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

Submission Title: [MB-OFDM Proposal -- Top-Ten Improvements]
Date Submitted: [19 September, 2005]
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Re: [MB-OFDM updates]

Abstract: [A review of the top-ten improvements to MB-OFDM stimulated in whole or in part by the IEEE standards process]

Purpose: [To inform]

Agenda

- An MB-OFDM “Top-10” List of Improvements
- More information on three issues:
  - Peak-to-RMS voltage ratios in MB-OFDM
  - Zero cyclic prefix for spectral ripple reduction
  - Fixed Frequency Interleave Mode
- Questions & Comments

Top-10 List
(in no particular order)

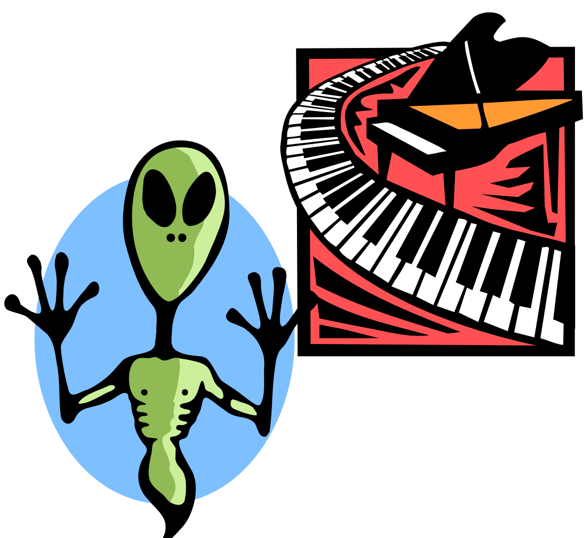
1. **Peak voltage-swing limitation to 9 dB above RMS (or less)**
2. **Fighting deep fades with DCM (Dual-Carrier Modulation)**
3. **Zero-prefix to reduce (already modest) spectral ripple**
4. **Making good use of guard tones to fight edge-tone roll-off**
5. **Multi-band hopping reduced to max 3-band hopping**
6. **Reed-Solomon coding for robust header reception**
7. **Added FFI mode for improved SOP & regulatory flexibility**
8. **Transmit power control for improved SOP, regulatory flexibility, interference control**
9. **Three-level interleaving for improved robustness to fading & interference**
10. **Waiver approval – allowing FCC PSD mask compliance testing with authentic *in situ* waveforms**

OFDM
Orthogonal Frequency Division Multiplexing
A Musical Sci-Fi Analogy

Transmitter

- *Extraordinary 128-key piano*
- *128-tone chord launched every 300ns*
- *Each tone launched with phase of 0^{o}, 90^{o}, 180^{o}, or 270^{o}*

128-Tone “Chord”



Receiver

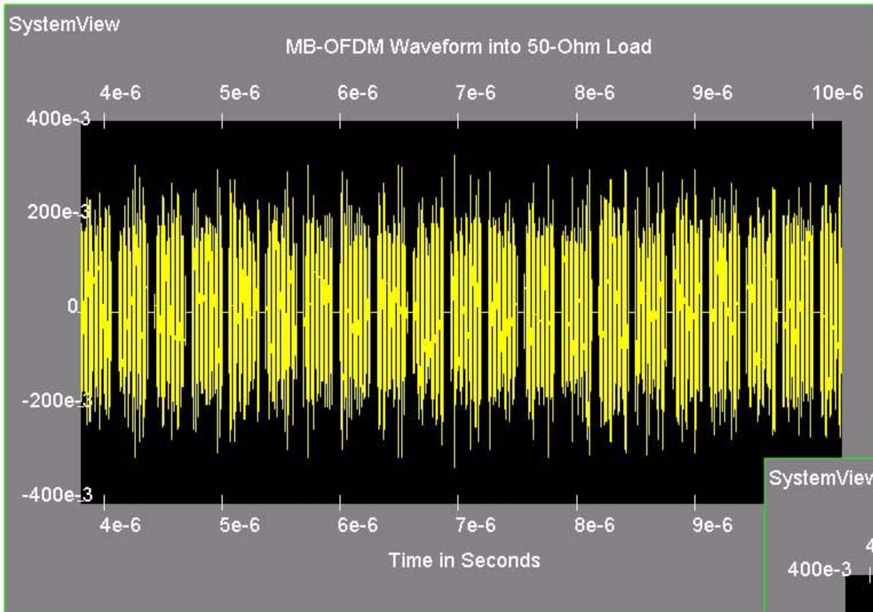
- *Perfect pitch*
- *Each tone heard separately*
- *Phase of each tone detectable*

