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W-OFDM Submission to IEEE 802.16.3 PHY, Rev. 2.0

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**Re:**  
This document is based on: W-OFDM Submission to IEEE 802.16.3 PHY  
http://ieee802.org/16/tg3/contrib/802163c-00_29.pdf

This is a response to the IEEE 802.16.3 Task Group, INVITATION TO CONTRIBUTE PHY PROPOSALS: Session #11, dated 2000-12-02.  
http://ieee802.org/16/tg3/docs/802163-00_24.pdf

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

**Purpose**  
This document forms the basis and source of a proposed presentation to the IEEE 802.16.3 Task Group at the Working Group Session #11 (22-26 January 2001 in Ottawa, Ontario, CANADA).

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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>.
Acknowledgements

The following people have contributed to this document:

Shawn Taylor
Norbert Chan
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Brian Gieschen
## Revision History

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

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

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

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

Overview

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

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

Reference Model

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

![OFDM Transmitter Diagram]

Figure 1: Transmitter Reference Configuration
Reed-Solomon Encoding

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

Interleaving

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

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

**Pilot Insertion**

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

**Random Phase Generation**

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

**Signal Whitening**

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

**iFFT**

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

**Training Symbols**

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

**Cyclic Extending**

Each time-domain OFDM data symbol is extended, by copying a portion from one end of the symbol to the other. This is done to make the OFDM data robust against multipath delays. The length of the extension will be selectable over a range of samples.
**Preamble Prefixing**
A preamble must be added to each OFDM packet. The receiver uses the preamble for:
- Packet synchronization
- Automatic Gain Control (AGC)
- Carrier Frequency Offset Compensation
It can also be used for signaling certain PHY parameters such as the FFT size.

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

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

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

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

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

**OFDM Frame Format**
The format of the OFDM frame is depicted below.
**Upper Layer Interfaces**

The MAC should send the following information to the PHY:

- Data Length
- Data
- Modulation (Mapping) Rate
- FEC Rate
- Tx Power
- Tx Time
- Tx Center frequency
- Rx Center frequency
The PHY should send the following information to the MAC:

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

Channel and Data Rate Analysis

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

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

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

Figure 4: Performance Analysis of 3MHz Channel
Evaluation Criteria

1 Meets system requirements

How well does the proposed PHY protocol meet the requirements described in the current version of the 802.16.3 Functional Requirements Document (FRD)?

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

2 Channel spectrum efficiency

Channel spectrum efficiency - defined in terms of single channel capacity (TDD or FDD) assuming all available spectrum is being utilized (in terms of bits/sec/Hz). Supply details of PHY overhead.
- Modulation Scheme
- Gross Transmission Bit Rate
- User information bit rate at PHY-to-MAC Interface
- Occupied Bandwidth

The modulation technique is OFDM. There are many factors to consider for channel spectrum efficiency. Some of them are:
- Cyclic extension (based on channel delay spread)
- FFT size
- QAM constellation mapping size
- Coding Rate

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

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

3 Simplicity of Implementation

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

For example:
- SS cost optimization. How does the proposed PHY affect SS cost.
- BS cost optimization. How does the proposed PHY affect BS cost.
- Installation cost
OFDM is quickly gaining widespread acceptance for wireless communications. The basic building blocks for OFDM are now well known and readily available individually or as complete systems. OFDM chipsets are already available.

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

4 Spectrum Resource Flexibility

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

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

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

5 System Spectral Efficiency

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

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

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

6 System Service Flexibility

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

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

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

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

8 Reference System Gain

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

<table>
<thead>
<tr>
<th>Transmit Power (dBm)</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Antenna Gain (dBi)</td>
<td>16</td>
</tr>
<tr>
<td>Receive Antenna Gain (dBi)</td>
<td>18</td>
</tr>
<tr>
<td>Receive Sensitivity (dBm)</td>
<td>-75</td>
</tr>
<tr>
<td>Cable/Connector Loss (dB)</td>
<td>1</td>
</tr>
<tr>
<td>Overall System Gain (dB)</td>
<td>131</td>
</tr>
</tbody>
</table>

