RF Lecture Series
Modulation Fundamentals 6
Introduction to WiMedia Alliance UWB (Wireless USB) 802.15.3a
Modulation Standard

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1. Introduction

This paper describes a Multiband-Orthogonal Frequency Division Multiplex (MB-OFDM) implementation of Ultra-Wideband (UWB) technologies.

Ultra-wideband (aka UWB, ultra-wide band, ultraband, etc.) is a radio technology that can be used at very low energy levels for short-range high-bandwidth communications by using a large portion of the radio spectrum. Since the 1970s UWB has traditional applications in military focused non cooperative radar imaging. Such applications targeted sensor data collection, precision locating, tracking and targeting applications. Basically warfare related applications.

But recently, the WiMedia Alliance has planned widespread implementation of certified wireless USB and possibly next-generation Bluetooth 3.0 products, using multi-band orthogonal division modulation (MB-OFDM)-based ultra-wideband (UWB) physical layer (PHY). It will target the Wireless Personal Area Network (WPAN) civilian market and will span the frequency ranges of 3.1GHz to 10.6GHz.

In these writings the basics of the IEEE 802.15.3a indoor operation standard will be described. The motivations for its use, and architectural comparisons to narrow band transceivers will be considered. Then, limitations to its omnipresence are visited, and finally, a thorough overview of the UWB modulation fundamentals is described.

This report can not be comprehensive as the amount of material published on this subject is voluminous. Instead, an attempt is made to make the reader familiar with what many consider are the key aspects of the technology.

2. UWB: Why another Wireless Protocol?

2.1. Enhanced Channel Capacity (Data Rates)

Ultra wide band is attractive and effective because of the Hartley-Shannon Law which states:

$$C = B\log_2(1+\frac{S}{N})$$

Where:

C = Maximum Channel Capacity (in Bits per second)

B = Channel Bandwidth (Hz)

S= Signal Power (watts)

N= Noise Power (watts)

C grows linearly with B, but only logarithmically with S/N. In short, UWB can provide extremely high wireless data transfer rates because of its large (7500MHz) bandwidth. Wireless USB UWB supports data rates of 53.3, 80, 106.7, 160, 200, 320, 400 and 480 Mb/s.

2.2. Superior Power Efficiency: Longer Batter life, More Stealth, Better Multi-Path Immunity.

The very large (ultra wide) width of the frequency band translates into extremely short time domain pulses (312.5nS per symbol). This is because frequency bandwidth is inversely related to pulse time. With short time domain pulses comes a low average transmit power. This directly translates to longer battery life for handheld equipment.

A result of the low average power of these signals and the short duration of the pulses make for a low probability of detection. This makes it much more secure than other commonly used WPAN protocols, like Bluetooth.

The shorter pulses also increase the multi-path immunity because any non line of site (or direct) path will result with a signal delay which is large in comparison to the time length of the UWB pulses. Hence correlation of such interfering multi-path waveforms will be poor.

3. Some of the Challenges

3.1. FCC Emissions Masks Mitigate Interference

Because of the width of the band, and the larger possibility to interfere with other users and or services, the FCC has ordered limitations on the transmission power in the US to be no more than -41.3dBm/MHz. On February 4th 2002 the FCC allowed unlicensed use of UWB below 960MHz and between 3.2 – 10.6GHz band. The power vs frequency emissions mask are outlined below. Notice that the largest legal power is very low: -41dBm/MHz.

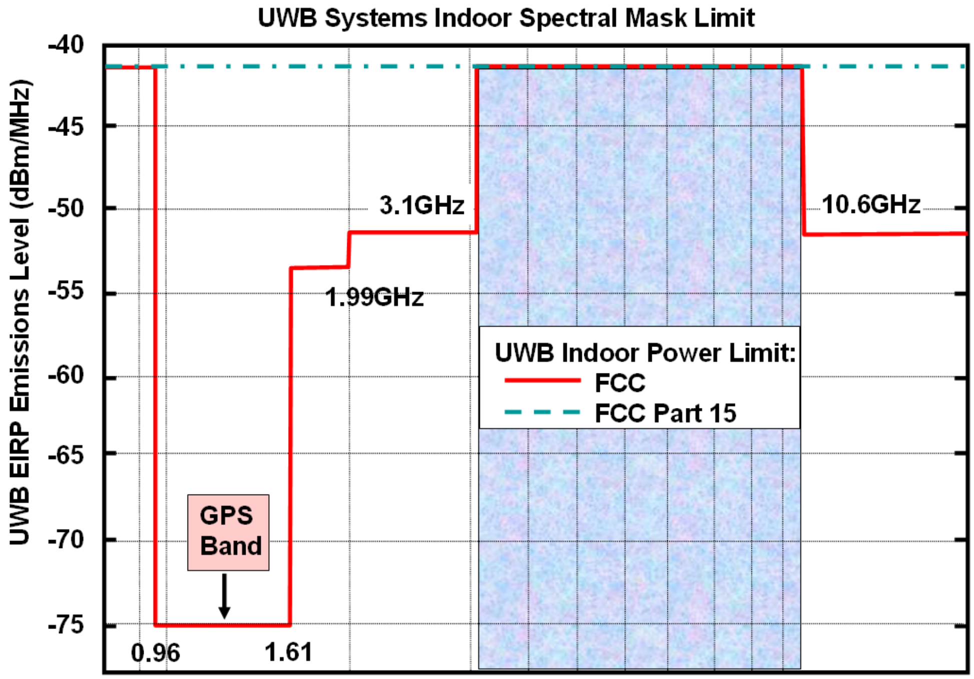


Figure 1 UWB system indoor spectral mask limit

3.2. MB-OFDM is Proposed to IEEE 802.15.3

To date, several proposals have been submitted to the IEEE 802.15.3a working group, and the final decision is yet to be made. But the two most popular standards are direct-sequence UWB (DS-UWB) and multiband orthogonal frequency division multiplexing (OFDM). The following will discuss only the MB-OFDM proposal.

The IEEE MB-OFDM implementation of UWB divides the FCC declared 7500 MHz spectrum bandwidth into (6) band groups and (14) non-overlapping bands spaced at 528 MHz bandwidth each, where each band provides a carrier frequency for an OFDM Symbol Baseband signal. See figure 3 below.

