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

Submission Title: [MB-OFDM Proposal Update]
Date Submitted: [17 July, 2005]
Source: [D. Leeper] Company [Intel Corporation]
Address [CH6-460, 5000 W Chandler Blvd., Chandler, AZ, 85226]
Voice:[+1 480 552 4574], FAX: [], E-Mail:[david.g.leeper@intel.com]

Re: [MB-OFDM updates]

Abstract: [Overview and Updates to Original MB-OFDM Proposal]

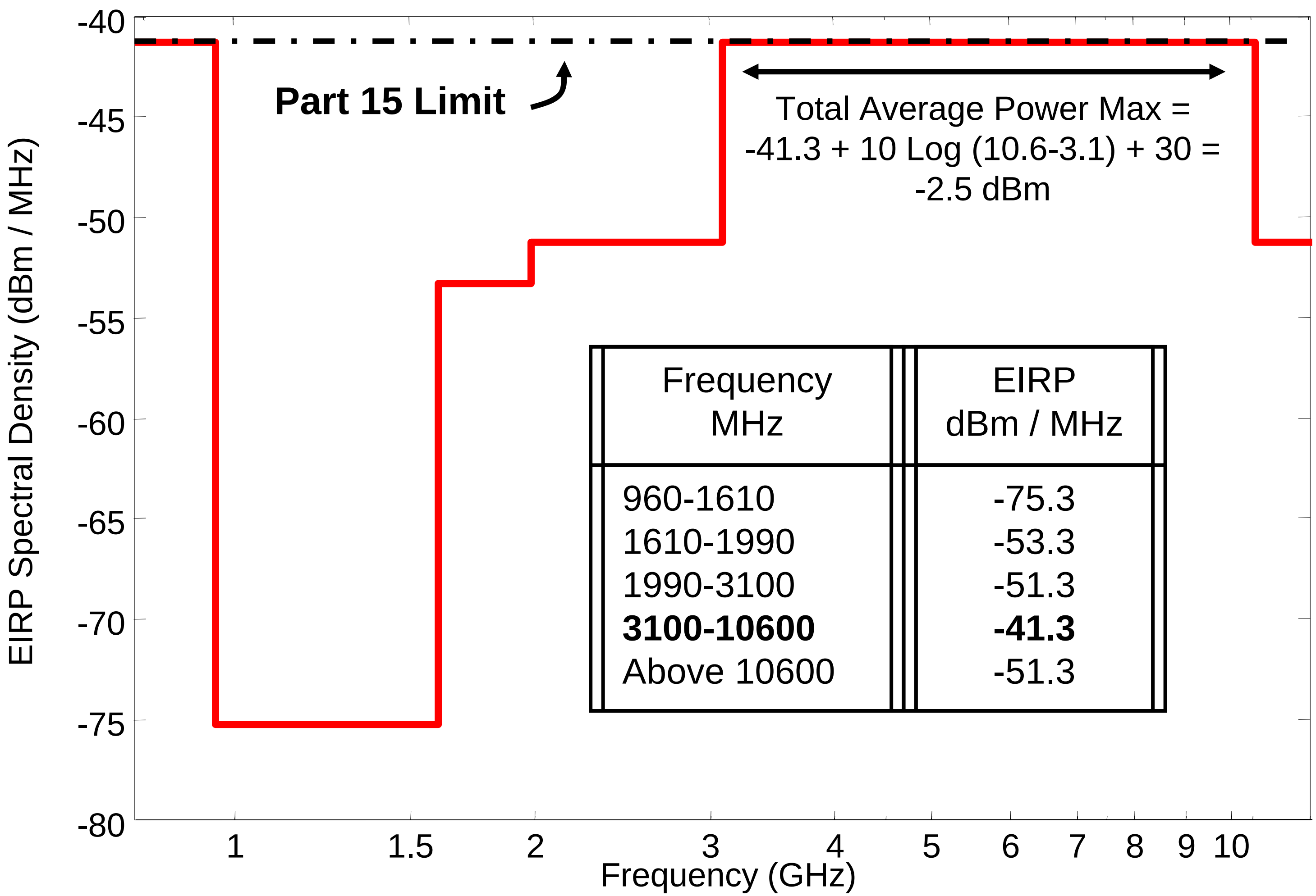
Purpose: [To inform and persuade]