Peak-to-RMS Ratios for MB-OFDM

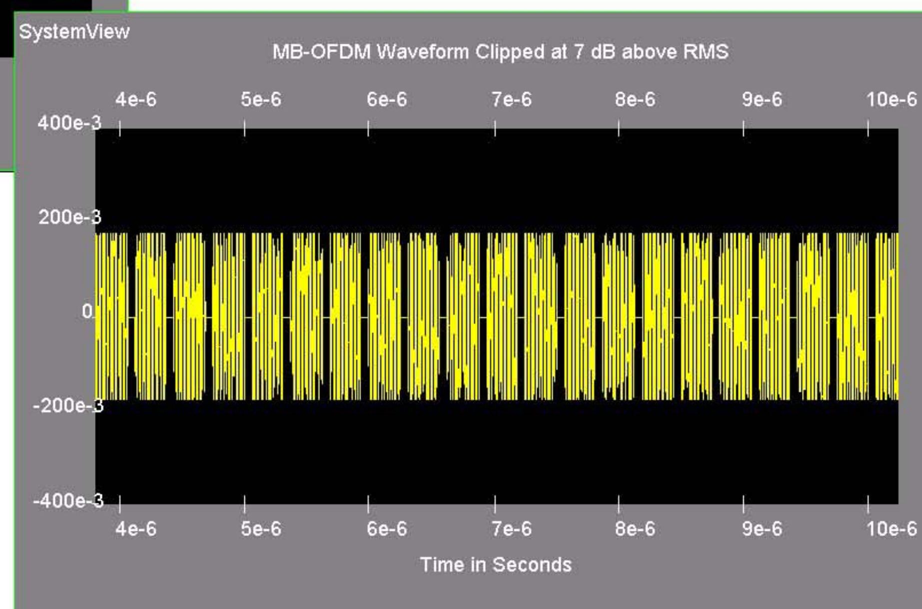
- True or False?
  - OFDM waveforms exhibit high peak-to-RMS voltage ratios. ***True.***

- True or False?
  - MB-OFDM waveforms must transmit/receive the peaks faithfully. ***False.***