3.3. World Wide Adoption and Band Group 6

As more of the world was brought into consideration, it became obvious that UWB products designed for the US would not be compatible for use in other countries. The WiMedia Alliance later drafted a frequency usage map which identified a new “Band Group 6” (7.4 to 9.0GHz) as being compatible world wide. Figure 3 below outlines the allocation as of this writing. As of 2008, this band has been approved in US, Europe, Japan, Korea, China, Canada, Singapore and Brazil.

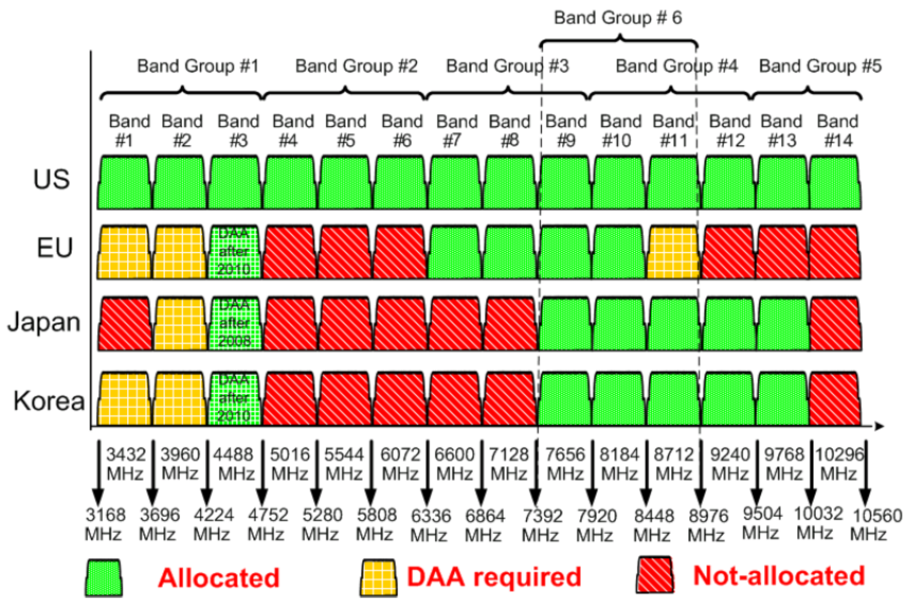


Figure 2 Worldwide frequency map 2008

3.4. Other Interfering Narrow Band Protocols

Figure 3 below relates the UWB spectral power as it pertains to other “in band” protocols. The combination of low power, spread spectrum, frequency hopping, and the use of Band Group 6 is intended to mitigate any likelihood of interference between the UWB signals and others transmitting in its band.

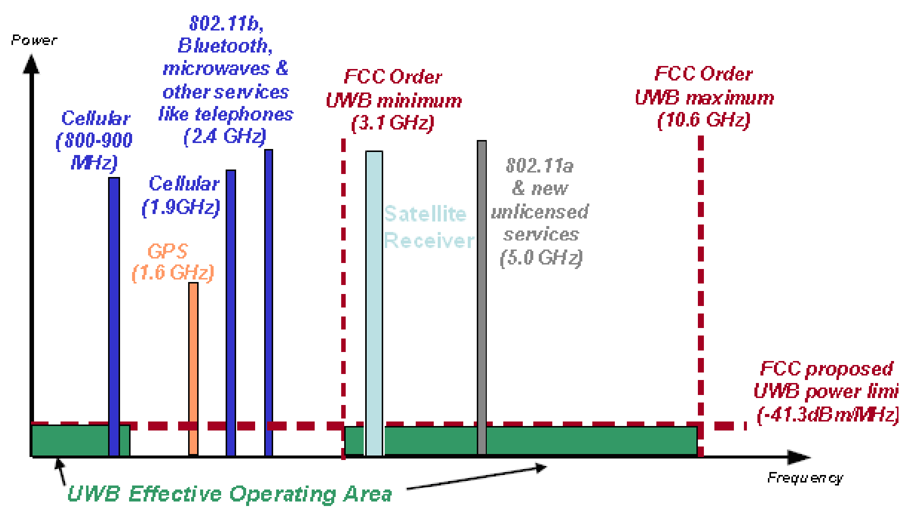


Figure 3 Power of UWB signals relative to other wireless protocols

3.5. Trade Offs: Power vs Range

The trade off, unfortunately is that with low transmission power comes diminished transmission range. Below is a chart showing the bit rates of each protocol and the intended transmission ranges.

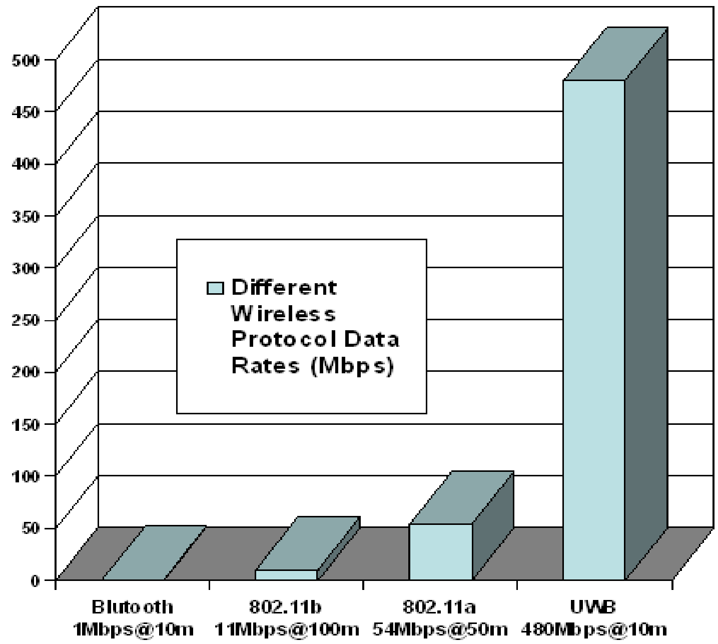


Figure 4a Modulation protocol vs transmission bit rate vs transmission range.

Another view of the same information can be seen below.