Agenda

- A Brief History of MB-OFDM
- Why OFDM is Preferred
- What’s New in MB-OFDM

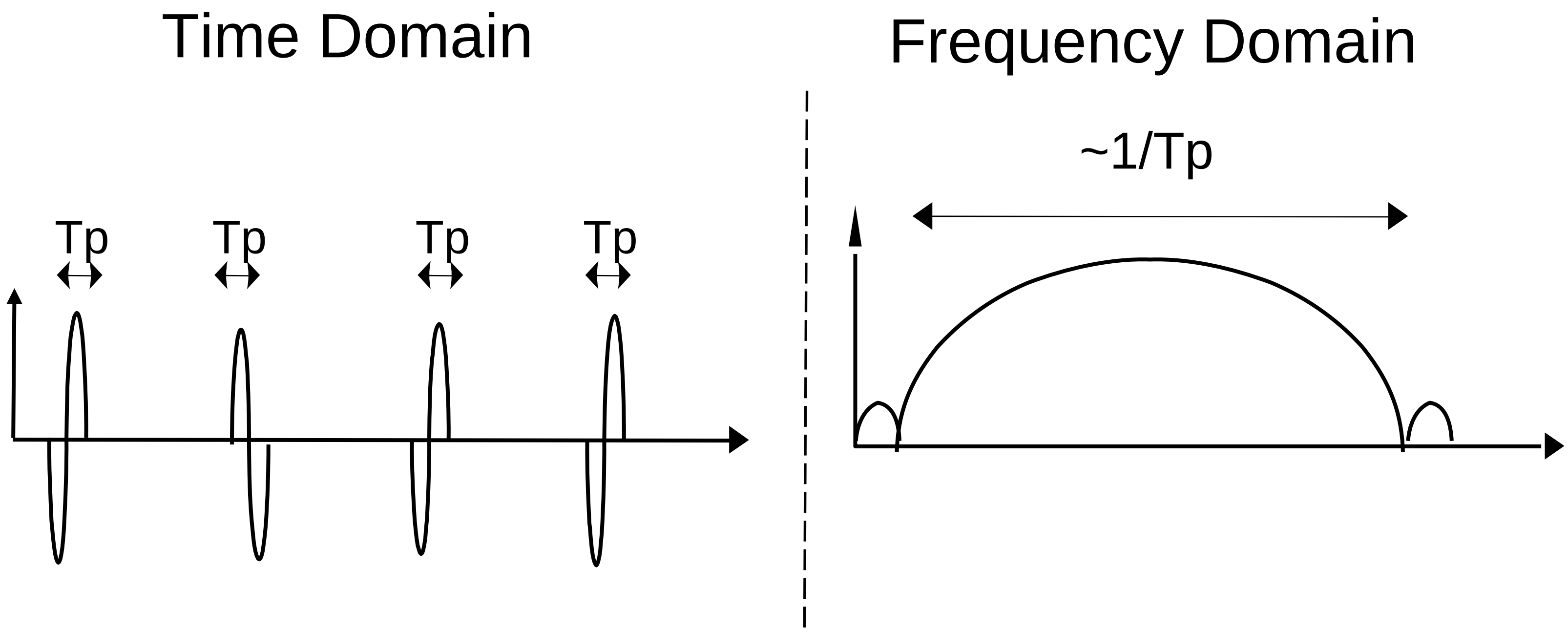
Common Constraint for All UWB Proposals

FCC Indoor Spectral Mask -- April 22, 2002



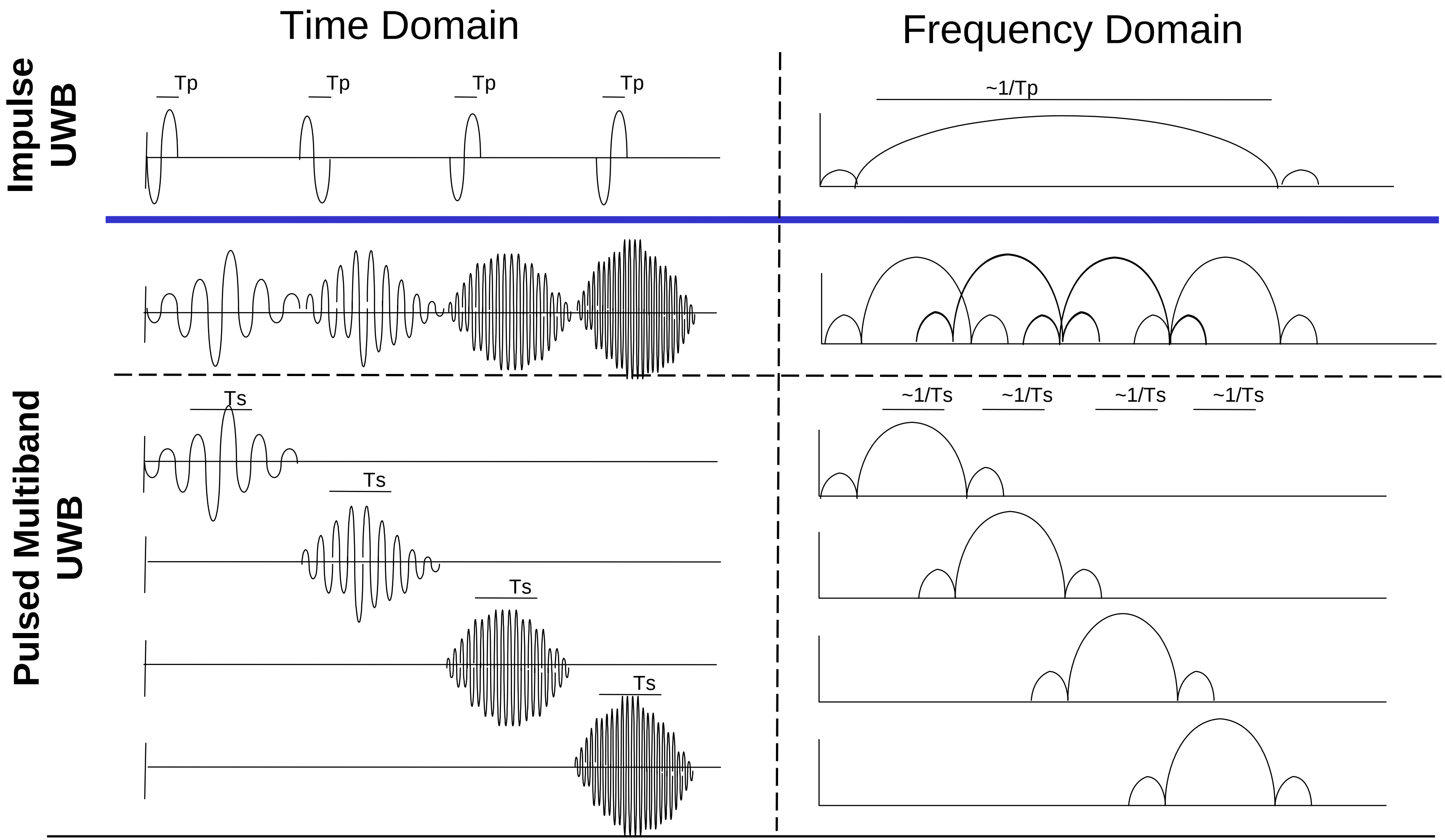
Frequency MHz	EIRP dBm / MHz
960-1610	-75.3
1610-1990	-53.3
1990-3100	-51.3
3100-10600	**-41.3**
Above 10600	-51.3

UWB Evolution
Starting Point: Traditional “Impulse UWB”