“Clipped” MB-OFDM Waveform

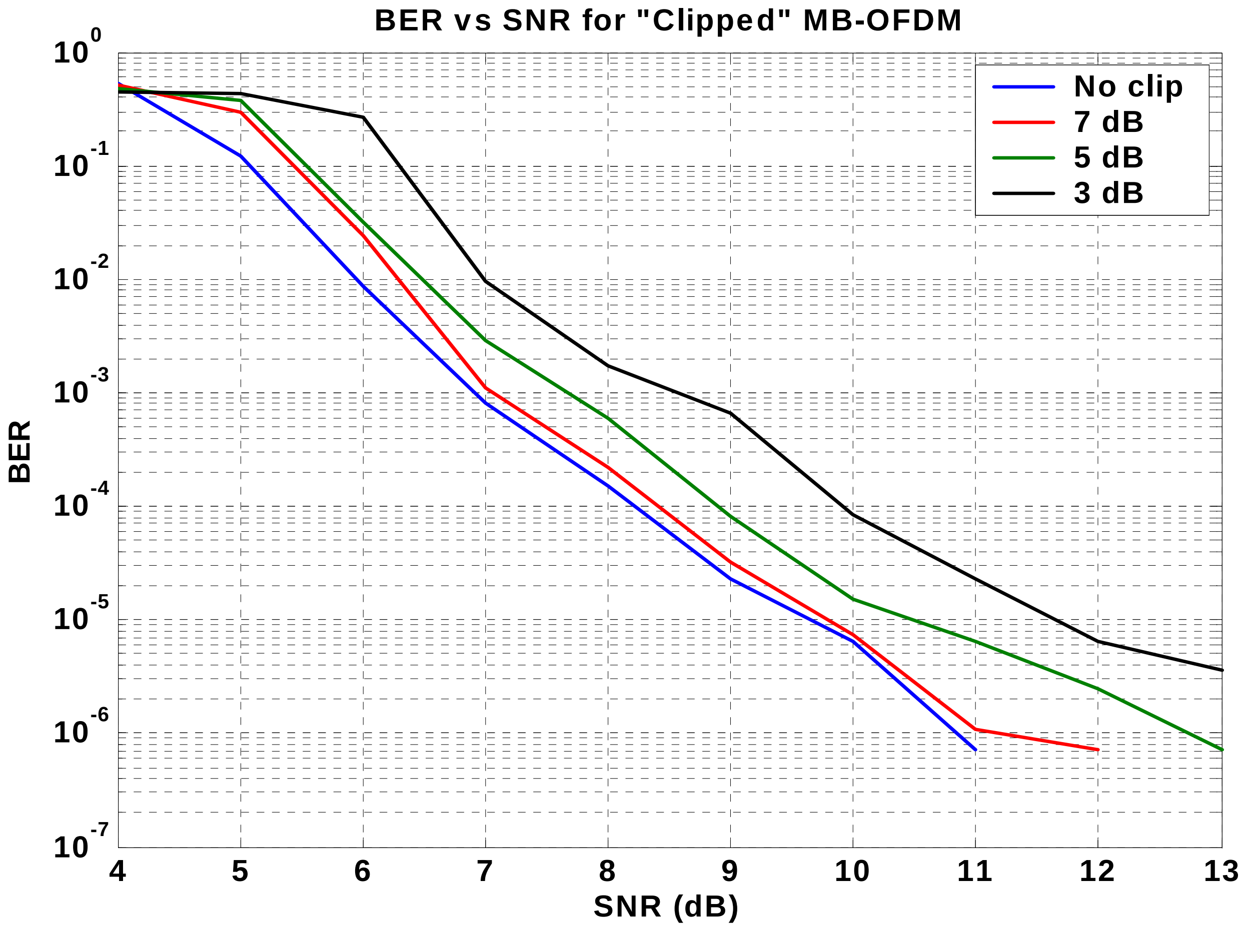


MB-OFDM waveform



Same waveform peak-limited to 7 dB above RMS

Impact of Peak Limiting (Clipping) on MB-OFDM Waveform



Simulation
480 Mbps
DCM
¾ Rate Coding
AWGN only

Implication
MB-OFDM can be safely clipped at 7dB above RMS voltage

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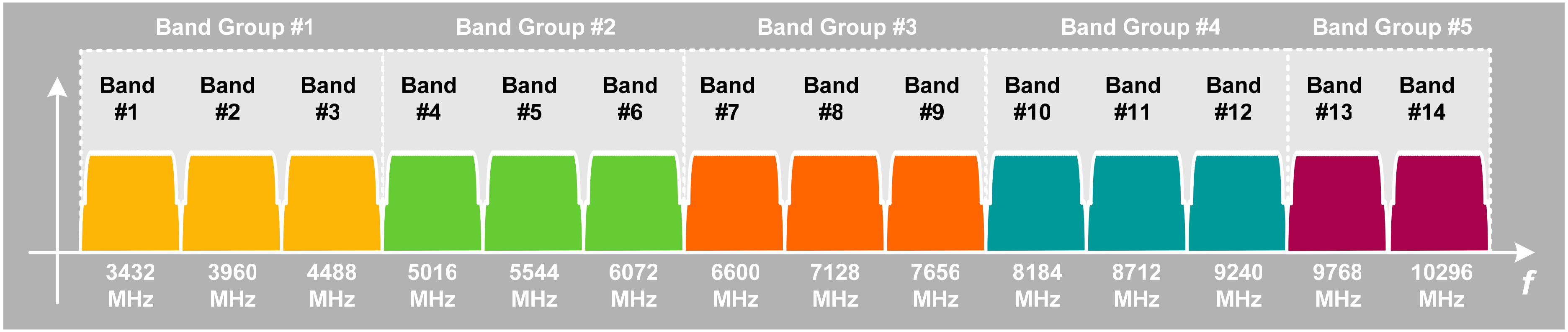
Multi-Band OFDM Band Plan