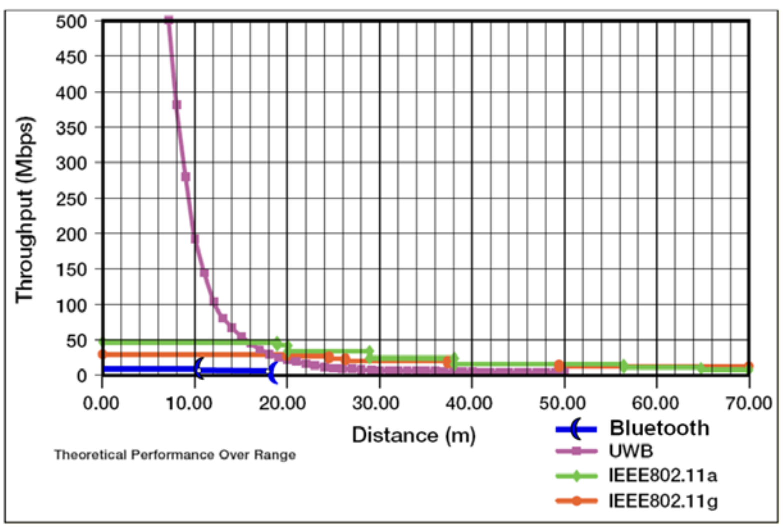


Figure 4b Modulation protocol vs transmission bit rate vs transmission range.

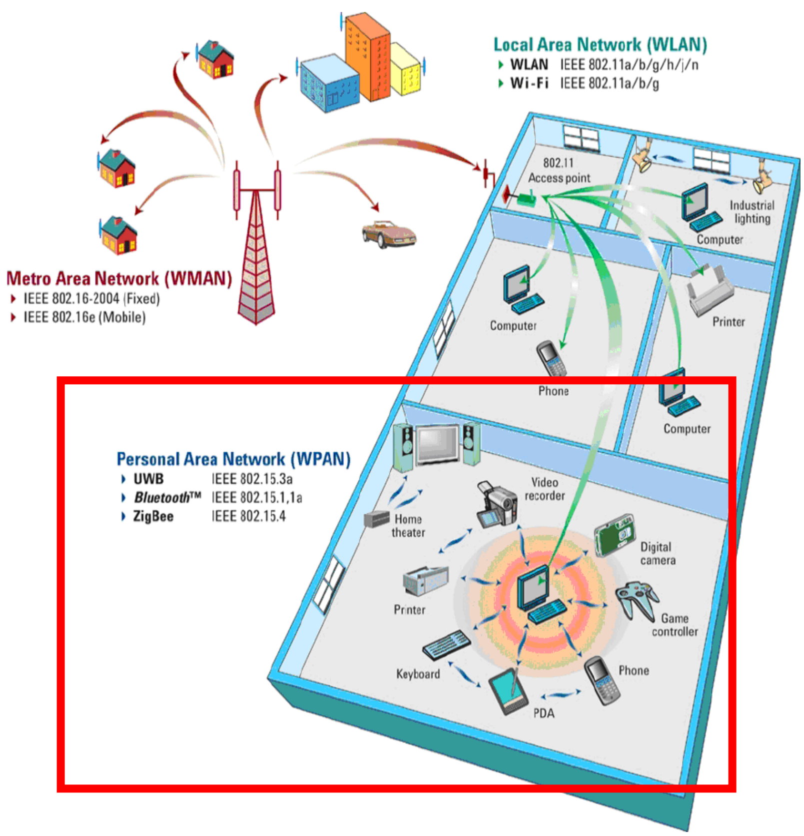
Still more information about the UWB capabilities compared to other IEEE standards is found in figure 4c below.

	IEEE Standard						
	WLAN			Bluetooth	WPAN	UWB	ZigBee
	802.11a	802.11b	802.11g	802.15.1	802.15.3	802.15.3a	802.15.4
Operational Frequency	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	3.1–10.6 GHz	2.4 GHz
Maximum Data Rate	54 Mbps	11 Mbps	54 Mbps	1 Mbps	55 Mbps	> 100 Mbps	250 Kbps
Maximum Range	100 meters	100 meters	100 meters	10 meters	10 meters	10 meters	50 meters

Figure 4c UWB capabilities compared to other IEEE standards.

3.6. Target Applications

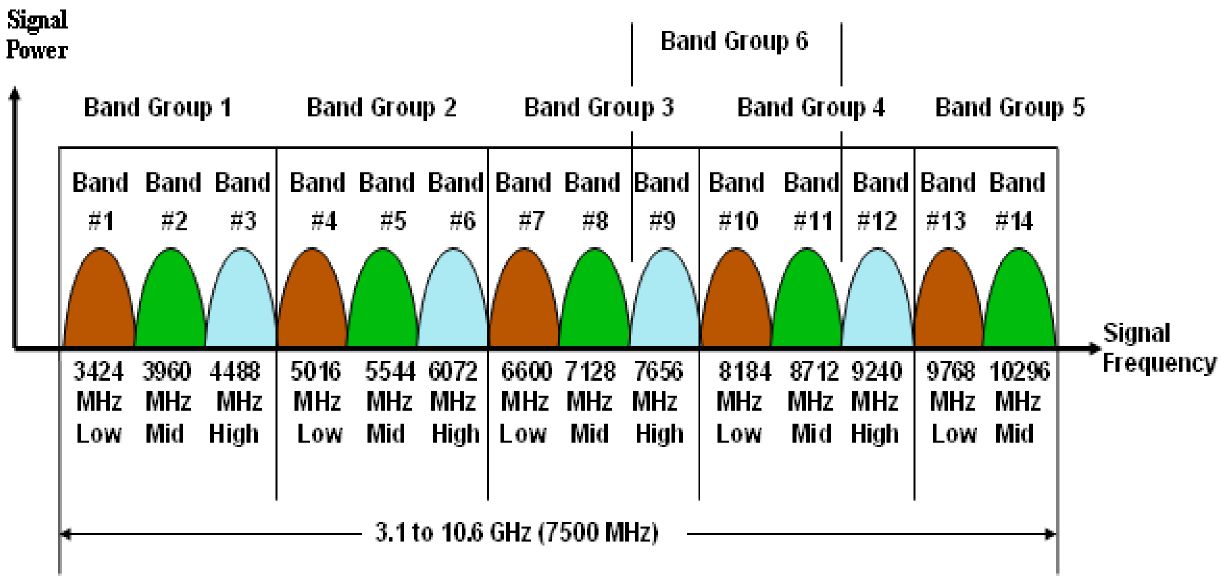
So, the obvious application for UWB would be for wireless personal area networks (WPAN) where the transmission distances are expected to be short but the required data rate would be high. Below is a picture of such a network – along with the types of networks serviced by other protocols.



