Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Multi-band OFDM Physical Layer Proposal Response to no Voters]
Date Submitted: [11 January, 2004]

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[see page 2,3 for the complete list of company names, authors, and supporters]

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Re: [This submission is in response to the IEEE P802.15 Alternate PHY Call for Proposal (doc. 02/372r8) that was issued on January 17, 2003.]

Abstract: [This document describes the Multi-band OFDM proposal for IEEE 802.15 TG3a.]

Purpose: [To address the concerns raised by the no voters in the Nov03 meeting.]

Authors of the MB-OFDM Proposal

from 17 affiliated companies/organizations

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No Vote Response

- Most responses referred to the FCC certification and interference issues.
  - Extensive resources were allocated to resolve this issue
  - Significant progress has been made in the analysis and measurements of interference and building good working relationship with the FCC to alleviate any concerns
- Some responses addressed the IP position of the MBOFDM author companies
  - Most companies have filed RAND statements
  - 5 companies with significant IP positions issued a RAND-Z statement
- Time to market
  - Quicker to market than alternatives
- Other specific issues were also responded to

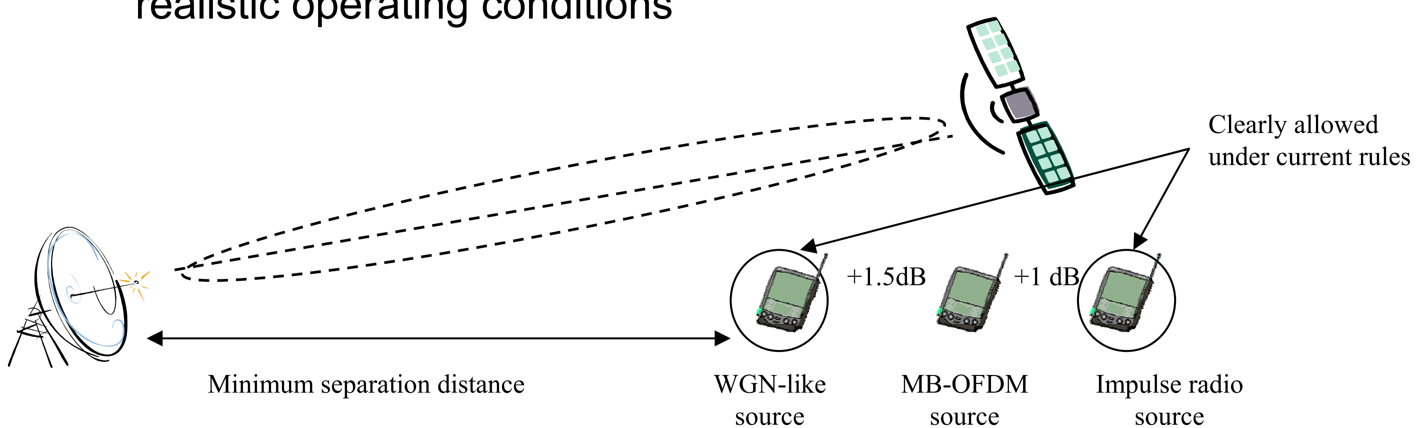
FCC Certification and Interference Issue

Introduction

- **The issue**: How is the average power measured for a MB-OFDM waveform?
  - Is it considered a ‘hopper’?
  - Does it need to reduce average Tx power compared to impulse based UWB waveforms?
- **FCC response**: Julius Knapp issued a statement that the issue is about interference and not about rules language interpretation
- **Our response**: Members of the MBOA took several steps to address the interference concerns
  - ***Detailed simulations*** of a PHY layer reflective of a broadband FSS system completed
  - ***Analysis*** of parameters effecting coexistence between UWB devices and FSS systems completed
  - Analysis of ***Amplitude Probability Distribution*** (APD) for MB-OFDM and other pulsed systems completed
  - ***Measurements*** of interference into a real FSS receiver completed
    - Includes MB-OFDM, WGN, and pulsed-UWB systems
  - Results in this briefing were shown to FCC

Executive Summary of Results

- Analysis, simulations, and measurements for wideband fixed satellite services (FSS) systems all come up with the same results
  - Interference from MB-OFDM waveforms is actually less than levels of interference caused by waveforms already allowed by the rules
  - Differences between all waveforms is on the order of 2-3 dB
- There is virtually no difference between DSSS, WGN, MB-OFDM, and impulse-UWB waveforms into narrowband receivers (less than 2.5 MHz)
- MB-OFDM waveforms can cause less interference than impulse radios in wideband receivers
  - MB-OFDM is ~ 1 dB better than 1 MHz PRF impulse radio
- WGN can cause less interference than MB-OFDM into wideband receivers
  - Difference between MB-OFDM and WGN interference is less than *1.5 dB* under realistic operating conditions



Substantial Interference Margin Exists with Current FCC Limits

- FCC/NTIA Interference results for various US government systems: Table taken directly from Final R&O and using the indoor mask

Most systems have substantial margin available

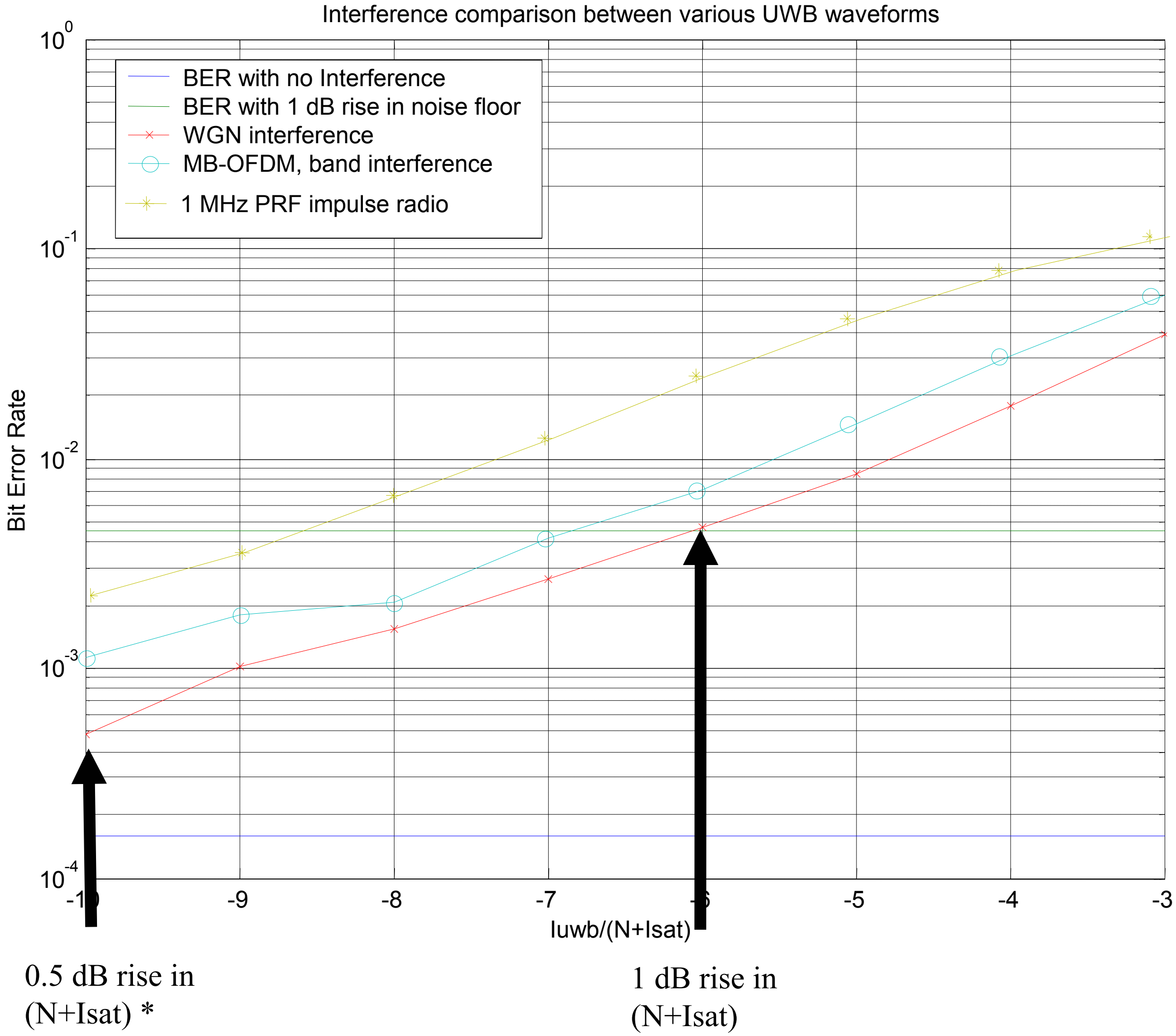
System	Frequency (MHz)	Maximum UWB EIRP (dBm/MHz) UWB Indoors 2 m height	Maximum UWB EIRP (dBm/MHz) UWB Indoors 30 m height	IF Bandwidth	Margin from current Part 15 limits
ARSR-4	1240-1370	-52	-73	690 KHz	23.3 dB (2 m) 2.3 dB (30 m)
SARSAT	1544-1545	-60	-57	800 KHz	15.3 dB (2 m) 18.3 dB (30 m)
ASR-9	2700-2900	-37	-57	653 KHz	14.3 dB (2 m)
NEXRAD	2700-2900	-33	-67	550 KHz	18.3 dB (2 m)
Marine Radar	2900-3100	-34	-45	4-20 MHz	17.3 dB (2 m) 6.3 dB (30 m)
FSS, 20 degrees	3700-4200	-24	-30	40 MHz	17.3 dB (2 m) 11.3 dB (30 m)
FSS*, 5 degrees	3700-4200	-39	-65	40 MHz	2.1 dB (2 m)
CW Altimeters	4200-4400	37	Not Applicable	N/A	78.3 dB (2 m)
Pulsed Altimeters	4200-4400	26	Not Applicable	30 MHz	67.3 dB (2 m)
MLS	5030-5091	-42	Not Applicable	150 KHz	-
TDWR	5600-5650	-23	-51	910 KHz	18.3 dB (2 m)