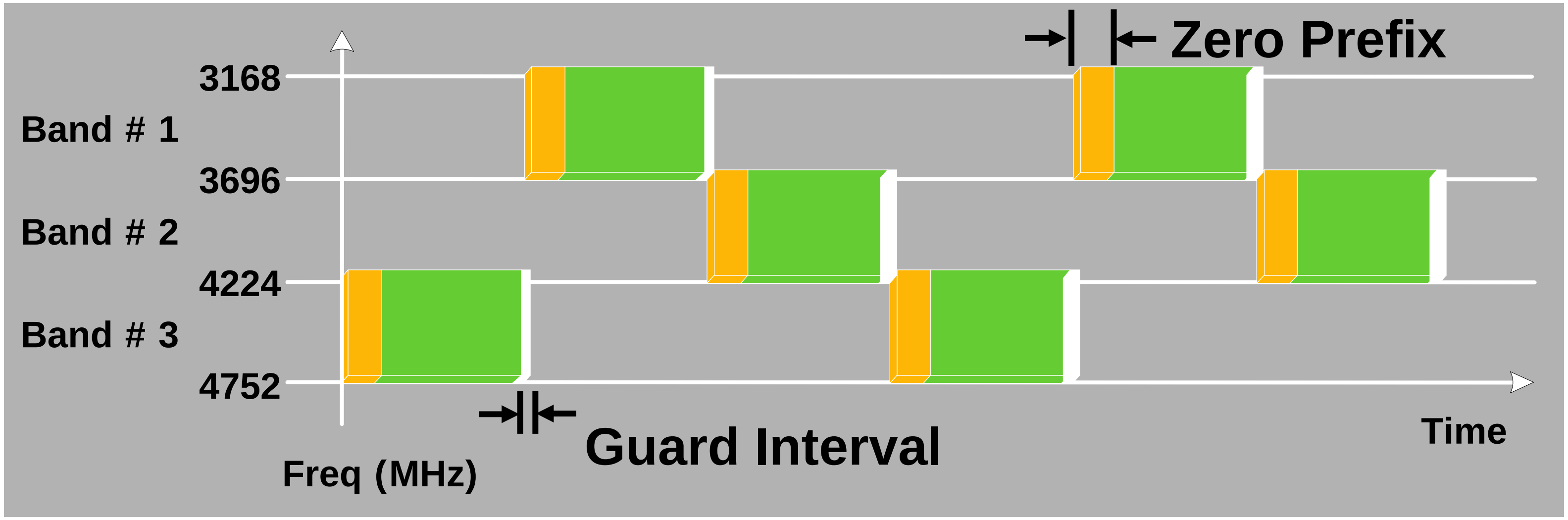
- Key Idea #1
  - Divide the spectrum into 528-MHz-wide bands
  - Occupy only one of the bands at a time



- Advantages:
  - Transmitter and receiver process smaller baseband bandwidth signals (528 MHz)

Overview of Multi-Band OFDM

- Key Ideas #2, 3, 4:
  - Band Interleaving, Zero Prefixes, & Guard Intervals



- Advantages:
  - Frequency diversity, full allowable Tx power
  - Robustness to Multipath
  - Tx/Rx settling times

Fixed-Frequency Interleaving

- Added three new time-frequency codes (TFCs):
  - New codes are equivalent to transmitting on a single frequency band (FDMA).
  - These new modes are referred to as Fixed-Frequency Interleaving (FFI).
  - Summary of all TFCs is shown below