4. UWB MB-OFDM 802.15.3a Modulation Fundamentals

4.1. MB-OFDM Band Groups and Bands

The WiMedia MB-OFDM implementation of UWB divides the FCC declared 7500 MHz spectrum bandwidth into (6) band groups and (14) non-overlapping bands spaced at 528 MHz bandwidth each, where each band provides a carrier frequency for an OFDM Symbol Baseband signal. To allow for such a large signal bandwidth, there are power restrictions which prevent MB-OFDM devices from disturbing narrower band devices nearby, such as 802.11ab/g radios. Typically, MB-OFDM devices operate within a 10 meter radius.



4.2. Band Group and Band Frequencies

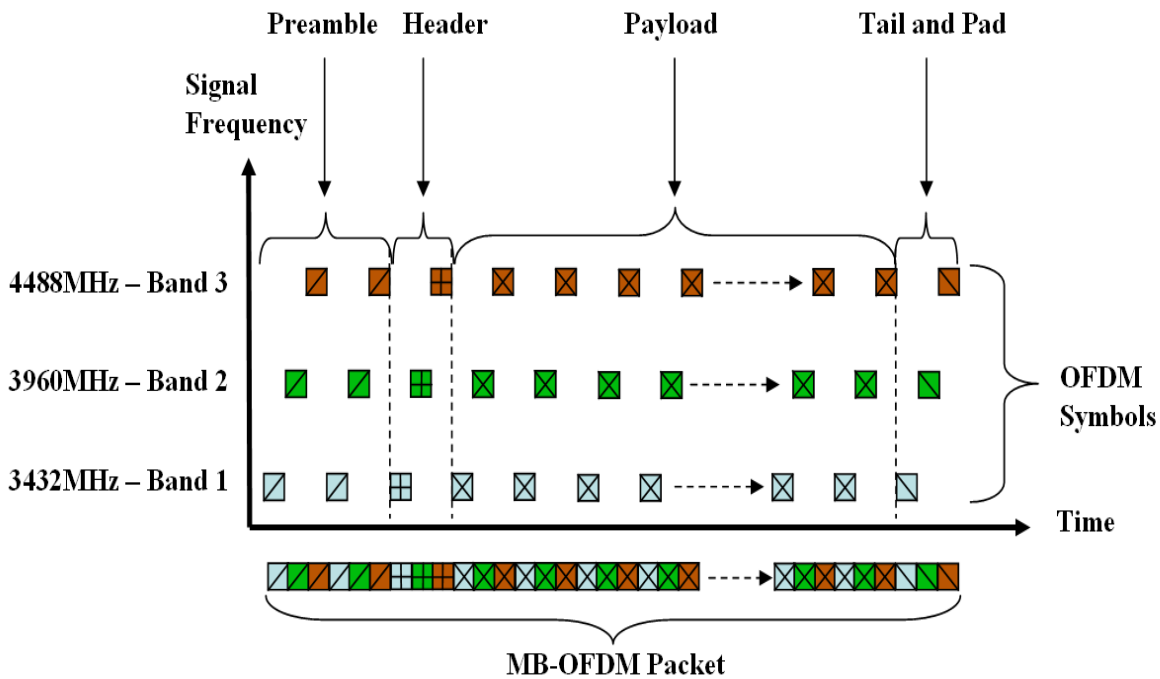
The table below summarizes the Band frequencies within each Band Group.

Band Group and Band Frequencies

Band Group	**Band**	**Lower Frequency (MHz)**	**Center Frequency (MHz)**	**Upper Frequency (MHz)**
1	1	3168	3432	3696
	2	3696	3960	4224
	3	4224	4488	4752
2	4	4752	5016	5280
	5	5280	5544	5808
	6	5808	6072	6336
3	7	6336	6600	6864
	8	6864	7128	7392
	9	7392	7656	7920
4	10	7920	8184	8448
	11	8448	8712	8976
	12	8976	9240	9504
5	13	9504	9768	10032
	14	10032	10296	10560
6	9	7392	7656	7920
	10	7920	8184	8448
	11	8448	8712	8976
Color codes:		Low	Mid	High

4.3. MB-OFDM Frequency Hopping

In operation, MB-OFDM “hops” between portions of the MB-OFDM spectrum and concatenates the individual OFDM symbol bursts into a single MB-OFDM packet (see below). A hopping sequence always consists of six hops between Bands but within a single Band Group. For example, Band Group 1, and hops of Bands 1-2-3-1-2-3.



4.4. Time-Frequency Codes (TFC)

The parameter that determines the hopping sequence of the six OFDM symbol bursts is the Time-Frequency Code (TFC). For example, the hopping sequence for TFC 1 in Band Group 1 is Band 1-2-3-1-2-3. Band Groups 2 - 4 and Band Group 6 follow the same sequences using their respective bands. For example, the sequence for TFC 1 in Band Group 2 is Band 4-5-6-4-5-6 and Band Group 6 is Band 9-10-11-9-10-11. Band Group 5 only hops between two bands and thus has it's own sequence.

There are three TFC categories:

- TFI or Time-Frequency Interleaved uses TFCs 1 - 4 (hop sequence between 3 bands)
- FFI or Fixed-Frequency Interleaved uses TFCs 5 - 7 (hop sequence stays within 1 band or non-hopping))
- TFI2 or two-band Time-Frequency Interleaved uses TFCs 8 - 10 (hop sequence between 2 bands)

The Table below displays the six-hop sequence for each TFC in Band Group 1 and the TFCs in Band Group 5. The bands are color coded to show the three TFC categories (TFI, FFI, and TFI2). Band Groups 1 - 4 and Band Group 6 each supports (4) TFI codes, (3) FFI codes, and (3) TFI2 codes. Band group 5 supports (2) FFI codes and (1) TFI2 code. Traces represent bands as Low, Mid, and High (see note in table below).