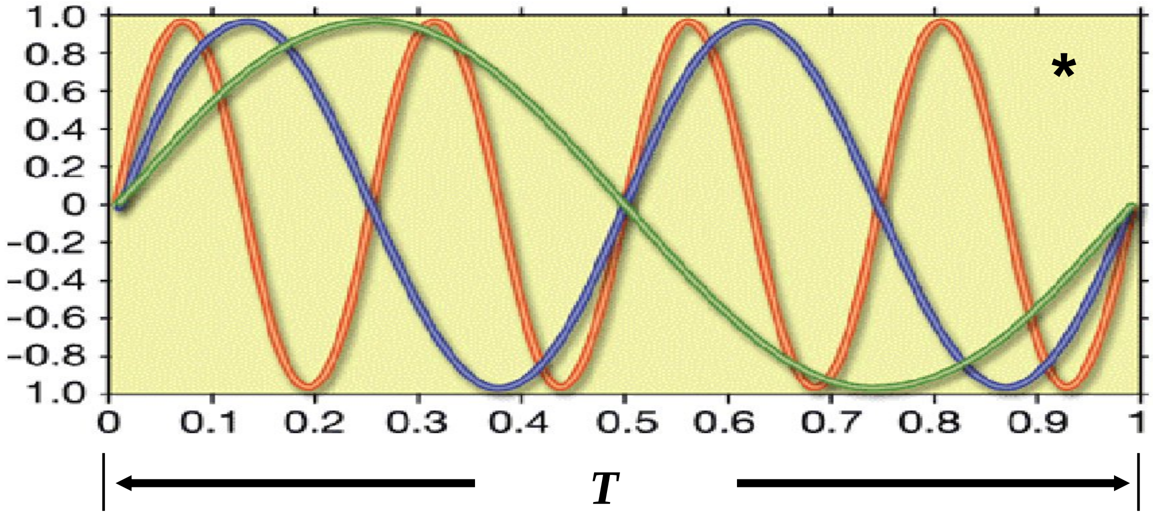
Tp < 1 nanosecond

UWB Evolution
Intermediate Form: “Pulsed Multiband” UWB



UWB Evolution: UWB via MB-OFDM

Original Proposal of Batra et al (Texas Instruments)**



$$Z(t) = \sum_{k=0}^{N-1} C_k e^{j2\pi(k-\frac{N}{2})t/T}$$

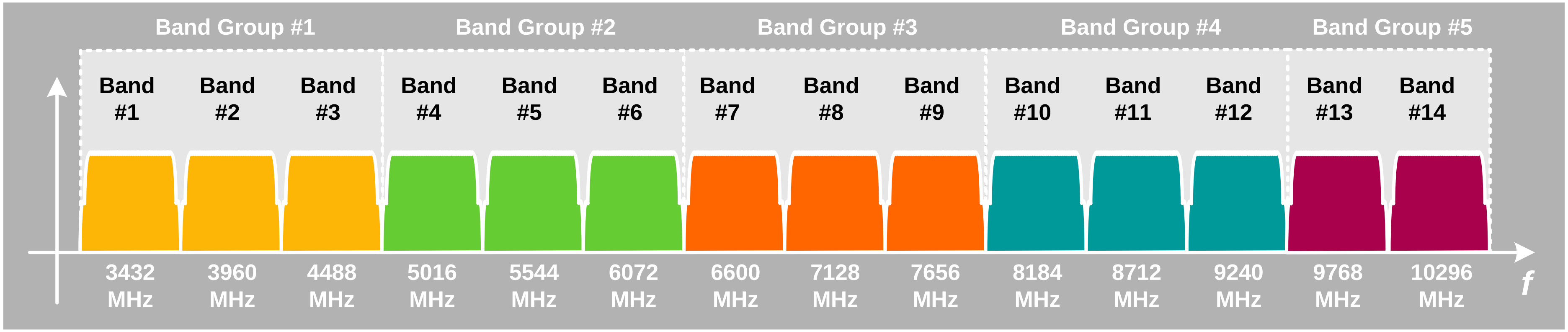
Symbol Statistics (Still Valid)

- *T = 312.5 ns***, N = 128 tones*
- *Tone spacing = 4.125 MHz*
- *Total bandwidth = 528 MHz*

* http://www.iec.org/online/tutorials/ofdm/
** IEEE P802.15-03/268r1, October, 2003
*** Including 70.08ns zero prefix & guard times

Overview of Multi-Band OFDM

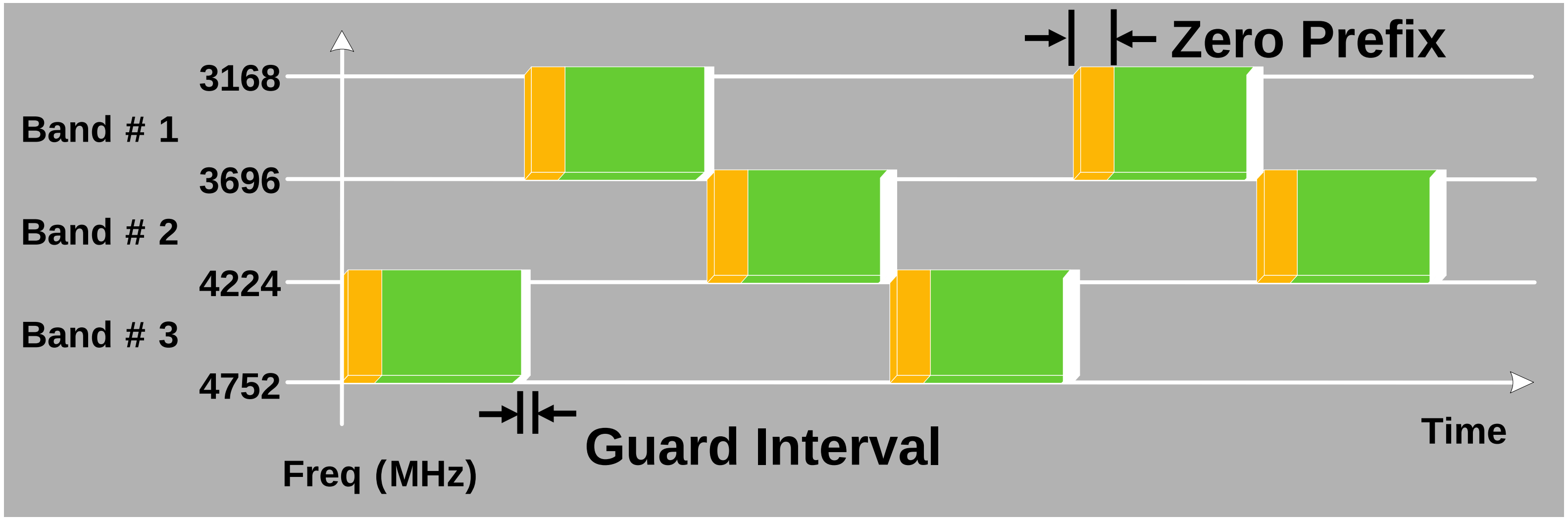
- Key Idea #1:
  - Divide the spectrum into 528-MHz-wide bands