***: Most Direct TV/DSS/DTH receivers usually do not operate in 3.7-4.2 GHz C-band. They operate in 10.7-12.2 GHz Ku-band**

Simulation Results
(Relative comparisons)

Fixed FSS performance results

- For a given performance, what is the increase in separation distance needed to maintain the same FSS performance?
  - 35 MHz symbol rate, 7/8 code rate, no interleaving, Es/(N+Isat)=7.6 dB (at sensitivity)



*Iuwb/(N+Isat) = -10 dB results in Iuwb/N = -6 dB which is a level defended by XSI in a contribution submitted to the FCC

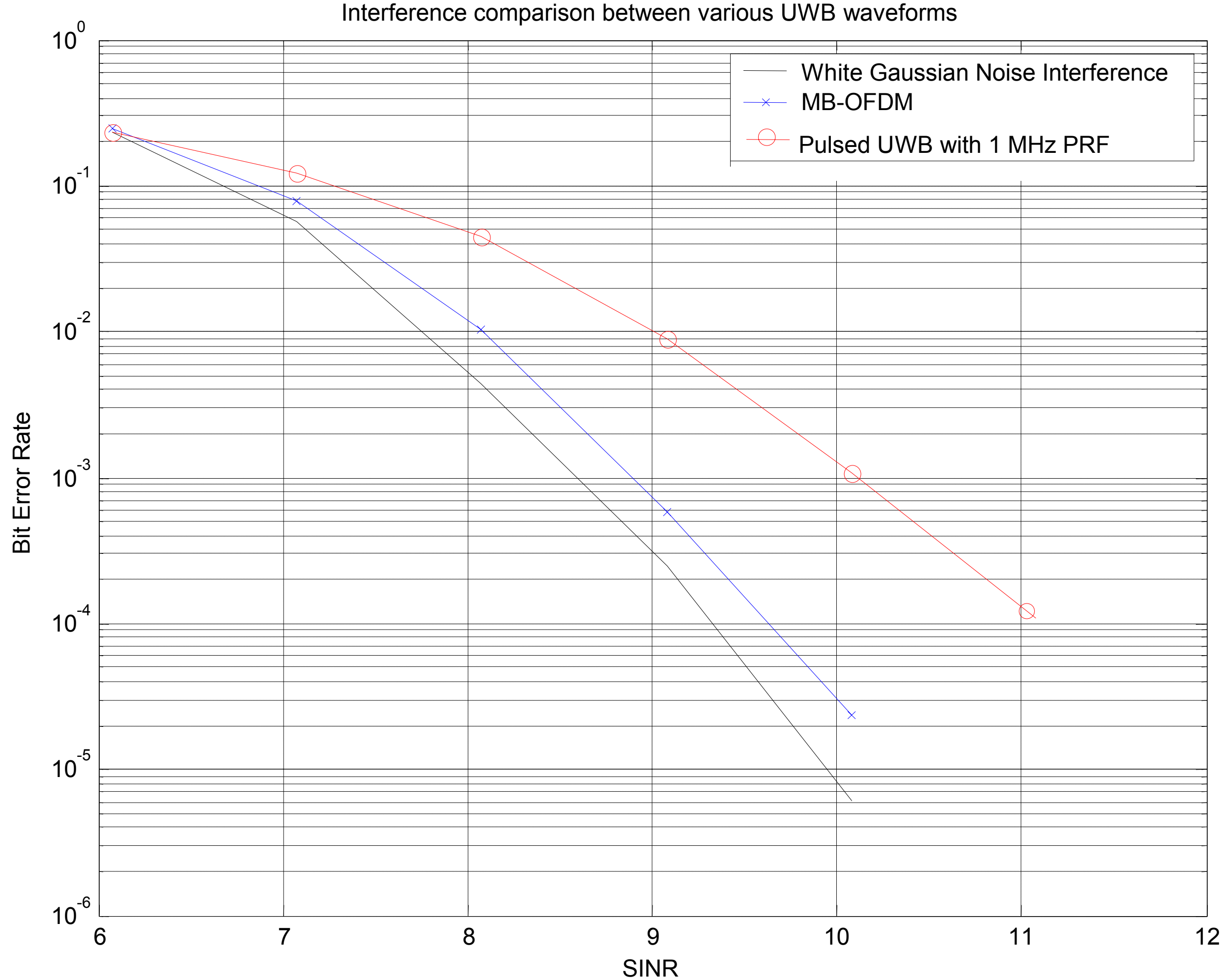
Fixed FSS performance results

- For a given performance, what is the increase in separation distance needed to maintain the same FSS performance?
  - Fixed FSS receiver performance (BER equivalent to 1 dB rise in SINR): 7/8 code

Interference Source	dB from WGN	Increase separation dist. (rel. to WGN, free space)	Increase separation dist. (rel. to WGN, path loss exp. = 3)
WGN	-	-	-
MB-OFDM	1 dB	12 %	8 %
1 MHz PRF Impulse	2.5 dB	33 %	21 %

Fixed UWB device separation distance

- For a given UWB device separation, what is the impact on FSS link margin?
  - 35 MHz, rate 7/8 coding, no interleaving, Iuwb/(N+Isat)=-4 dB



Fixed UWB device separation distance

- For a given UWB device separation, what is the impact on FSS link margin?
  - Fixed Separation distance (BER = 10e-3) : 7/8 code (no interleaving)

Interference Source	Iuwb/(N+Isat)	Reduced FSS Margin (dB)	Difference from WGN (dB)
WGN	-10 dB	0.5 dB	-
	-6 dB	1 dB	-
	-4 dB	1.5 dB	-
MB-OFDM	-10 dB	0.5	0
	-6 dB	1.1	0.1
	-4 dB	1.75	0.25
1 MHz PRF pulse	-10 dB	0.75	0.25
	-6 dB	2	1
	-4 dB	3	1.5

Link Budget Analysis Showing Absolute Separation Distance Results and Impact of Assumptions

Absolute Separation Distance Results

- What is the absolute separation distance required between a UWB device (modeled here as WGN) and a FSS receiver?
  - What is the impact of assumptions used in the analysis?

