluate all the FIR filter responses, which are the wavelets.

The wavelet filters can also be implemented as SAW filters, in which case they can do double duty to process the wavelets and simultaneously perform image rejection in the analog RF section. If the number of sub-bands is kept small then SAWs should make very low-cost modems.

Unlike QAM, wavelet modulation is in fact a filtering operation and does not require a carrier except when up-converting beyond the realm of D/A converters (or wavelet SAW's). Therefore, separate I and Q paths are not required in the up/down conversion which simplifies the RF section by eliminating quadrature mixers, quadrature A/Ds and so forth.

Having no quadrature component, the constellation for the wavelet modem is one dimensional, which simplifies the post-processing for higher order modulation and also makes adaptive modulation easy to implement.

A feature of wavelet modulation is that because it is a filter the roll-off or stop-band attenuation of the modulation is designable and -50 dB stop-bands are easily achieved. This simplifies the analog IF filtering and also permits flexible system band allocation, since the signal is 50 dB down in the space of less than 1 sub-band. This feature can be used to isolate user services into groups of bands isolated by 50 dB.

3.1 SS Cost Optimization

Cost optimization results from several factors:

- Real modulation simplifies RF
- High stop-band simplifies RF/IF design
- High stop-band makes multinational design easier
- Base band processing uses 1-D constellation
- Low sensitivity to timing offset
- Simple and accurate frequency tracking from the data itself
- Performance equivalent to QPSK doesn't measure amplitude
- Non-linear wavelet modulations can reduce power
- Wavelet SAW's can be used for low-end products

3.2 BS Cost Optimization

Fast transforms with FFT engine can process multiple sectors
Real, 1-D modulation simplifies RF and digital processing.

4.0 Robustness to Interference

Channel Interference can arise from several sources in a wireless network

NB Interference
Co-channel interference

For NB (narrow-band) noise the high stop-band (~50dB) of wavelets provides a significant advantage over other modulations. Because the high stop-band applies for each sub-band without additional filtering, robustness is greater than that obtained from adding "notch" filters to non-wavelet modulations.

Because the BW of the customer's service is a large fraction of the available frequency allocation, re-use of frequencies can cause severe (i.e. -11 db) co-channel interference in a cellular system. Non-linear wavelet modulation suppresses co-channel interference.

5.0 Robustness to Channel Impairments

The performance of wavelets in Gaussian noise is nominally the same as QAM and OFDM. However, wavelet modulations are intrinsically a convolutional modulation and further improvements appear possible for the "raw" modulation (i.e. before adding FEC).