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

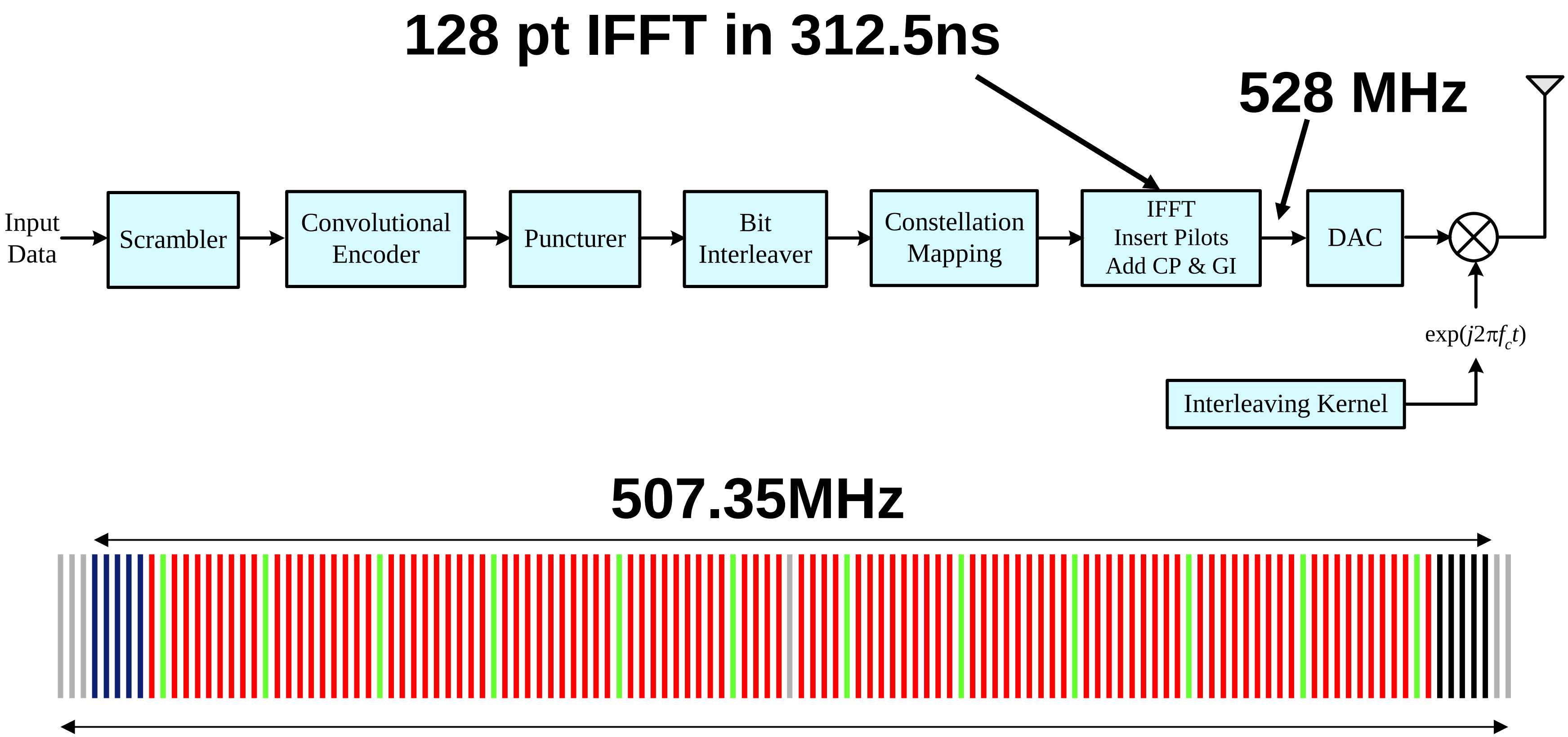
Overview of Multi-Band OFDM

- 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

Example MB-OFDM UWB Tx chain



128 pt IFFT, 100 QPSK/DCM data tones, 12 pilots, 10 Guards, 6 nulls

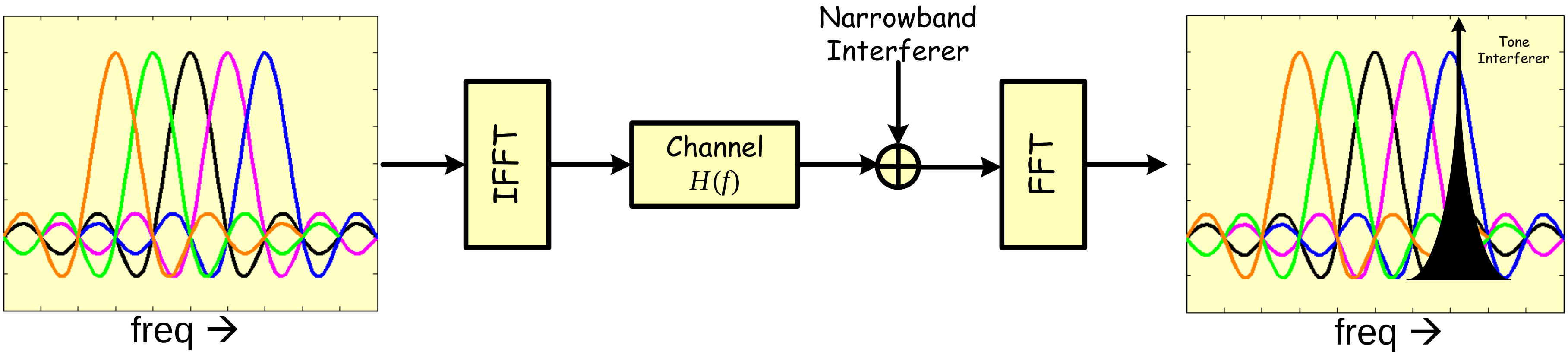
OFDM Fast Facts

- Invented more than 40 years ago
- Adopted & proven many times over
  - Asymmetric DSL (ADSL)
  - IEEE 802.11a/g/n, WiMax
  - Power Line Networking (HomePlug and HomePlug A/V)
  - Digital Audio (DAB) & Video (DVB)
- A “natural” for the future
  - FCC’s Sought-After *Cognitive Radios*
  - Multimode Radios

Why OFDM is Preferred(1)