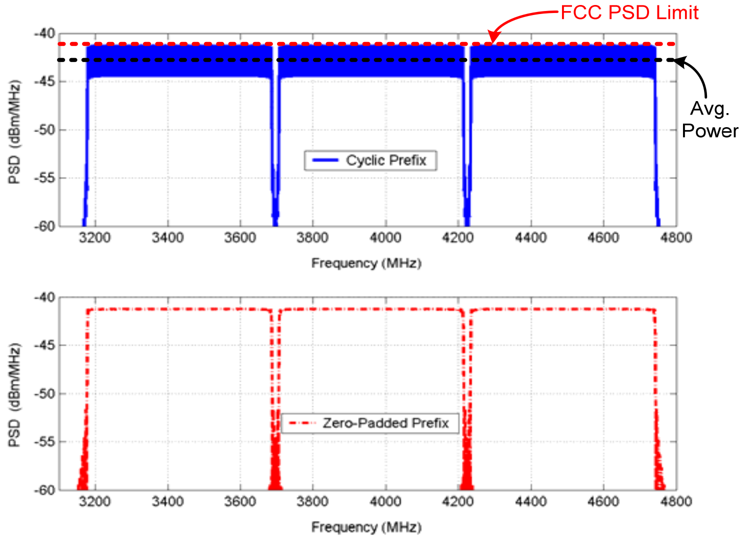
TFC Number	Type	Preamble	BAND_ID					
1	TFI	1	1	2	3	1	2	3
2	TFI	2	1	3	2	1	3	2
3	TFI	3	1	1	2	2	3	3
4	TFI	4	1	1	3	3	2	2
5	FFI	5	1	1	1	1	1	1
6	FFI	6	2	2	2	2	2	2
7	FFI	7	3	3	3	3	3	3

- Support for TFI and FFI is mandatory within the standard:
  - No hardware penalty for supporting FFI modes in addition to TFI modes.

- Advantages of FFI modes:
  - Improved SOP performance, interference avoidance

Zero-padded Prefix

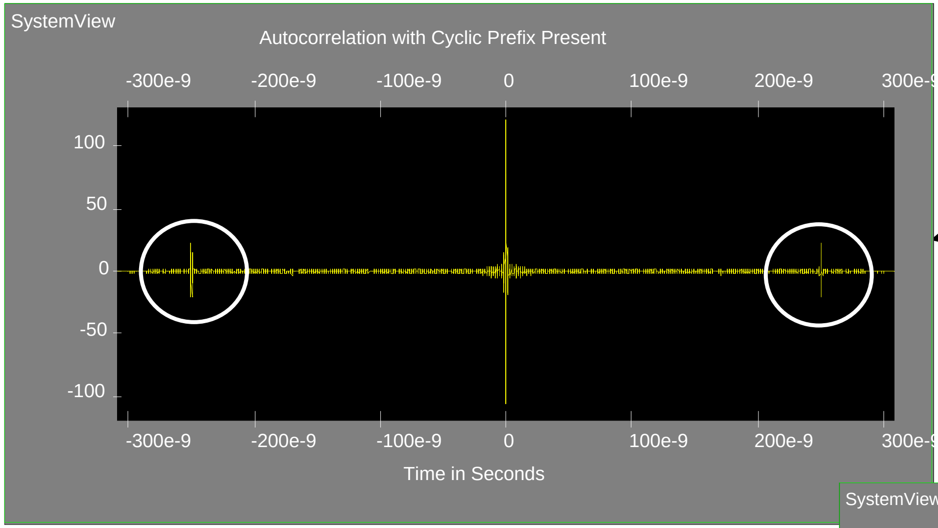
- In a conventional OFDM system, a cyclic prefix is added to provide multi-path protection.



- Cyclic prefix introduces structure into the TX waveform $\Rightarrow$ structure in the signal produces ripples in the PSD.
- In an average PSD-limited system, *any ripples in the TX waveform* will results in back-off at the TX (reduction in range).
- Ripple in the transmitted spectrum can be eliminated by using a zero-padded prefix.
- A Zero-Padded Prefix provides the same multi-path robustness as a cyclic prefix (60.6 ns of protection).