Table 1. Link budget of downlink deployment

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

9 Robustness to interference

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

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

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

10 Robustness to channel impairments

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

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

11 Robustness to radio impairments

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

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

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

12 Support of advanced antenna techniques

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

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

13 Compatibility with existing relevant standards and regulations

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

Summary
Benefits of PHY

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

Drawbacks of PHY

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

Comparison to Existing Standards

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

Intellectual Property Rights

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

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATDD</td>
<td>Adaptive Time Division Duplexing</td>
</tr>
<tr>
<td>BR</td>
<td>Bandwidth Request</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CG</td>
<td>Continuous Grant</td>
</tr>
<tr>
<td>CID</td>
<td>Connection Identifier.</td>
</tr>
<tr>
<td>CPE</td>
<td>Customer Premises Equipment (equivalent to SS)</td>
</tr>
<tr>
<td>CS</td>
<td>Convergence Subprocess</td>
</tr>
<tr>
<td>CSI</td>
<td>Convergence Subprocess Indicator</td>
</tr>
<tr>
<td>CTG</td>
<td>CPE Transition Gap</td>
</tr>
<tr>
<td>DAMA</td>
<td>Demand Assign Multiple Access</td>
</tr>
<tr>
<td>DES</td>
<td>Data Encryption Standard</td>
</tr>
<tr>
<td>DL</td>
<td>Down Link</td>
</tr>
<tr>
<td>DSA</td>
<td>Dynamic Service Addition</td>
</tr>
<tr>
<td>DSC</td>
<td>Dynamic Service Change</td>
</tr>
<tr>
<td>DSD</td>
<td>Dynamic Service Deletion</td>
</tr>
<tr>
<td>EC</td>
<td>Encryption Control</td>
</tr>
<tr>
<td>EKS</td>
<td>Encryption Key Sequence</td>
</tr>
<tr>
<td>FC</td>
<td>Fragment Control</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FSN</td>
<td>Fragment Sequence Number</td>
</tr>
<tr>
<td>GM</td>
<td>Grant Management</td>
</tr>
<tr>
<td>GPC</td>
<td>Grant Per Connection</td>
</tr>
<tr>
<td>GPT</td>
<td>Grant Per Terminal</td>
</tr>
<tr>
<td>HCS</td>
<td>Header Check Sequence</td>
</tr>
<tr>
<td>H-FDD</td>
<td>Half-duplex FDD</td>
</tr>
<tr>
<td>HL-MAA</td>
<td>High Level Media Access Arbitration</td>
</tr>
<tr>
<td>HT</td>
<td>Header Type</td>
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<tr>
<td>IE</td>
<td>Information Element</td>
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<td>IUC</td>
<td>Interval Usage Code</td>
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<tr>
<td>LL-MAA</td>
<td>Low Level Media Access Arbitration</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------------------</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MIC</td>
<td>Message Integrity Check</td>
</tr>
<tr>
<td>MPDU</td>
<td>MAC Protocol Data Unit</td>
</tr>
<tr>
<td>MTG</td>
<td>Modulation Transition Gap</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>PCD</td>
<td>Physical Channel Descriptor</td>
</tr>
<tr>
<td>PBR</td>
<td>Piggy-Back Request</td>
</tr>
<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical layer</td>
</tr>
<tr>
<td>PI PHY</td>
<td>PHY Information element</td>
</tr>
<tr>
<td>PKM</td>
<td>Privacy Key Management</td>
</tr>
<tr>
<td>PM</td>
<td>Poll Me bit</td>
</tr>
<tr>
<td>PS</td>
<td>Physical Slot</td>
</tr>
<tr>
<td>PSDU</td>
<td>Physical sublayer Service Data Unit</td>
</tr>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RS</td>
<td>Reed-Solomon</td>
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<td>SAP</td>
<td>Service Access Point</td>
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<tr>
<td>SI</td>
<td>Slip Indicator</td>
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<tr>
<td>SDU</td>
<td>Service Data Unit</td>
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<tr>
<td>SS</td>
<td>Subscriber Station</td>
</tr>
<tr>
<td>TC</td>
<td>Transmission Convergence</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDM</td>
<td>Time Division Multiplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TDU</td>
<td>TC Data Unit</td>
</tr>
<tr>
<td>TLV</td>
<td>Type-Length-Value</td>
</tr>
<tr>
<td>TRG T</td>
<td>Tx/Rx Transmission Gap</td>
</tr>
<tr>
<td>UGS</td>
<td>Unsolicited Grant Service</td>
</tr>
<tr>
<td>UGS-AD</td>
<td>Unsolicited Grant Service with Activity Detection</td>
</tr>
<tr>
<td>UL</td>
<td>Link</td>
</tr>
<tr>
<td>W-OFDM</td>
<td>Wideband - Orthogonal Frequency Division Multiplexing</td>
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