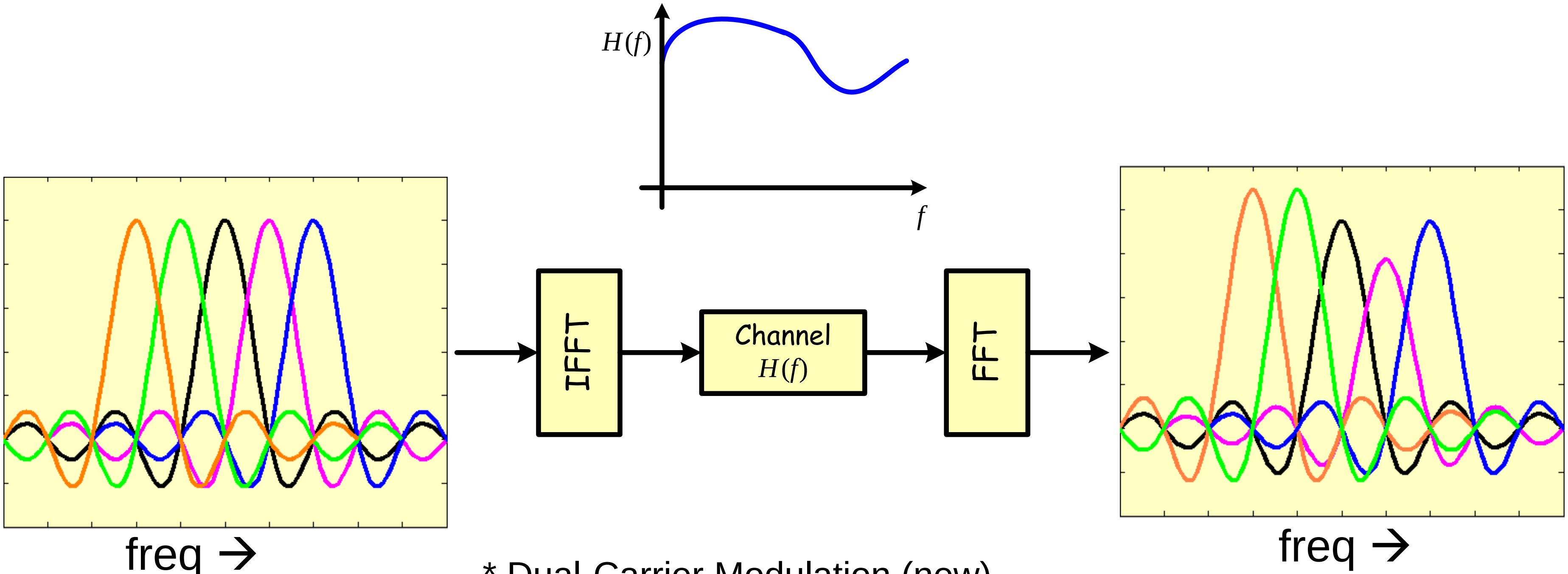
- OFDM is spectrally efficient:
  - IFFT/FFT operation ensures that sub-carriers do not interfere with one other.
  - Since the sub-carriers do not interfere, the sub-carriers can be brought closer together ⇒ High spectral efficiency.

- OFDM has an inherent robustness against narrowband interference:
  - Narrowband interference will affect at most a couple of tones.
  - ⇒ Do not have to drop the entire band because of narrowband interference.
  - ⇒ Erase information from the affected tones, since they are known to be unreliable. Already-present FEC recovers lost information.



Why OFDM is Preferred(2)

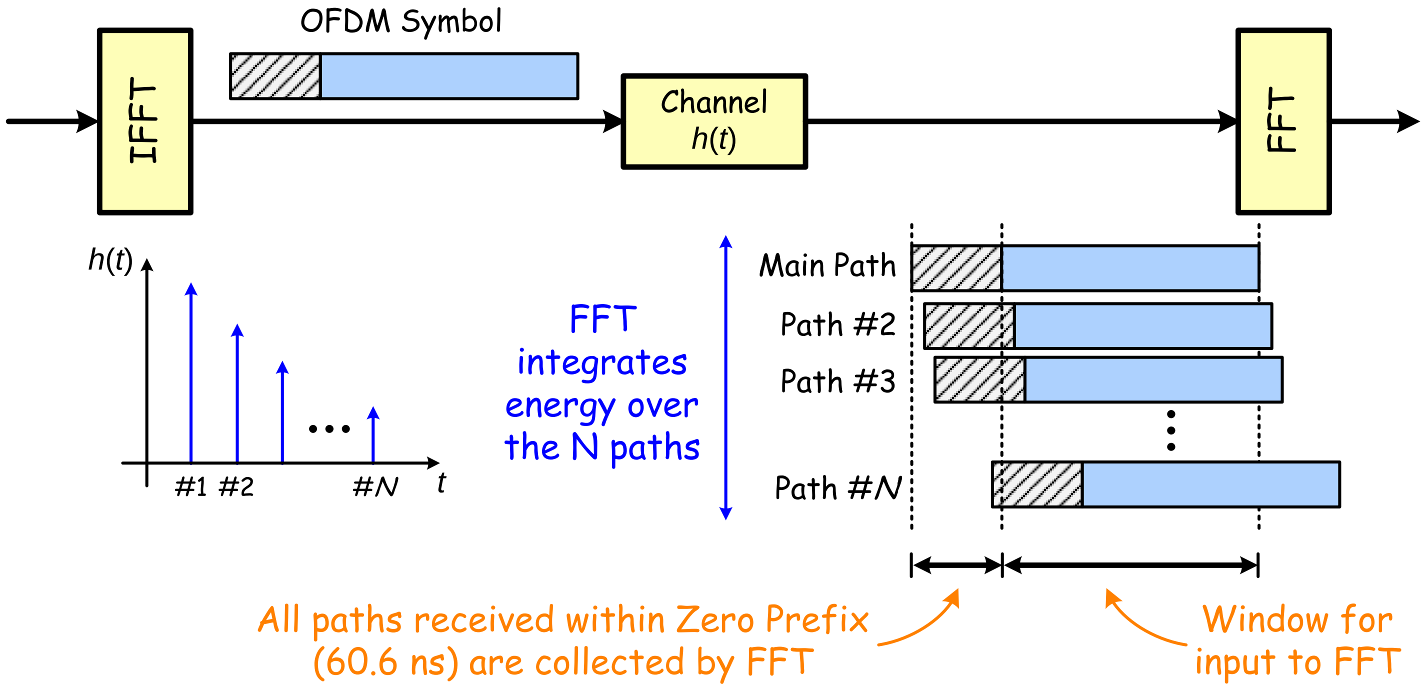
- OFDM has excellent robustness to multipath.
- FEC and DCM* compensate for faded tones.