Indoor parameters (includes 12 dB building attenuation factor)

Changing 1 assumption at a time →

Assumptions	Case 1 (Baseline)	Case 2	Case 3	Case 4	Case 5
Antenna Gain[1]	32-25log(θ)	**29-25log(θ)**	**29-25log(θ)**	**29-25log(θ)**	**29-25log(θ)**
Isat/N ratio[2]	-100 dB (no Isat)	-100 dB (no Isat)	**1.4 dB**	**1.4 dB**	**1.4 dB**
Path loss model	Free space (n=2)	Free space (n=2)	Free space (n=2)	**NLOS Path loss exp. (n=3)**	**NLOS Path loss exp. (n=3)**
Iuwb/(N+Isat) criteria	-10 dB	-10 dB	-10 dB	-10 dB	**-6 dB**

[1] Antenna gain in Case 1 proposed by SIA, gain in Case 2 proposed by XSI based on FCC 25.209 and ITU-R S.580.

[2] Isat/N = 1.4 dB derived from SIA filing to FCC, May 2003.

Absolute Separation Distance Results

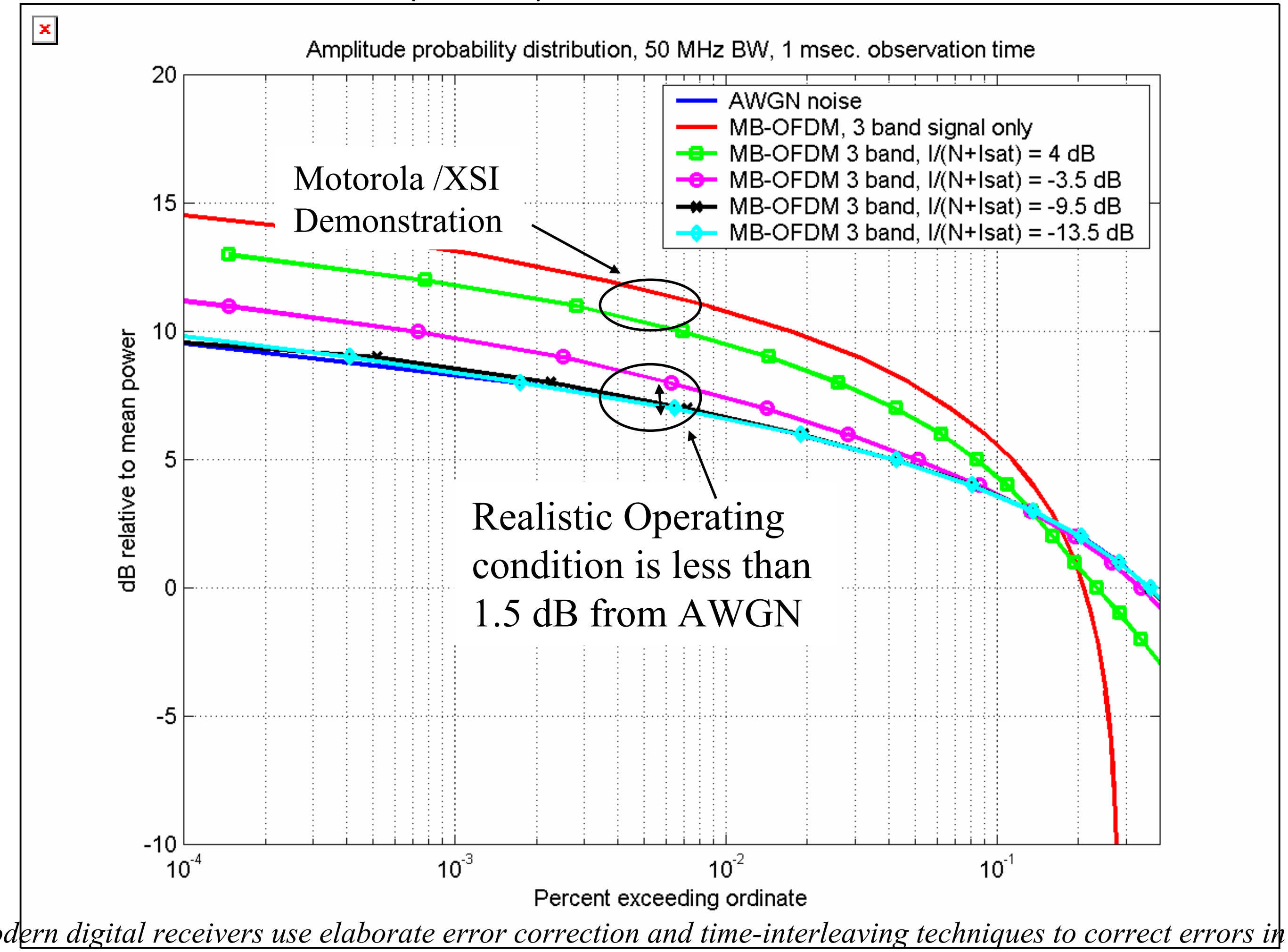
20 degree indoor					
FSS Interference Table	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Tx Power	-41.30	-41.30	-41.30	-41.30	-41.30
FSS Antenna angle (deg.)	20.00	20.00	20.00	20.00	20.00
Antenna Gain	-0.53	-3.53	-3.53	-3.53	-3.53
Center freq. (GHz)	3.75	3.75	3.75	3.75	3.75
Breakpoint (BP) (m)	1.00	1.00	1.00	1.00	1.00
Building attenuation (dB)	12	12	12	12	12
Rx power at BP (dBm)	-85.75	-88.75	-88.75	-88.75	-88.75
Noise floor (N) (dBm)	-117.00	-117.00	-117.00	-117.00	-117.00
Isat/N ratio (dB)	-100.00	-100.00	1.40	1.40	1.40
(N+Isat) floor (dBm)	-117	-117	-113.234	-113.234	-113.234
Iuwb/(N+Isat) criteria (dB)	-10	-10	-10	-10	-6
Max. Iuwb (dBm)	-127	-127	-123.234	-123.234	-119.234
Path loss required (dB)	29.25	26.25	22.49	22.49	18.49
Path loss exp. after BP	2	2	2	3	3
Min. separation dist (m)	29.013	20.53963	13.31279	5.617107	4.132182

~17 dB difference depending on system assumptions
(vs. 1-3 dB difference depending on structure of UWB waveform)

Amplitude Probability Distribution (APD) Analysis

APD[1] for MB-OFDM with different I/(N+Isat)