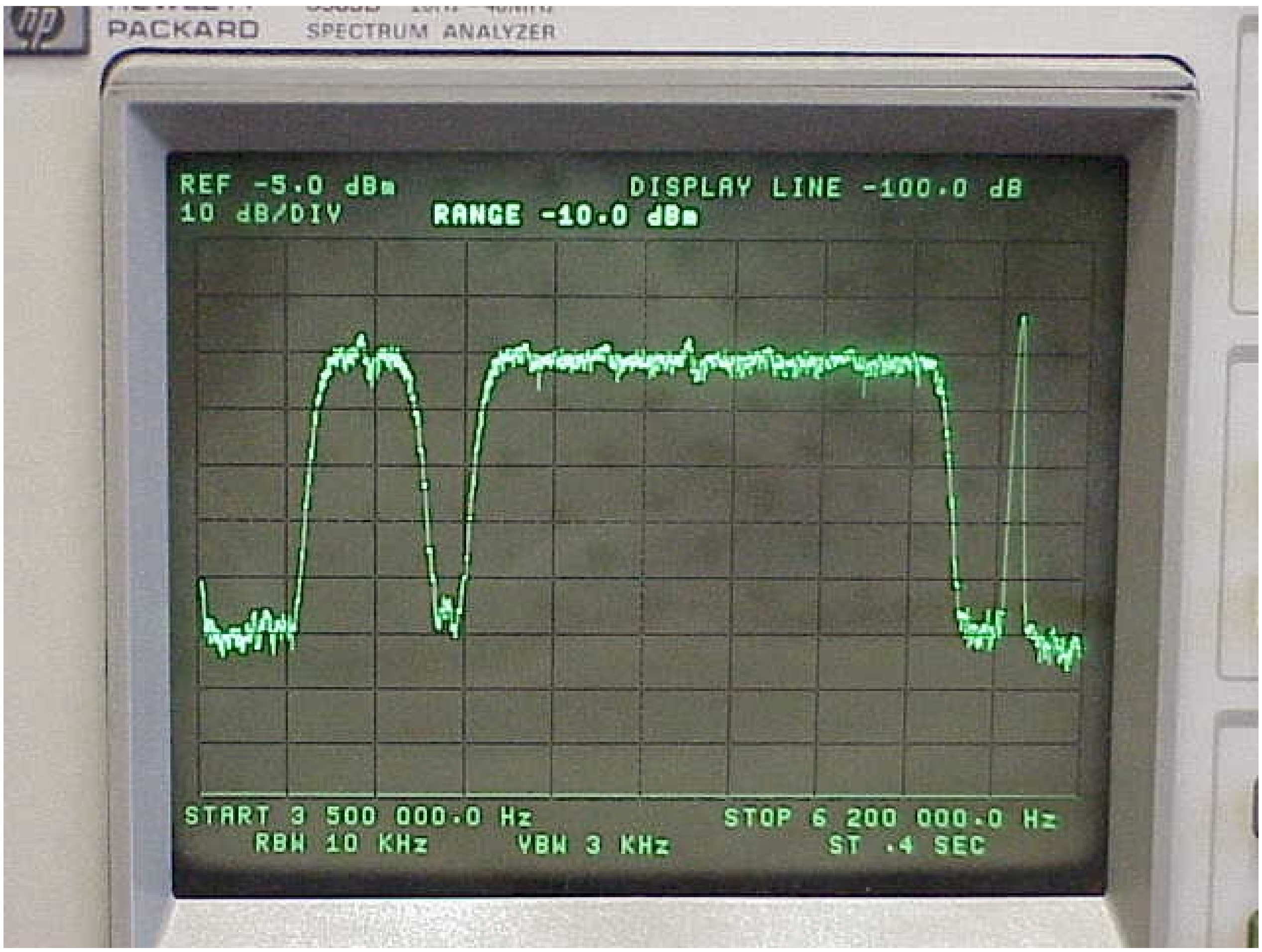
The effects of multi-path Rayleigh fading are negligible for wavelets when the mean delay is less that 10 % of the symbol time.