* Dual-Carrier Modulation (new)

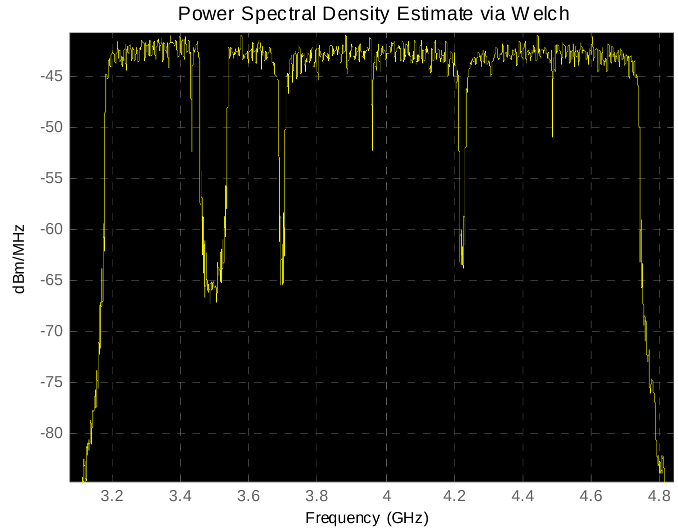
Why OFDM is Preferred(3)

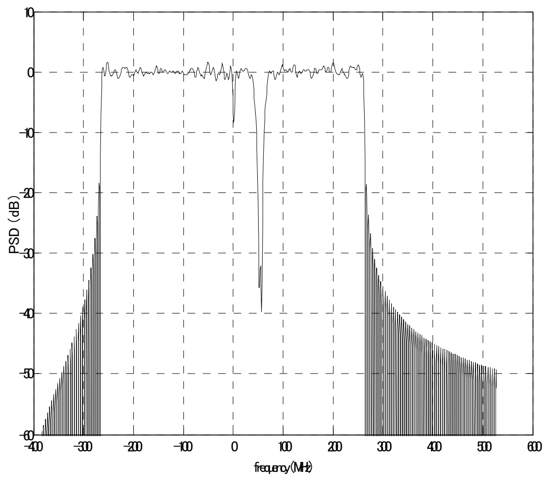
- Typical channels have hundreds of paths
- MB-OFDM captures energy from virtually all of them.



Why OFDM is Preferred(4)

- Ability to comply with worldwide regulations:
  - Channels and tones can be turned on/off dynamically to comply with changing regulations.
  - Can arbitrarily shape spectrum in software with a resolution of ~4 MHz.





Notch bandwidth: 7.25 MHz
Notch depth: 30 dB
AIC tones: 2(left) + 2(right)
In-band tones: 3 (zeros)
AIC coef. quantization: 5 bit (see below)
Interference cancellation: 6 bit
Transmitter DAC: 6 bit
Total tones used for mitigation: 7
Total number of computed AIC tones: 4

- Additional notch depth via “Active Interference Cancellation” (AIC)
  - Under consideration for inclusion in the MB-OFDM spec
  - Modest addition to system complexity
  - Reference: H. Yamaguchi (TI), 10th ECC TG3 Meeting, Copenhagen, July 11, 2005

What's New in MB-OFDM?

- Fixed-Frequency Interleave (FFI) Codes
- 106.7 Mbps Data Rate
- Dual-Carrier Modulation (DCM)
- Transmit Power Control (TPC)
- Three-Stage Interleaver
- Explicitly Recommended OOB Limits

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.

New Data Rate of 106.7 Mbps

- MB-OFDM authors continue to maintain 110 Mbps data rate to allow direct comparison against the TG3a selection criteria (≥10m range @ ≥110Mbps)
- However, from a practical point of view, the required code rate of 11/32 is not particularly elegant or necessary
- We prefer to use a 1/3 rate code with no puncturing and provide a slightly lower data rate
- The legacy 110Mbps rate will continue to be part of the proposal for purposes of comparison with other contending proposals, and to demonstrate compliance with the original selection criteria
  - Silicon implementation of the legacy 110Mbps rate is optional.

Updated Data Rate Table

Note: Over-the-Air "Chip" Rate = 640 Mcps in All Cases

Info Data Rate	Modu-lation	Coding Rate (*R*)	2X FDS	2X TDS	Coded Bits / 6 OFDM Symbol	Info Bits / 6 OFDM Symbol
53.3 Mbps	QPSK	1/3	YES	YES	300	100
80	QPSK	1/2	YES	YES	300	150
106.7	QPSK	1/3	NO	YES	600	200
110	QPSK	11/32	NO	YES	600	206.25
160	QPSK	1/2	NO	YES	600	300
200	QPSK	5/8	NO	YES	600	375
320	DCM	1/2	NO	NO	1200	600
400	DCM	5/8	NO	NO	1200	750
480	DCM	3/4	NO	NO	1200	900

FDS = Frequency Domain Spreading, TDS = Time Domain Spreading

Dual Carrier Modulation (1)

- Previous modulation approach for 320, 400, 480 Mbps:
  - Map 2 interleaved bits onto a QPSK constellation and then map symbol onto the appropriate IFFT tone.

  - When there is a deep fade on the tone, the system has to rely solely on strength of error correction code to recover lost information.
- As the code strength decreases, the performance gap from AWGN starts to increase (also known as loss in diversity).
- Some have suggested that this loss in diversity is “fundamental” and can never be recovered.
- We have shown in the past that Guard Tone mapping is one way to reduce this loss. In the following slides, we will show another simple technique to reduce the loss even further.

Dual Carrier Modulation (2)

- Basic idea behind DCM:
  - Map 4 interleaved bits onto *two* 16-point symbols using two fixed but different mappings. This yields a 16-QAM-like constellation (see backup).
  - Map the resulting two 16-point symbols onto two different IFFT tones separated by 50 tones.
- Advantage of DCM:
  - The same 4 bits of information are mapped onto two tones that are separated by at least 200 MHz.
  - The probability that there is a deep fade on both tones is QUITE SMALL.
  - Even if there is a deep fade on one of the two tones, the 4 bits of information can be recovered using simple detection schemes.
  - Therefore, the loss in diversity will be much smaller.
- <u>Benefit:</u> Reduce diversity loss (by ~1.5 dB) for the higher data rates, where there is no frequency-domain or time-domain spreading.
- <u>No change</u> to PSD, no change to interference potential of Tx signal.