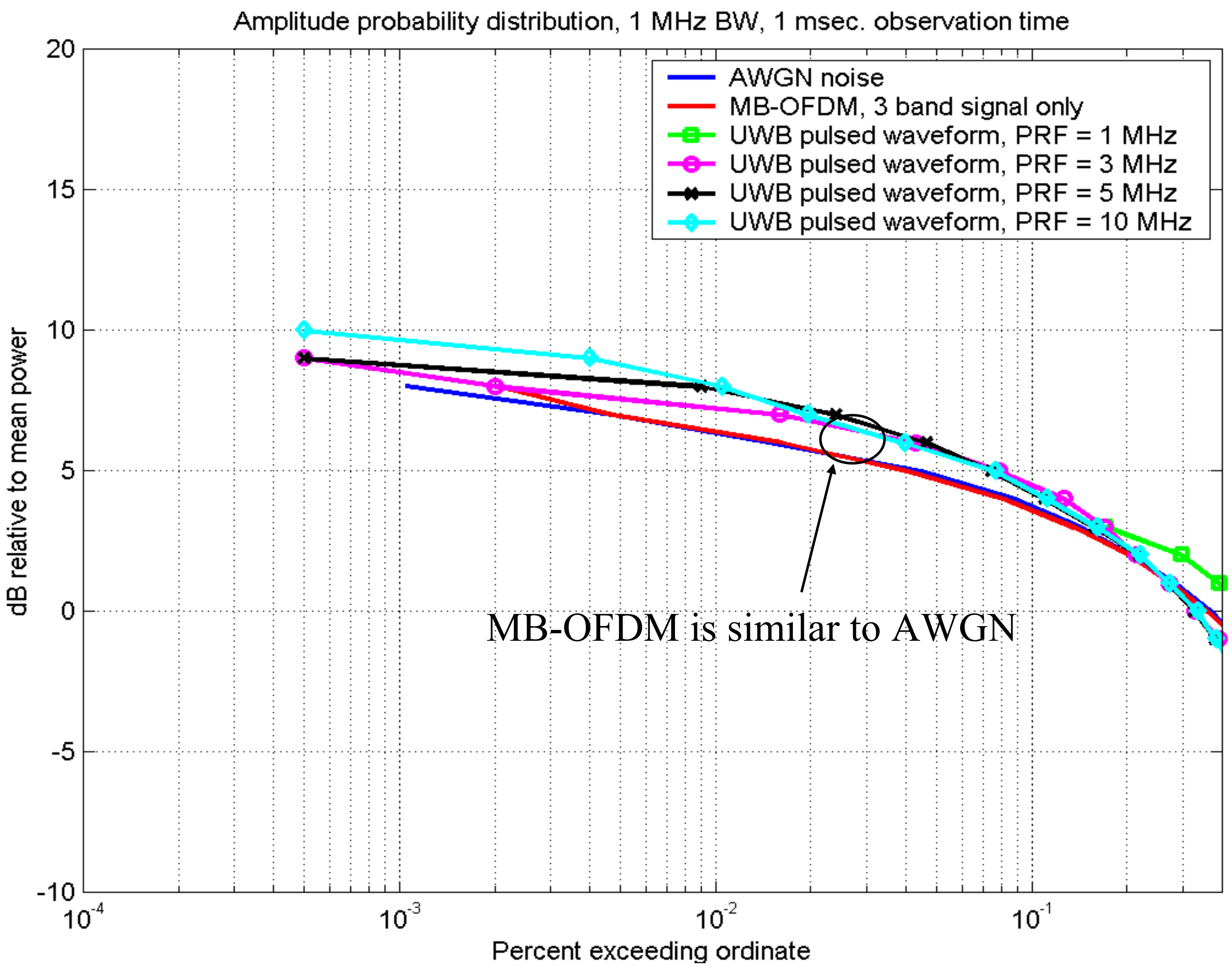
- The APD of MB-OFDM with I/(N+Isat) = -3.5, -9.5, -13.5 is less than 1.5 dB from AWGN.



[1] *Many modern digital receivers use elaborate error correction and time-interleaving techniques to correct errors in the received bit sequence. In such receivers, the corrected BER delived to the user will be substantially different from the received BER. Computation of BERs in these receivers will require much more detailed interference information than is contained in the APDs.* [R. Achatz, NTIA, Appendix A. Tutorial on Using Amplitude Probability Distributions to Characterize the Interference of Ultrawideband Transmitters to Narrowband Receivers]

APDs for narrowband receivers

- MB-OFDM APD is similar to AWGN with a 1 MHz resolution bandwidth.