Time-Frequency Codes (TFC)

TFC	Band Group	Base Sequence Preamble	Band Hopping Sequence					
1	1	1	1	2	3	1	2	3
2		2	1	3	2	1	3	2
3		3	1	1	2	2	3	3
4		4	1	1	3	3	2	2
5		5	1	1	1	1	1	1
6		6	2	2	2	2	2	2
7		7	3	3	3	3	3	3
8		8	1	2	1	2	1	2
9		9	1	3	1	3	1	3
10		10	2	3	2	3	2	3
5	5	5*	13	13	13	13	13	13
6		6*	14	14	14	14	14	14
8		8*	13	14	13	14	13	14

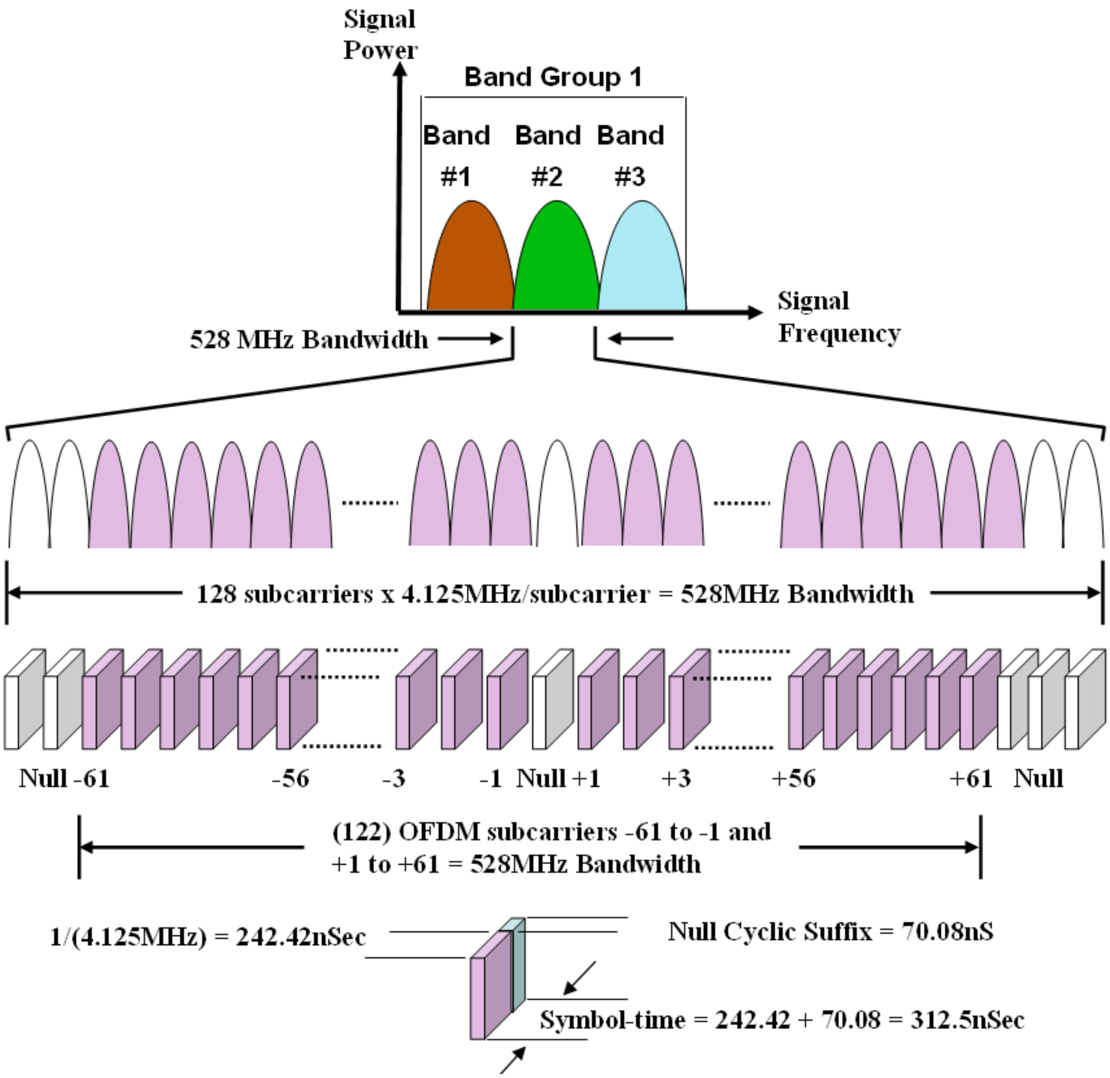
* Only 5, 6 and 8 are defined.

Color codes: Low | Mid | High

4.5. OFDM Symbols

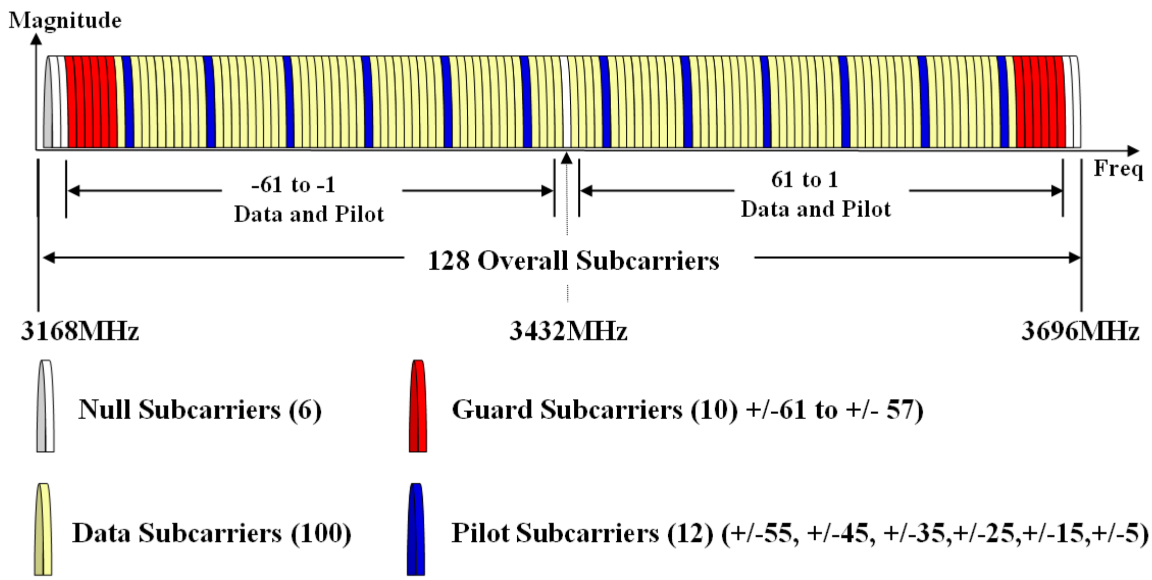
Each band of 528 MHz bandwidth is divided into 128 orthogonal subcarriers spaced 4.125 MHz apart. There are six null subcarriers with two at the lower end, one in the middle, and three at the upper end, resulting in 128 - 6 = 122 useful subcarriers, numbered -61 to -1, and +1 to +61 (see illustration below).