System Performance with DCM and GT "Copy Over"

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

	AWGN	CM1	CM2	CM3	CM4
110 Mbps	21.5 m	New: 12.0 m Original: 11.4 m	New: 11.4 m Original: 10.7 m	New: 12.3 m Original: 11.5 m	New: 11.3 m Original: 10.9 m
200 Mbps	14.8 m	New: 7.4 m Original: 6.9 m	New: 7.1 m Original: 6.3 m	New: 7.5 m Original: 6.8 m	New: 6.6 m Original: 4.7 m
480 Mbps	9.1 m	New: 3.8 m Original: 2.9 m	New: 3.5 m Original: 2.6 m	N/A	N/A

* Includes losses due to front-end filtering, clipping at the DAC, ADC degradation, multi-path degradation, channel estimation, carrier tracking, packet acquisition, etc.

Performance Exceeds IEEE PAR Requirements

Improvement with DCM + GT

- System performance improves for both channel models:
  - CM1: 2.9 m $\rightarrow$ 3.8 m (+2.4 dB improvement).
  - CM2: 2.6 m $\rightarrow$ 3.5 m (+2.6 dB improvement).
- Using the fact that shadowing contribution is ~3.9 dB to the overall degradation, the gap from AWGN to the 480 Mbps mode using DCM + Guard Tone Mapping has already been reduced by ~2.5 dB!
- This analysis shows that the Rayleigh fading for MB-OFDM can be mitigated by additional signal processing.

Gap of 6 dB in fading is *NOT* a fundamental issue

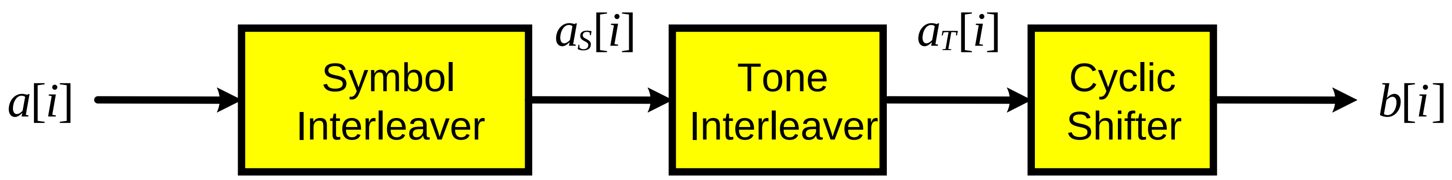
Transmit Power Control

- Mapping between TXPWR_LEVEL and Transmit Power Attenuation

TXPWR_LEVEL	TX Power Attenuation for TFI Modes	TX Power Attenuation for FFI Modes
0	0 dB	0 dB
1	2 dB	2 dB
2	4 dB	4 dB
3	6 dB	6 dB
4	8 dB	8 dB
5	10 dB	RESERVED
6	12 dB	RESERVED
7	RESERVED	RESERVED

- Relative accuracy of the transmit power attenuation shall be the maximum of ±1 dB or ±20% of the change in attenuation (dB scale).

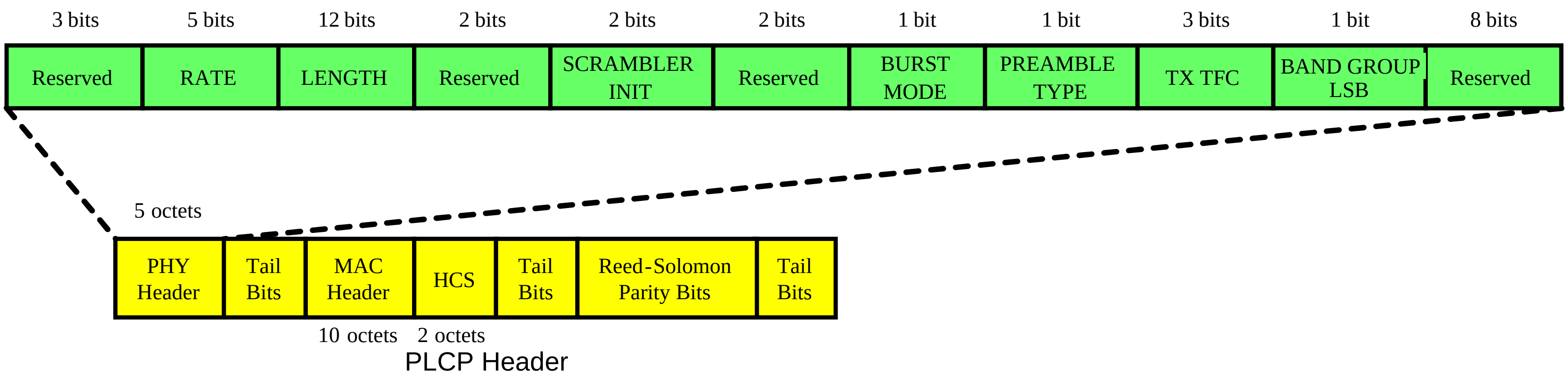
Three-Stage Interleaver



1. The **symbol interleaver** permutes the bits across 6 consecutive OFDM symbols enables the PHY to exploit frequency diversity within a band group.
2. The intra-symbol **tone interleaver** permutes the bits within an OFDM symbol to exploit frequency diversity across subcarriers and provide robustness against narrow-band interferers.
3. The intra-symbol **cyclic shifter** shifts the bits in successive OFDM symbols by deterministic amounts to better exploit frequency diversity for modes that employ time-domain spreading and fixed-frequency interleaving.

Changes to PLCP Header (1)

- New PLCP Header format:



- Changes to the PHY Header:
  - Added two bits to support burst mode capabilities. (1) Burst Mode bit specifies whether next packet is part of the burst, (2) Preamble Type bit specifies whether next preamble is a standard preamble or burst preamble. (Burst Mode supports streaming with shorter preamble.)
  - Added two bits to mitigate potential problems from adjacent channel interference: (1) TX_TFC specifies the TFC used for transmission, (2) BG_LSB specifies the LSB of the BG used for transmission.

Changes to PLCP Header (2)

- Changes to the PLCP Header:
  - Replaced PAD bits with Reed-Solomon (RS) parity bits.
  - A (23,17) systematic Reed-Solomon outer code is added in order to increase the robustness of the PLCP header.
  - RS protects only the PHY header, MAC header, and HCS (total = 17 bytes).
  - Encoding of RS parity bits is mandatory at the transmitter (additional complexity is quite small).
  - Since RS code is systematic, a RS decoder is optional at the receiver.
- Reasons for adding RS outer code:
  - Increases robustness of the PLCP header.
  - "Future proofs" standard $\Rightarrow$ PLCP header will not be the limiting factor for packet error rate.
  - This means that we can add advanced coding schemes to the standard in the future without having to change packet structure.
- RS (23, 17) code is derived from a shortened RS(255, 249) code.