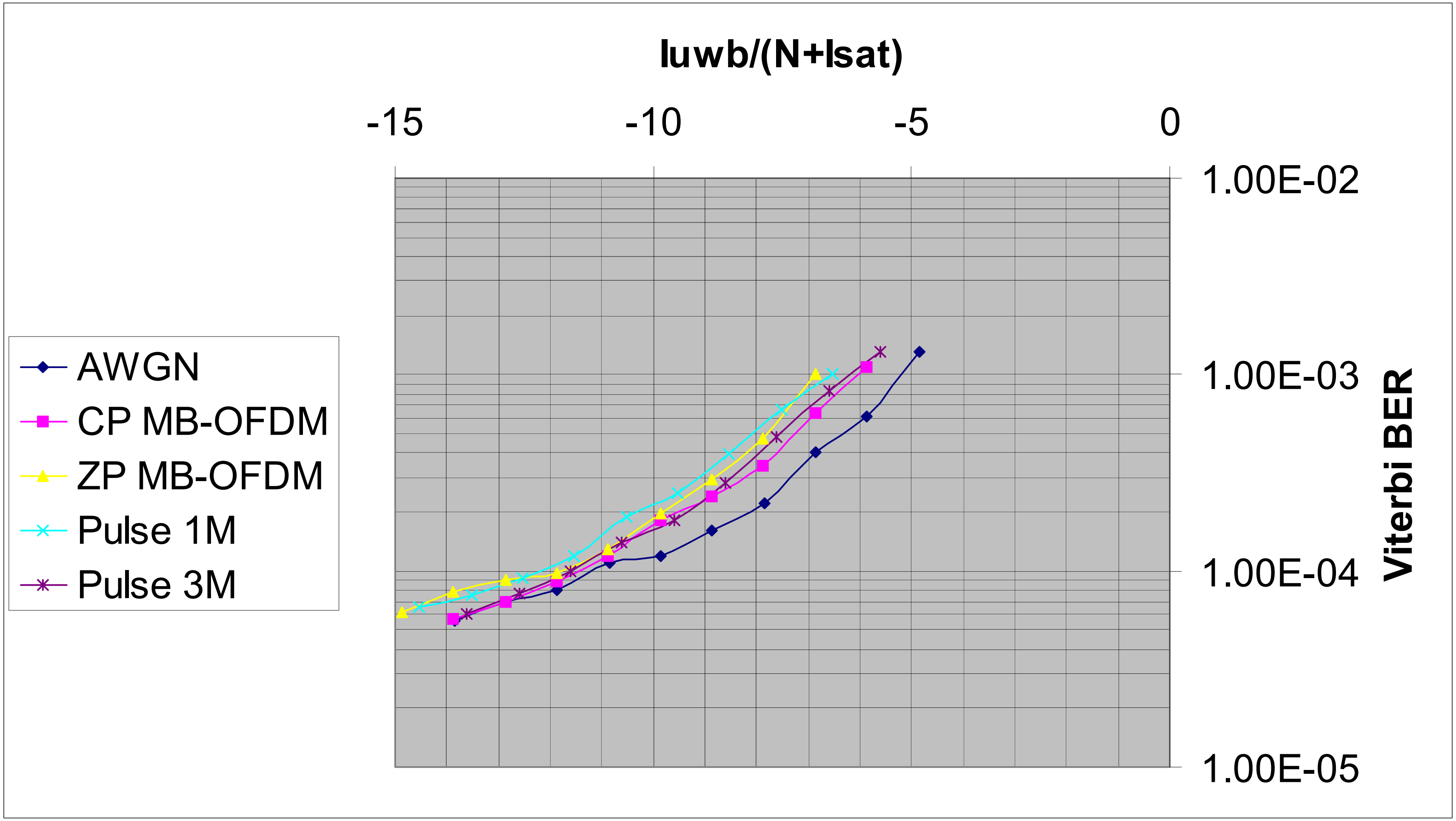
Measurements

Wisair Conducted Measurements

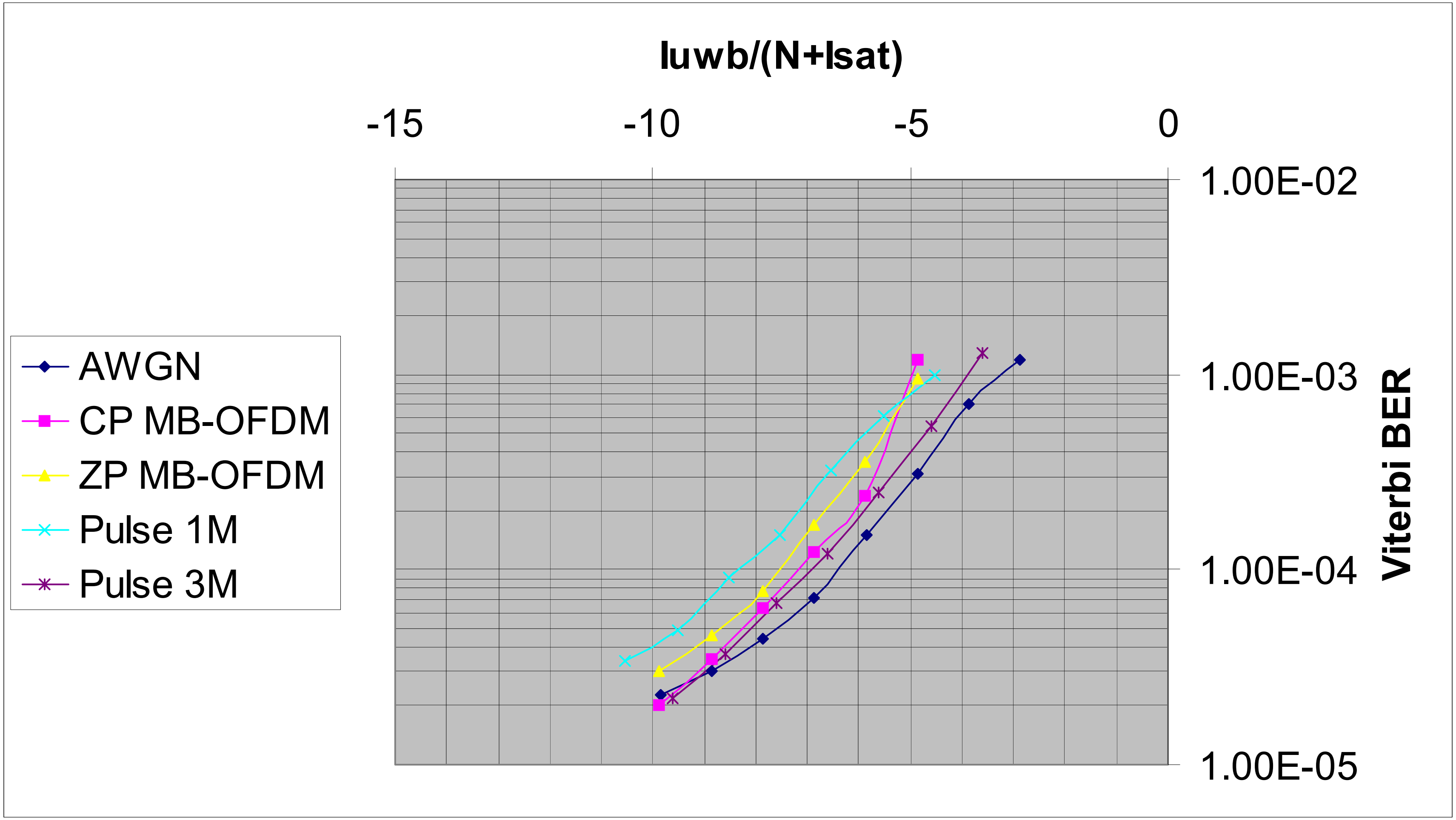
- Measurements were taken with a digital C-Band victim receiver in a carefully calibrated laboratory environment
- Performed testing for 2.5 Msps and 20 Msps with convolutional and RS encoders
- Measurement results match simulation results when considering measurement accuracy and implementation degradation
  - Less than 1.5 dB difference between MB-OFDM and AWGN for 20 Msps receivers under realistic operating conditions similar to simulation and analysis results
  - No difference between MB-OFDM and AWGN for 2.5 Msps receivers

Measurement Test Setup

Measurement Results (1)
FSS signal ~0.5 dB above Sensitivity



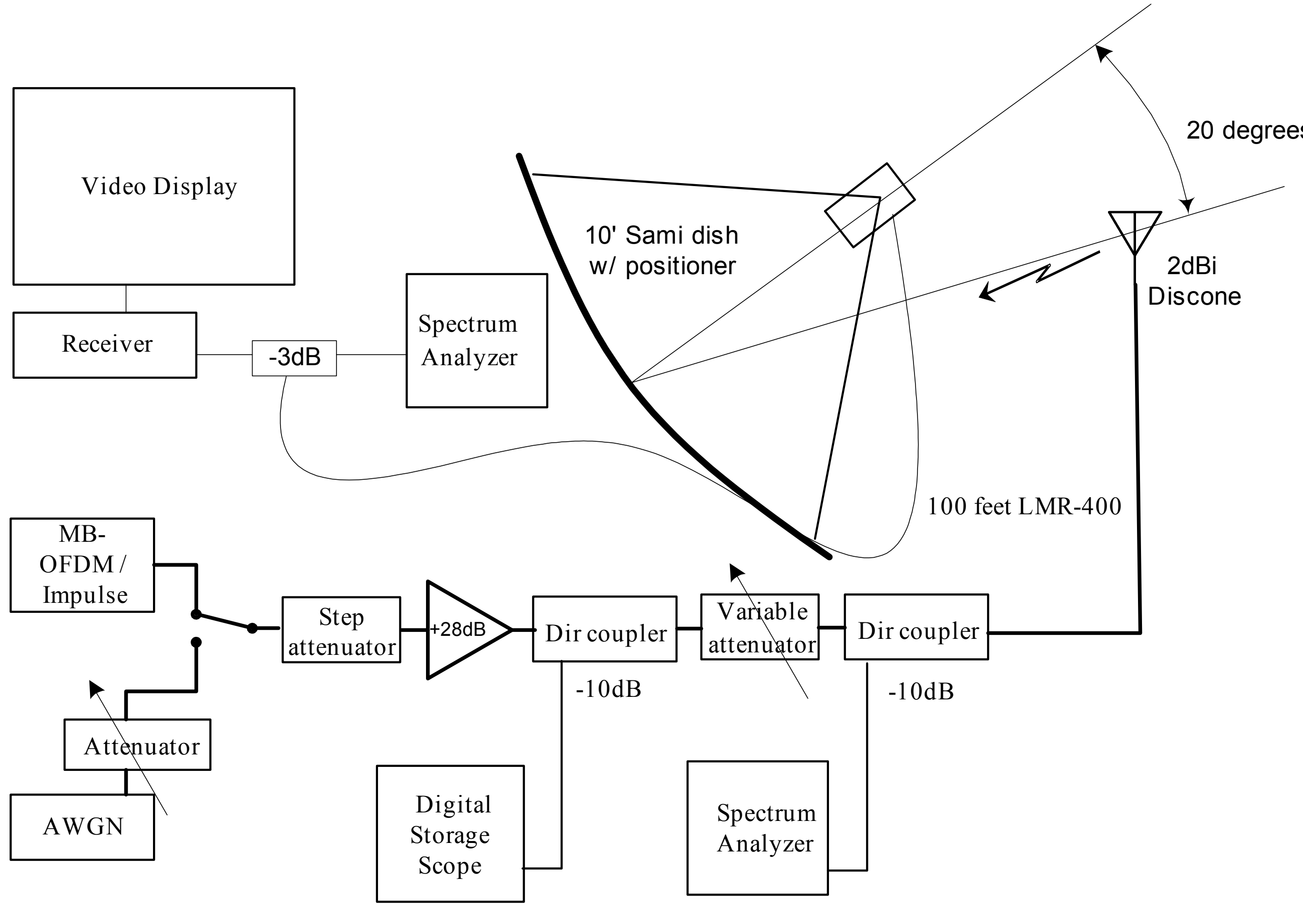
Measurement Results (2) FSS signal ~1 dB above Sensitivity