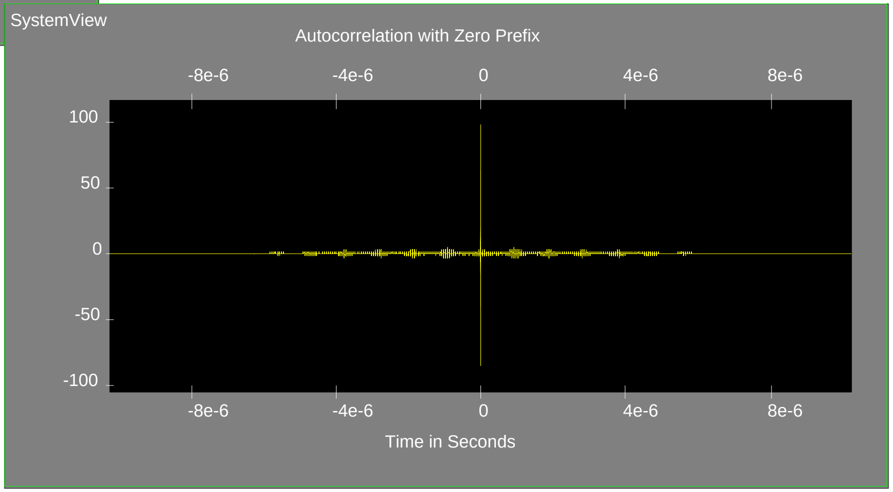
Removing Spectral Ripple with Zero Prefix

Autocorrelation Waveforms Disclose Periodicities



With 60.61ns cyclic prefix

With zero prefix



MB-OFDM – Summary*

- **Has improved by way of the IEEE process**
- Now offers even more robust performance in presence of multipath & interference (DCM, GT, Interleaving, …)
- Has performance that exceeds IEEE PAR requirements
- Offers digitally generated signal / spectrum that
  - can accommodate differing world-wide regulations and “on-the-fly” interference scenarios
  - has degrees of freedom for the future not present in impulse-based designs
- Has garnered support of hundreds of companies in silicon, telecom, computing, and entertainment electronics
- Has multiple companies announcing silicon availability

***See also prior presentations listed in backup material.**

Backup

Previous Submissions (1 of 2)

1. **MB-OFDM Update and Overview**, Matthew B. Shoemake (WiQuest), doc. 15-04-0518
2. **MB-OFDM Specification**, Anuj Batra (Texas Instruments), et al., doc. 15-04-493
3. **Market Needs for a High-Speed WPAN Specification,** Robert Huang (Sony) and Mark Fidler (Hewlett Packard), doc. 15-04-0410
4. **MB-OFDM for Mobile Handhelds,** Pekka A. Ranta (Nokia), doc. 15-04-432
5. **In-band Interference Properties of MB-OFDM,** Charles Razzell (Philips), doc. 15-04-0412

Previous Submissions (2 of 2)

6. **Spectral Sculpting and Future-Ready UWB,** David Leeper (Intel), Hirohisa Yamaguchi (TI), et al., doc. 15-04-0425
7. **CCA Algorithm Proposal for MB-OFDM,** Charles Razzell, doc. 15-04-0413
8. **What is Fundamental?**, Anuj Batra, et al., doc. 15-04-430
9. **Time to market for MB-OFDM**, Roberto Aiello (Staccato) Eric Broockman (Alereon) and David Yaish (Wisair) doc. 15-04-432
10. **MB-OFDM Update**, Matt Shoemake (WiQuest), doc. 15-04-518
11. **MB-OFDM Update**, Charles Razzell (Philips), doc 15-04-273
12. **MB-OFDM Update**, David Leeper (Intel) et al, doc 15-05-397-r2

Selected References

15-03-0343, **MultiBand OFDM September 2003 presentation**, Anuj Batra

15-03-0449, **MultiBand OFDM Physical Layer Presentation**, Roberto Aiello and Anand Dabak

15-04-0010, **MultiBand OFDM January 2004 Presentation**, Roberto Aiello, Gadi Shor and Naiel Askar

15-04-0013, **C-Band Satellite Interference Measurements TDK RF Test Range**, Evan Green, Gerald Rogerson and Bud Nation

15-04-0017, **Coexistence MultiBand OFDM and IEEE 802.11a Interference Measurements**, Dave Magee, Mike DiRenzo, Jaiganesh Balakrishnan, Anuj Batra

15-04-0018, **Video of MB-OFDM, DS-UWB and AWGN Interference Test**, Pat Carson and Evan Green