An OFDM symbol-time is 1/4.125 MHz = 242.42 nSec. Additional processing adds a Null Cyclic Suffix time of duration 70.08 nSec, resulting in an overall OFDM symbol-time of 312.50 nSec (see below). The Null Cyclic Suffix mitigates the effects of multi-path at the receiving end, plus provides a time window to allow sufficient time for the transmitter and receiver to switch between the different band center frequencies during hopping (burst) sequences.



4.6. OFDM Symbol Baseband

The multiplexed baseband signal provides 122 subcarriers: -61 to -1, and +1 to +61. Of these 122 subcarriers, (10) are Guards, (12) are Pilots, and the remaining (100) are Data. The center frequency (3432 MHz in this example) is null subcarrier 0, which is a characteristic of orthogonal signals. Note that in trace displays, guard subcarriers and pilot subcarriers are different colors than the data subcarriers.



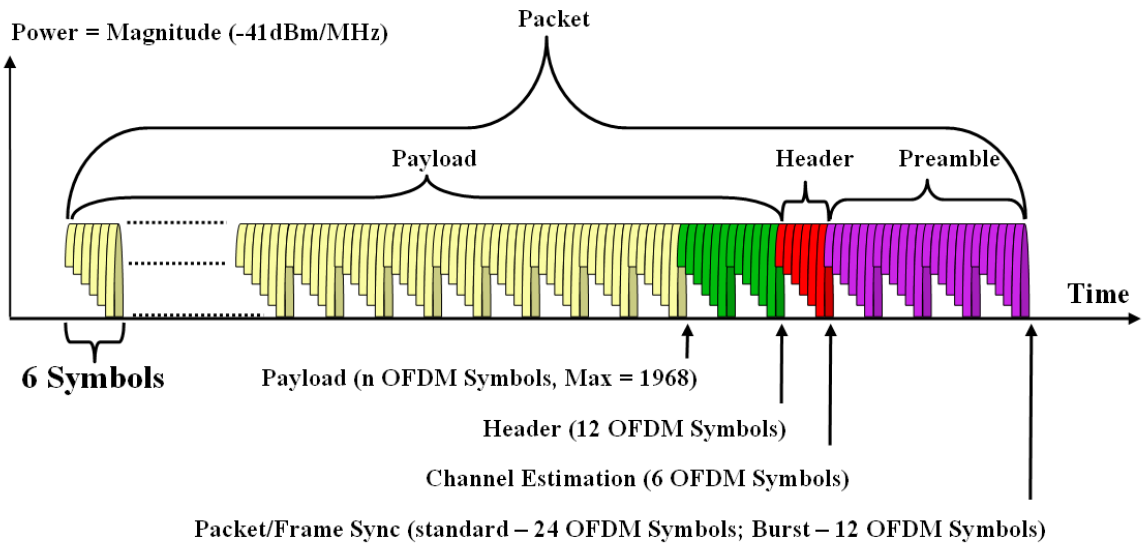
4.7. OFDM Symbol-Times

MB-OFDM parameter entries on the Time tab, Packet tab, and advanced tab are in units of symbol-time. As discussed above in OFDM Symbols, a symbol-time is 312.5 nSec in duration and consists of an OFDM Symbol (242.42 nSec) plus a Null Cyclic Suffix (70.08 nSec).