6.0 Robustness to Radio Impairments

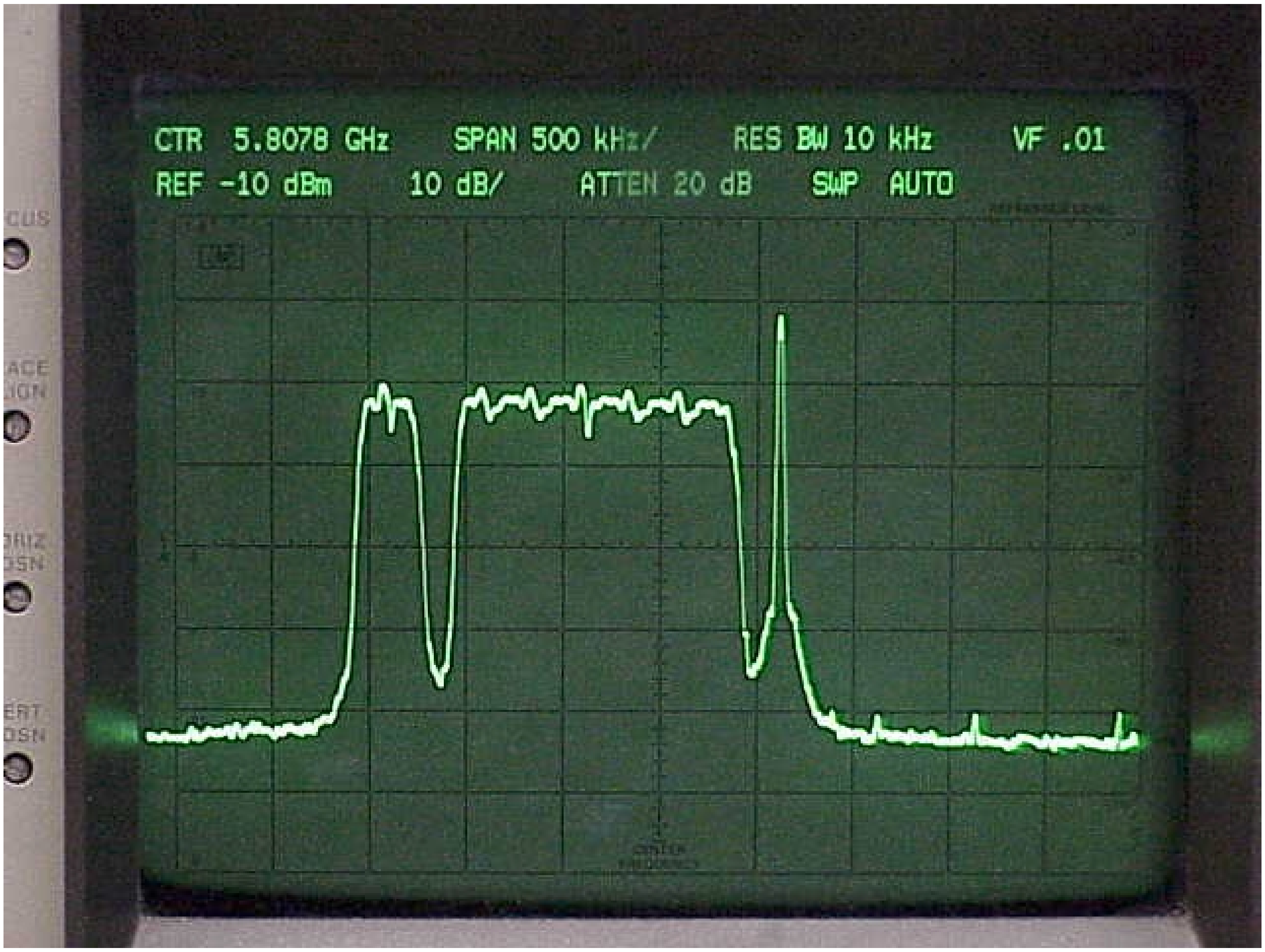
Currently there is an implementation of a WOFDM on multiple FPGA's running simplified packets over the air measured at distances up to 100 feet, going through 5 walls in the 5.8 GHz range of the UNII band.

The following shows the stop-band characteristics of the actual implementation in the lab for a data rate of 3.75Mbps of a 2-level WOFDM PHY.

Base-band signal showing the ability of the prototype in notching out bands, getting close to 47dB of stop-band attenuation. Notching out of two bands is shown below:



Similar results shown from the lab, operating in the UNII band:


CTR 5.8078 GHz SPAN 500 kHz/ RES BW 10 kHz VF .01
REF -10 dBm 10 dB/ ATTEN 20 dB SWP AUTO

8.0 Evaluation Criteria Table:

#	Criterion	Discussion
1	Meets System Requirements	Yes Calculated range meets 50Km requirements
2	Spectrum Efficiency	2→8 Bits/Sec/Hz Target: 4 Bits/Sec/Hz for a data rate of 100Mbps over a bandwidth of 25MHz
3	Simplicity of Implementation	Similarity to MCM and OFDM techniques can be fully leveraged.
3abc	SS/BS/Inst Cost Optimization	Simplified RF and Digital processing Multi-Carrier modulation is well understood; Wavelets form a superset of the existing OFDM and DMT knowledge base.
4	Spectrum Resource Flexibility	Extremely flexible and modular design Channelization, data-asymmetry supported
5	System Spectrum Efficiency	Similar to OFDM based standards TBD
6	System Service Flexibility	No known restrictions, Large stop-band attenuation provides great multi-service potential. BW increase to 100Mbps is doable today to accommodate BW hungry services, simultaneous data, video and other services.
7	Protocol Interfacing Complexity	TBD
8	Reference System Gain	TBD
9	Robustness to Interference	Much more robust to inter-channel and spectral spillage than OFDM
10	Robustness to Channel Impairment	Much more robust than OFDM
11	Robustness to Radio Impairments	Similar to OFDM
12	Support of Advanced Antenna Techniques	Similar to OFDM
13	Compatibility with existing relevant standards and regulations	TBD