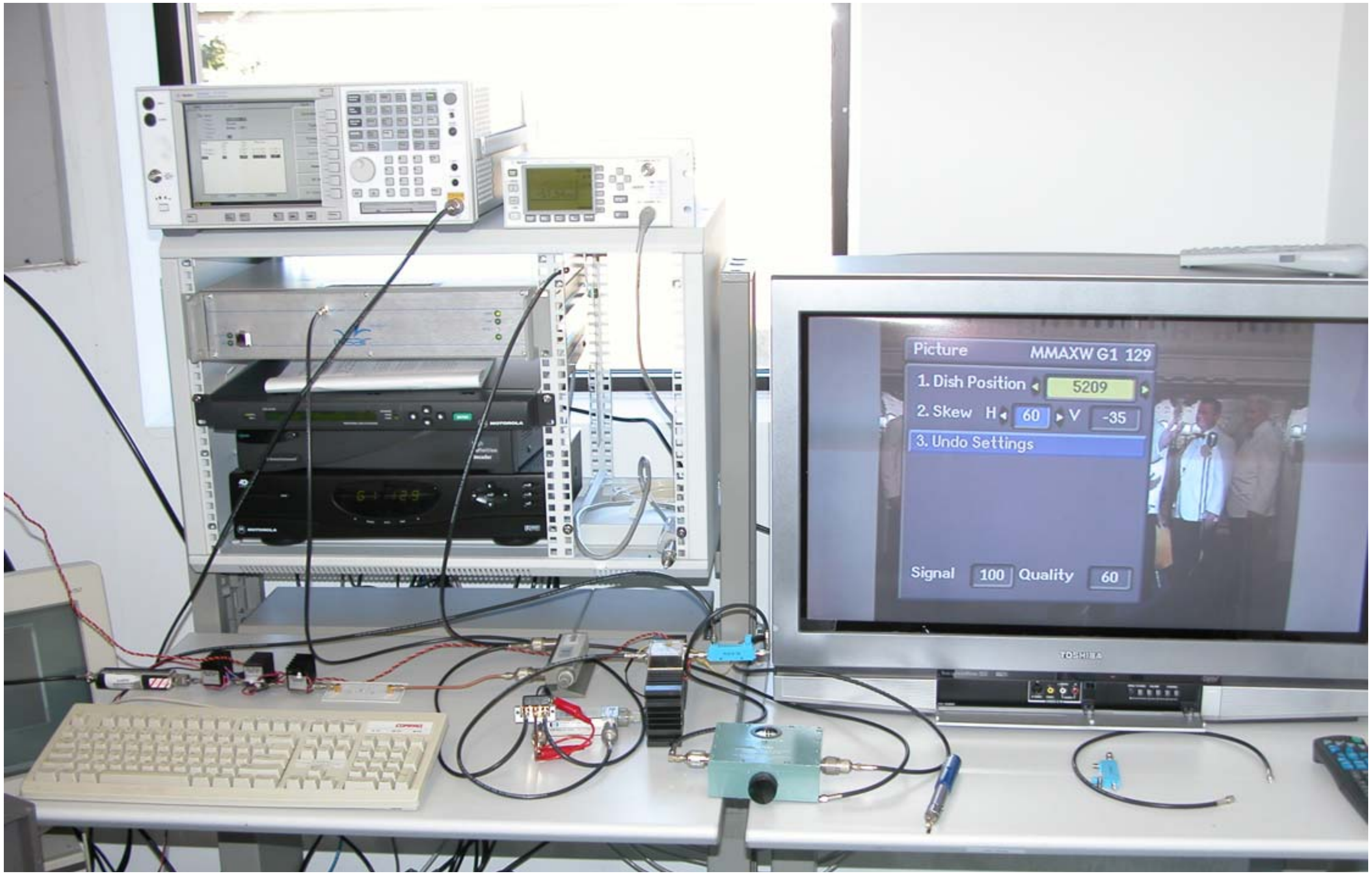
Interference Measurements at TDK RF test range

- Interference measurements conducted at TDK RF test facility in Austin, TX Dec 8-18, 2003
- Victim receiver is C-Band television broadcast
  - fc=4.16GHz
  - Digicipher II stream (QPSK, 7/8 FEC, 29.27Ms/s)
- Dish size selected as typical for the Austin area
- Interference measurements conducted over entire receiver operating margin:
  - 0.5 dB above sensitivity
  - 1.0 dB above sensitivity
  - 2.5 dB above sensitivity (maximum)
- Detailed test report in a later document.

INTERFERENCE TEST BLOCK DIAGRAM



Test equipment setup



Interference threshold Measurements dB relative to AWGN

Emission	0.5dB Above Sensitivity	1dB Above Sensitivity	2.5dB Above Sensitivity
AWGN (DSSS)	0.0dB	0.0dB	0.0dB
MB-OFDM	-1.1dB	-1.2dB	-1.6dB
Impulse 3 MHz PRF	-1.9dB	-3.8dB	-4.0dB

Separation Distance Test

Interference Threshold
at -41.3dBm per MHz (FCC)

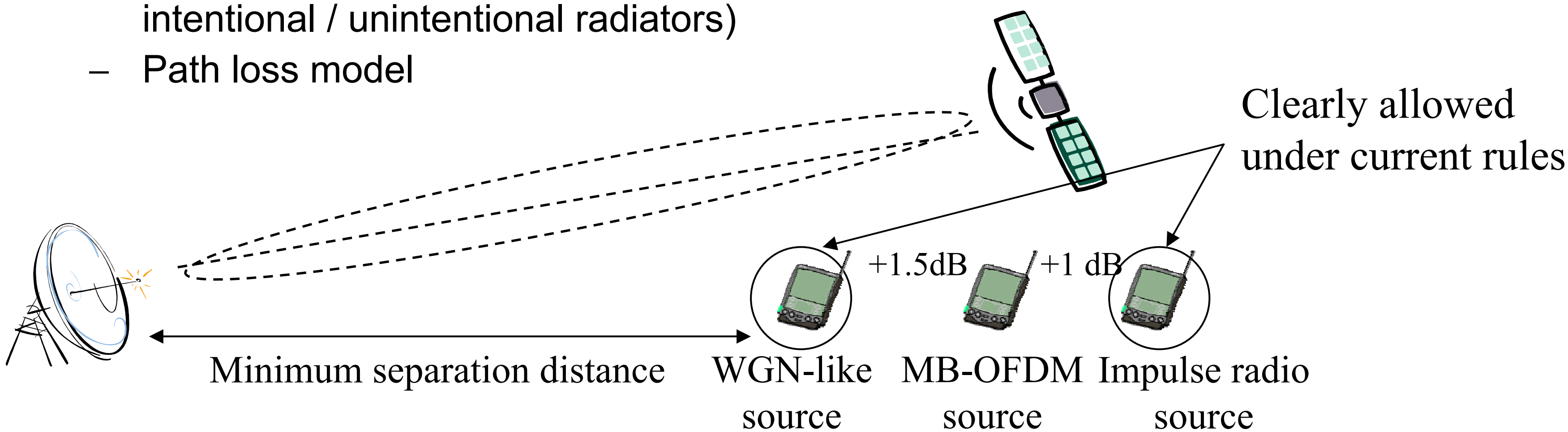
Red flags mark
AWGN

Green flags mark
MB-OFDM

Summary of Results and Conclusions

Summary of FSS Interference Studies

- Analysis, simulations, and measurements for wideband FSS systems all come up with the same results
  - MB-OFDM causes ~ 1 dB less interference than 1 MHz PRF impulse radio (with nsec pulse duration)
  - MB-OFMD is < 1.5 dB more interference than WGN
  - Impact on FSS link margin is on order of *tenths of a dB (~0.1 dB)* difference under realistic scenarios
  - Results do not show 'substantial' interference potential claimed by Motorola
- Relative differences are very small when other parameter variations are considered:
  - Antenna response (elevation and azimuth gain)
  - Operating signal level relative to thermal noise floor
  - Presence of other sources of interference (intra-system interference, other intentional / unintentional radiators)
  - Path loss model



Conclusions

- MBOA has followed FCC's directions to perform technical analyses to ensure that the UWB standard does not cause levels of interference beyond that already allowed by the rules
  - These results have already been presented to the FCC
  - MBOA can reproduce test setup if companies are interested in further testing and/or validation of results
- Simulation, analysis and measurements of FSS systems were performed by several companies in the MBOA
  - Measurement results have been validated by 2 independent tests
  - Results have shown levels of interference similar to what is already allowed by the rules
- MBOA will continue to work with the FCC to expedite resolution of this issue

What does this mean for the IEEE voters?