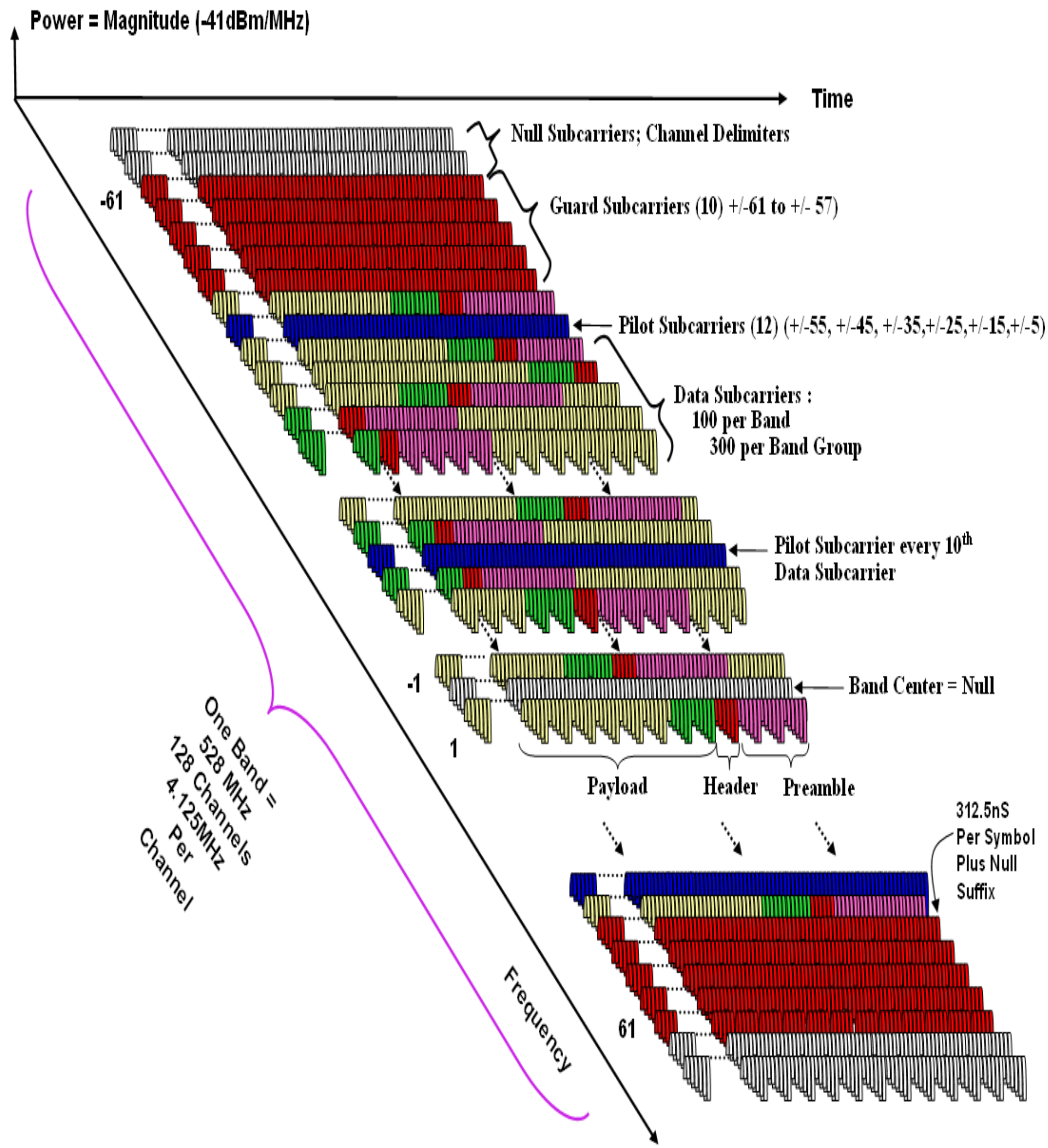
4.8. MB-OFDM Packet

An MB-OFDM packet consists of concatenated OFDM Symbols dedicated to Packet/Frame Sync, Channel Estimation, Header, and then Payload (see below). The combination of Packet/Frame Sync and Channel Estimation forms the Preamble. The preamble appears in two forms: the Standard Preamble consists of (24) Packet/Frame Sync symbol-times and (6) Channel Estimation symbol-times for a total of (30) symbol-times, while the Burst Preamble consists of (12) Packet/Frame Sync and (6) Channel Estimation symbol-times for a total of (18) symbol-times. The number of symbol-times in a packet is always divisible by 6 since the basic coding unit is 6 symbols. Packet length can be any length from a minimum of (42) OFDM Symbols (no Payload) to (2010) OFDM Symbols (full Payload) at the lowest data rate.

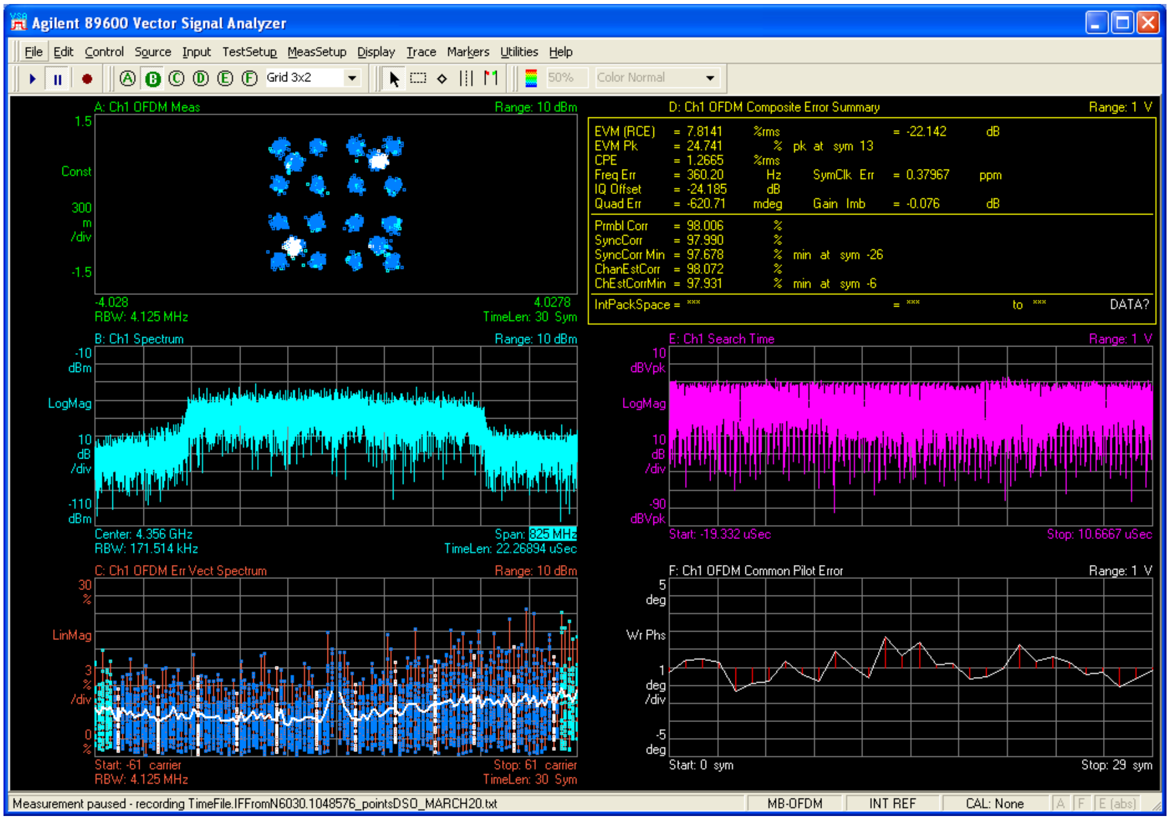
For Data Rates of 53.3, 80, 106.7, 160.0 and 200.0Mb/sec, all packets use the Standard Preamble; for Data Rates of 320.0, 400.0 and 480Mb/sec, the first packet uses the Standard Preamble, after which the remaining packets may use either the Standard Preamble -or- the Burst Preamble, in which case the preamble type is coded in the Header for the next packet. Typically, you use the Burst Preamble in a streaming mode, where a burst of packets is transmitted with only a minimum inter-frame separation time.


Power = Magnitude (-41dBm/MHz)
Packet
Payload
Header
Preamble
Time
6 Symbols
Payload (n OFDM Symbols, Max = 1968)
Header (12 OFDM Symbols)
Channel Estimation (6 OFDM Symbols)
Packet/Frame Sync (standard – 24 OFDM Symbols; Burst – 12 OFDM Symbols)

To better visualize the way frequency and time information is arranged in a single UWB channel, we can create a three dimensional plot below. Keep in mind that while there are only 13 data subcarriers shown. In fact there are 100 per band and 300 per band group.



Below are pictures of a capture of a UWB signal: TFC6 480Msps. It was generated using the Agilent wide band signal generator, E8267D and captured by the Verigy 6Gig Sampler (MCC) set to the 0.3Vpp range. EVM was measured to as 7.8% at a 4.356Ghz carrier Frequency (Pout = 0dBm).



4.9. MB-OFDM Data Rate Parameters

The following table lists the eight Data Rate choices and shows the operating parameters for each choice.

Data Rate (Mb/sec) - Allows you to choose the Data Rate for your signal under test. The choices are: 53.3, 80.0, 106.7, 160.0, 200.0, 320.0, 400.0, and 480.0Mb/sec.

Modulation Types - Modulation types include Quadrature Phase Shift Keying (QPSK), and Dual-Carrier Modulation (DCM), where DCM is effectively 16-Quadrature Amplitude Modulation at the bit level.

Coding Rate - Coding Rate indicates the ratio between an input bit stream and the resulting output bit stream, which is used for forward error correction. For example, a coding rate of 1/3 means an input bit stream produces three output bits for every input bit; or 5/8 where an input stream produces 8 output bits for every 5 inputs bits, and so forth.

FDS/TDS - Frequency-Domain Spreading (FDS) within an OFDM Symbol, and Time-Domain Spreading (TDS) across two consecutive OFDM Symbols, is used to obtain further MB-OFDM bandwidth expansion. FDS entails transmitting the same information (complex number) on two separate subcarriers within the same OFDM Symbol; TDS involves transmitting the same information across two consecutive OFDM Symbols. Using this technique, frequency diversity is maximized and performance is improved in the presence of non-coordinated devices.

Coded Bits/Info Bits - Coded Bits/Info Bits refers to the overall coded bits from 6 OFDM Symbols and the overall information bits from 6 OFDM symbols.

Preamble - Shows the preamble type for each Data Rate; Standard or Burst

MB-OFDM Data Rate Parameters

Data Rate (Mb/sec)	Modulation Type	Coding Rate	FDS	TDS	Coded Bits*	Info Bits*	Preamble
53.3	QPSK	1/3	Yes	Yes	300	100	Standard
80.0	QPSK	1/2	Yes	Yes	300	150	Standard
106.7	QPSK	1/3	No	Yes	600	200	Standard
160.0	QPSK	1/2	No	Yes	600	300	Standard
200.0	QPSK	5/8	No	Yes	600	375	Standard
320.0	DCM	1/2	No	No	1200	600	Standard/ Burst
400.0	DCM	5/8	No	No	1200	750	Standard/ Burst
480.0	DCM	3/4	No	No	1200	900	Standard/ Burst

* Per (6) OFDM Symbols

5. Conclusion

This paper has described the indoor operation of the Multiband-Orthogonal Frequency Division Multiplex (MB-OFDM) implementation of Ultra-Wideband (UWB) technologies. The motivations for its use have been considered. Then, limitations to its omnipresence were visited, and finally, a thorough overview of the UWB modulation fundamentals was described. We realized that such a technology was best suited for the WPAN type of applications.

This report can not be considered comprehensive as the amount of material published on this subject is very large and to attempt covering the subject in totality would prove outside the scope and intent of this paper. Instead, an attempt has been made to make the reader familiar with what many consider are the key aspects of the IEEE 802.15a MB OFDM UWB technology.

Not discussed are the technical challenges involved in production test of such devices. Nor was mentioned the types of Automatic Test Equipment modification which will be required to meet the test challenges put forth by this technology.

6. Appendix / Notes

6.1. Industry Trend: The need for greater “gaming” bandwidth

As of the date of this writing (1/5/2009), the video gaming industry has experienced a significant increase in revenue relative to other entertainment avenues (i.e. Movies, TV, outdoor activities/sports). Below are some data points which are relevant to those looking for growing trends in the consumer electronics industry where UWB may play a large role:

1) During the first week of introduction of the popular video game, Grand Theft Auto, 500 million dollars was grossed.
2) Hollywood's latest movie "Iron Man" grossed 300 million.
3) The cost to produce a movie typically costs 100 million dollars.
4) The cost to produce a video game is a maximum of 50 million dollars.
5) In 2008, video gaming represents a 10 billion dollar industry. This is expected to grow this year.
6) In November 2008 alone, 2.64 billion dollars was spent on gaming consuls and games.
7) Two million Nintendo Wi systems where sold in November 2008 alone. This amount is expected to grow as more people recognize this system as less of a traditional "gaming" device and more of a new interface to computer interaction.

All of this indicates the growing trend of "on line" gaming. As gaming ramps in popularity, so it will in bandwidth consumption. When this happens, it can be expected that UWB will provide a useful high speed data link from wireless head/hand sets to gaming consuls. The next "killer app" may be interactive gaming where the resolution of the interaction is very high and more realistic. When this happens, gamers will find themselves "suspending disbelief" far less than they ever had in the past, and able to vicariously enjoy the experience even more than they do in the movies. The only way to accomplish this using a wireless protocol will be through the use of UWB.

7. References

[1] http://www.informit.com/content/images/0131463268/samplechapter/0131463268_ch01.pdf
[2] Camera battery power graphs and studies between Bluetooth, 802.11 and UWB http://www.wirelessnetdesignline.com/207200448;jsessionid=UER0FLBEVGOEGQSNDLQCKHSCJUNN2JVN?printableArticle=true
[3] http://www.ofcom.org.uk/static/archive/ra/topics/uwb/uwb-radio.pdf
[4] The WiMedia standards page. http://www.wimedia.org/en/index.asp