- Simulations, analysis, and measurements all show
  - MB-OFDM waveform causes no greater interference than 1 MHz impulse radios allowed under the rules
  - Worst-case difference (for wideband receivers) between MB-OFDM and WGN is ~1.5 dB for a fixed FSS performance level
  - Impact on FSS link margin is on order of *tenths of a dB (~0.1 dB)* difference under realistic scenarios
  - All UWB devices need to be very close to a FSS antenna before interference is seen
- Voters need to consider these results when casting their vote.

IP Position of MB-OFDM Proposal

Companies with significant IP in the proposal have already signed a RAND-Z statement

- Alereon
- INTEL
- Staccato Communications
- Texas Instruments
- Wisair

- All author companies will conform to the IEEE patent policy and issue a letter of assurance.
  - Most have already signed a RAND statement

Time to Market

MB-OFDM Meets TTM Needs

Time to Market

- **“No Voters” expressed concerns about TTM**
- **Claims that XSI solution would be much earlier to market**
- **Concerns expressed that MB-OFDM Time To Market would be unacceptable to users**

All MB-OFDM Supporters are Comfortable With MB-OFDM 1st Half’05 TTM

The Truth About TTM

The PHY Work Is Not the Critical Path

Elements Needed For A *Complete* Product

1) PHY
2) MAC
3) Interoperability / Co-existence / Security
4) User models
5) Applications interfaces (USB, 1394, WiMedia, etc)

MBOA will work these in parallel to deliver a COMPLETE Product in early '05

Time to Market Reality

- MBOFDM supporters will work with WiMedia and other interests to develop complete solutions
- MBOFDM silicon samples: Q4 2004
- MBOFDM integrated modules: Q1 2005
- MBOFDM based products: Q2 2005
- A DS-CDMA proposal PHY/MAC standard would not be earlier
  - Proposed PHY not same as shipping PHY
- Applications Interfaces (USB, 1394, WiMedia, etc.), Interoperability, Security and Coexistence issues are TTM drivers
- MBOFDM proposal meets CE, computer and peripheral vendors TTM needs
- Needless delays in the standards process are the real threat to Time to Market

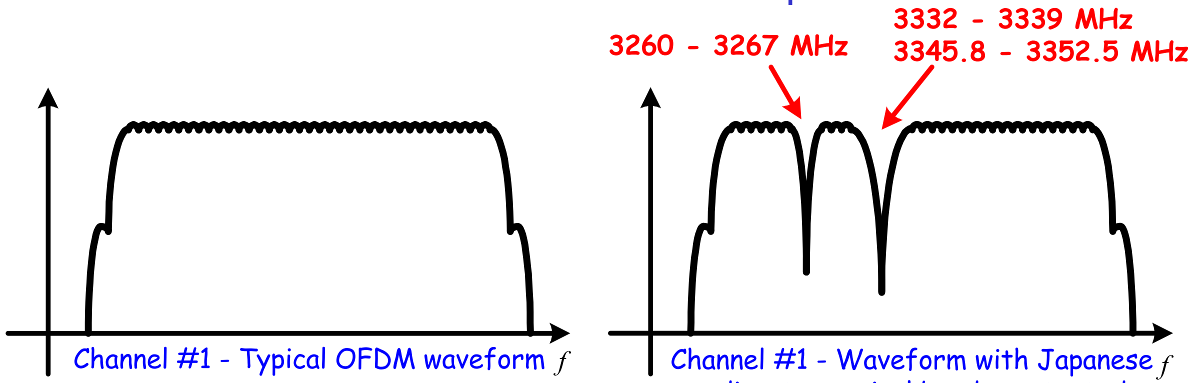
Conclusion

MB-OFDM meets the Time to Market Needs
and will provide a robust solution

Response to Specific No vote Comments

Worldwide Regulatory Concerns

- Area of Concern:
  - Global regulatory concerns (not just in FCC)
- Response:
  - We are (as individual companies) actively involved in various global UWB regulatory proceedings
  - Bands and tones can be dynamically turned on and off in order to comply with changing world-wide regulations.
  - By using OFDM, small and narrow bandwidths can easily be protected by turning off tones near the frequencies of interest.
  - For example, consider the radio-astronomy bands allocated in Japan. Only need to zero out a few tones in order to protect these services.



Channel #1 - Typical OFDM waveform

Channel #1 - Waveform with Japanese radioastronomical bands protected.

Development Outside IEEE

- Area of Concern:
  - "Development of results in MBOA outside IEEE body; results not made available to IEEE task group"
- Response:
  - Per IEEE rules, the TG owns the specification upon confirmation. Until then, all proposals are developed outside the TG.
  - Development of results in MBOA has been based on the publicly available spec, i.e., no hidden information. Mature results have been disclosed in each revision of the proposal.
  - Multiple parties have validated simulation results

"Stability" of Proposal

- Area of Concern:
  - "MB-OFDM proposal would be somewhat changed. RF architecture of MB-OFDM looks stable, but base band algorithm looks with fluctuation.."
- Response:
  - Any proposal will undergo changes through confirmation and beyond.
  - The MB-OFDM proposal is largely stable at this point. Last major changes were in September
    - introduction of time spreading
    - Introduction of zero padded cyclic prefix
  - Only one technical change for November
    - Minor modifications in time domain preamble structure (based on contribution available on the doc. server in September meeting)
  - No changes for January
  - Further technical changes being considered to address high data rate performance, SOP performance improvement, scalability to lower and higher data rates.

SOP Results

- Area of Concern:
  - SOP performance simulation results for 2 and 3 interfering piconets have not been updated
- Response:
  - Current proposal demonstrates support for multiple piconets as before
  - Alternate spreading options reported in September improved SOP results with 1 interfering piconet, results for 2 and 3 interfering piconets largely unchanged (i.e., as in July)
  - Exploration of different ideas to improve SOP performance ongoing – new results will be presented as soon as available

TF Code Selection

- Area of Concern:
  - "have not showed the method to get the information of time frequency hopping sequence. How to get the information of TF sequence when a PNC makes a new piconet? PNC must know which TF sequence is used or not. That may make longer time to connect devices with UWB technologies."
- Response:
  - PNC searches through space of all T-F sequences to find available ones to select from
  - This is no different from searching over code space for DSSS systems to find available DS codes for creating a piconet
  - The timescale for initiating a new piconet (or connecting a new device) is on the order of milliseconds; the time to search the T-F code space is on the order of a few microseconds

Link Budget

- Area of Concern:
  - "The link budget calculations, as described in doc #03268r2, with a 0dB spectral backoff (i.e. flat spectrum), seem overly optimistic. Merger proposal N1 is a FH system, with a very fast hopping rate, and, as such, will exhibit additional spectral components due to the periodic hopping pattern … The test results presented by TDK in Singapore last September seem to confirm those assumptions (slides 55 & 56 of doc 03449r0)."
- Response:
  - The power spectral density with zero-padded prefix is theoretically nearly flat; the T-F codes with antipodal signaling will not introduce spectral lines
  - The TDK test results from Singapore did not incorporate zero padded prefix. They also demonstrate some effects of the test setup (e.g., antenna, connectors, etc.) which are independent of the modulation scheme

Gating

- Area of Concern:
  - “Within the bandwidth of a victim receiver, a MBOA system is identical to a gated UWB system, *“where the transmitter is quiescent for intervals that are long compared to the pulse repetition interval”.*”
- Response:
  - The MB-OFDM pulse duration is 242ns.
  - The MB-OFDM signaling pulse repetition interval is 1 microsecond, and the ‘off’ period is approximately 67% of that interval.
  - From the above definition of gating, the MB-OFDM waveform employs pulsing on/off within the pulse repetition interval, and thus, is not a gated signal
  - Moreover, the reference to gating duration in the NTIA/GPS test results refers to millisecond intervals, much longer than the intervals considered here.

Multiband Attenuation

- Area of Concern:
  - “Large change in antenna aperture across multiple sub-bands, especially for mode 2 devices and more specifically mode x devices (up to 14 sub-bands), will lead to unequal SNR in each band. This effect will lead to degradation in the performance of FEC”
- Response:
  - The MB-OFDM signal spreads coded information bits across multiple bands to take advantage of frequency diversity
  - The simulations results presented model the effect of the varying SNR in different bands for the used modes.

User defined tones

- Area of Concern:
  - "User tones are only utilized for the sole purpose of filling a 500 MHz bandwidth so that it meets minimum FCC UWB bandwidth rules…. The addition of unmodulated tones with the sole purpose of increasing bandwidth in order to meet minimum FCC bandwidth requirements is not an efficient use of the UWB spectrum "
- Response:
  - Guard subcarriers have been provided for implementation feasibility purposes – i.e., to provide relaxed filter requirements
  - OFDM is in fact a very efficient modulation for filling available spectrum, with relatively steep skirts to the spectrum compared to single carrier modulation

Co-location with Out of Band Devices

- Area of Concern:
  - Demonstration of co-location capability with portable electronic devices such as cell phones, portable MP3 players, etc. This has not been addressed at all.
  - Proven levels of radiated and conducted emissions not only per the FCC rules, but sufficiently low to permit co-integration of the resulting devices in units mentioned above.
- Response
  - MB-OFDM signal has very low out of band emissions since the subcarrier has a 4 MHz bandwidth
  - If needed extra suppression can be achieved with filters

RF Sections

- Area of Concern:
  - "Substantiated proof that the analog RF sections are realizable and less complex than those seen in 802.11a IC's."
- Response
  - A number of companies have prototyped the MB-OFDM RF section and are in the middle of chip design
  - For complexity comparison to 11a refer to 15-03-0343 slide 82-83

Power Consumption Comparison

- Comment:
  - "DS-CDMA seems more DC power efficient, making low-power transmitter implementation more practical"
- Response
  - Based on our estimates the power consumption of an MBOFDM solution will be much lower than MBOK solution. See 15-03-449 for detailed comparison between the 2 solutions

Conclusions

- MBOFDM proposal meets CE, computer and peripheral vendors performance and time to market needs
- Significant progress in the FCC certification and interference issue
  - Provided analysis, simulation and measurements that show that MB-OFDM does not cause more harmful interference than expected by the rules
- Companies with significant IP positions have already issued RAND-Z statements.

Backup slides

Overview of MBOFDM Proposal

Overview of Multi-band OFDM

- Basic idea: divide spectrum into several 528 MHz bands.
- Information is transmitted using OFDM modulation on each band.
  - OFDM carriers are efficiently generated using an 128-point IFFT/FFT.
  - Internal precision requirement is reduced by limiting the constellation size to QPSK.
- Information is coded across all bands in use to exploit frequency diversity and provide robustness against multi-path and interference.
- 60.6 ns prefix provides robustness against multi-path even in the worst channel environments.
- 9.5 ns guard interval provides sufficient time for switching between bands.

Multi-band OFDM System Parameters

- System parameters for mandatory and optional data rates:

Info. Data Rate	55 Mbps*	80 Mbps**	110 Mbps*	160 Mbps**	200 Mbps*	320 Mbps**	480 Mbps**
Modulation/Constellation	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK
FFT Size	128	128	128	128	128	128	128
Coding Rate (K=7)	R = 11/32	R = 1/2	R = 11/32	R = 1/2	R = 5/8	R = 1/2	R = 3/4
Spreading Rate	4	4	2	2	2	1	1
Data Tones	100	100	100	100	100	100	100
Info. Length	242.4 ns	242.4 ns	242.4 ns	242.4 ns	242.4 ns	242.4 ns	242.4 ns
Cyclic Prefix	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns
Guard Interval	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns
Symbol Length	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns
Channel Bit Rate	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps
Multi-path Tolerance	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns

* Mandatory information data rate, ** Optional information data rate

Link Budget and Receiver Sensitivity

- Assumption: **Mode 1 DEV** (3-band), AWGN, and 0 dBi gain at TX/RX antennas.

Parameter	Value	Value	Value
Information Data Rate	110 Mb/s	200 Mb/s	480 Mb/s
Average TX Power	-10.3 dBm	-10.3 dBm	-10.3 dBm
Total Path Loss	64.2 dB (@ 10 meters)	56.2 dB (@ 4 meters)	50.2 dB (@ 2 meters)
Average RX Power	-74.5 dBm	-66.5 dBm	-60.5 dBm
Noise Power Per Bit	-93.6 dBm	-91.0 dBm	-87.2 dBm
CMOS RX Noise Figure	6.6 dB	6.6 dB	6.6 dB
Total Noise Power	-87.0 dBm	-84.4 dBm	-80.6 dBm
Required Eb/N0	4.0 dB	4.7 dB	4.9 dB
Implementation Loss	2.5 dB	2.5 dB	3.0 dB
Link Margin	6.0 dB	10.7 dB	12.2 dB
RX Sensitivity Level	-80.5 dBm	-77.2 dBm	-72.7 dB

Multipath Performance

- The distance at which the Multi-band OFDM system can achieve a PER of 8% for a 90% link success probability is tabulated below:

Range*	AWGN	CM1	CM2	CM3	CM4
110 Mbps	20.5 m	11.4 m	10.7 m	11.5 m	10.9 m
200 Mbps	14.1m	6.9 m	6.3 m	6.8 m	4.7 m
480 Mbps	7.8 m	2.9 m	2.6 m	N/A	N/A

Notes:

1. Simulations includes losses due to front-end filtering, clipping at the DAC, DAC precision, ADC degradation, multi-path degradation, channel estimation, carrier tracking, packet acquisition, overlap and add of 32 samples (equivalent to 60.6 ns of multi-path protection), etc.
2. Increase in noise power due to overlap and add is compensated by increase in transmit power (1 dB) $\Rightarrow$ same performance as an OFDM system using a cyclic prefix.

Simultaneously Operating Piconets

- Assumptions:
  - operating at a data rate of 110 Mbps with 3 bands.
- Simultaneously operating piconet performance as a function of the multipath channel environments:

Channel Environment	1 Interfering piconets	2 Interfering piconets	3 Interfering piconets
CM1 (d_{int}/d_{ref})	0.4	1.18	1.45
CM2 (d_{int}/d_{ref})	0.4	1.24	1.47
CM3 (d_{int}/d_{ref})	0.4	1.21	1.46
CM4 (d_{int}/d_{ref})	0.4	1.53	1.85

- Results incorporate SIR estimation at the receiver.

Signal Robustness/Coexistence

- Assumption: Received signal is 6 dB above sensitivity.
- Value listed below are the required distance or power level needed to obtain a PER ≤ 8% for a 1024 byte packet at 110 Mb/s and a Mode 1 DEV (3-band).

Interferer	Value
IEEE 802.11b @ 2.4 GHz	$d_{int} \cong$ 0.2 meter
IEEE 802.11a @ 5.3 GHz	$d_{int} \cong$ 0.2 meter
Modulated interferer	SIR ≥ -9.0 dB
Tone interferer	SIR ≥ -7.9 dB

- Coexistence with 802.11a/b and Bluetooth is relatively straightforward because these bands are completely avoided.

Complexity

- Unit manufacturing cost (selected information):
  - Process: CMOS 90 nm technology node in 2005.
  - CMOS 90 nm production will be available from all major SC foundries by early 2004.
- Die size for Mode 1 (3-band) device:

	Complete Analog*	Complete Digital
90 nm	2.7 mm^2	1.9 mm^2
130 nm	3.0 mm^2	3.8 mm^2

* Component area.

* Component area.

Power Consumption

- Active CMOS power consumption

Block	90 nm	130 nm
TX AFE (110, 200 Mb/s)	76 mW	91 mW
TX Digital (110, 200 Mb/s)	17 mW	26 mW
TX Total (110 Mb/s)	93 mW	117 mW
RX AFE (110, 200 Mb/s)	101 mW	121 mW
RX Digital (110 Mb/s)	54 mW	84 mW
RX Digital (200 Mb/s)	68 mW	106 mW
RX Total (110 Mb/s)	155 mW	205 mW
RX Total (200 Mb/s)	169 mW	227 mW
Deep Sleep	15 μW	18 μW