Complexity (numbers supplied by TI)

- Die size for PHY core:

Process	Complete Analog*	Complete Digital
90 nm	3.0 mm^2	1.9 mm^2
130 nm	3.3 mm^2	3.8 mm^2

* Component area.

- Active CMOS power consumption for PHY core:

Process	TX 55 Mb/s	TX 110, 200 Mb/s	RX 55 Mb/s	RX 110 Mb/s	RX 200 Mb/s
90 nm	85 mW	128 mW	147 mW	155 mW	169 mW
130 nm	104 mW	156 mW	192 mW	205 mW	227 mW

Recommended Out-of-band Emissions (1)

- For cases, when UWB devices will be in close proximity to cellular devices and GPS downlink devices, the authors of Merged Proposal #1 recommended tighter out-of-band (OOB) emissions.
- The OOB emissions mask is specified for average power emissions and excludes possible narrowband spectrum spikes or spurs.
- Assumptions for new OOB emissions mask:
    1. Device separation of 60 cm.
    2. Noise figure of 7 dB for cellular devices, and 3.5 dB for GPS devices
    3. Allowed noise floor increase of 1 dB for cellular devices, and 0.5 dB for GPS devices.
    4. Victim gain antenna of –3 dBi.
    5. Free space path loss model (frequency used in path loss model is defined to be the lowest frequency of victim’s operating band).

Recommended Out-of-band Emissions (2)

- Recommended OOB mask:

Frequency Band (MHz)	FCC Handheld Limit (dBm/MHz)	Recommended limit (dBm/MHz)
869-894	§15.209	-83.3
925-960	§15.209	-82.5
1570-1581	-75.3	-84.7
1805-1880	-63.3	-76.8
1930-1990	-63.3	-76.2
2110-2170	-61.3	-75.4

- These new recommended emission limits should help to address some of the concerns that are being raised within the ITU.

MB-OFDM -- Conclusions

- Has performance that exceeds IEEE PAR requirements.
- Now offers even more robust performance in presence of multipath & interference (DCM, GT, Interleaving, …)
- 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

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

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

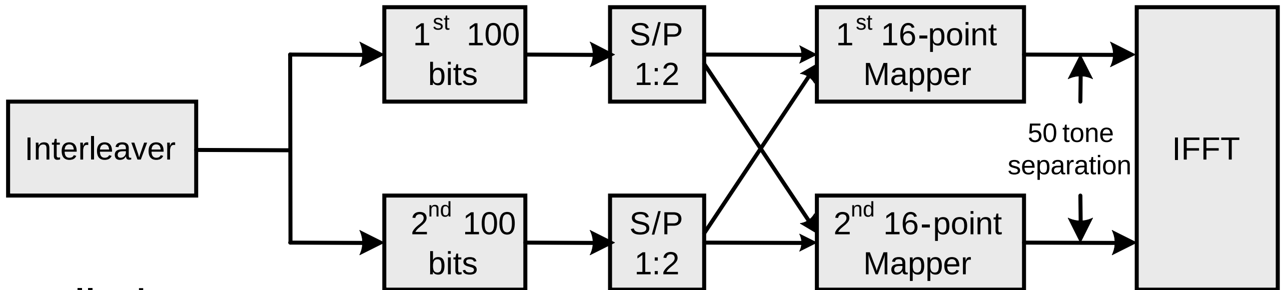
15-04-0013, **C-Band Satellite Interference Measurements TDK RF Test Range**, Evan Green, Gerald Rogerson and Bud Nation

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

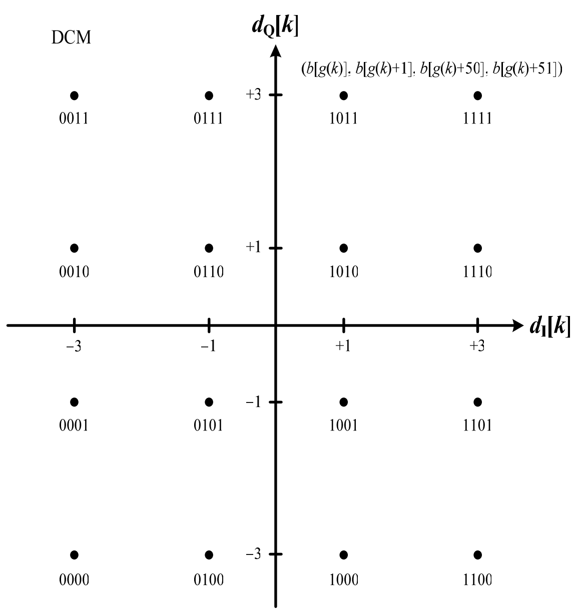
15-04-0018, **Video of MB-OFDM, DS-UWB and AWGN Interference Test**, Pat Carson and Evan Green

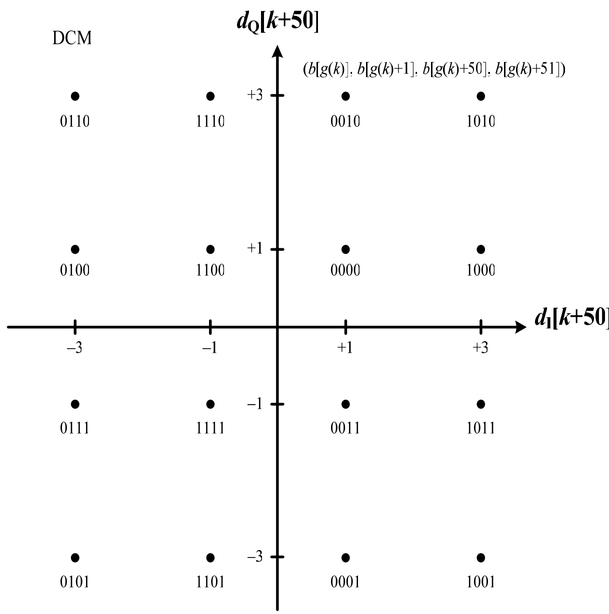
Dual Carrier Modulation

- Block diagram of DCM:



- 16-point constellations:

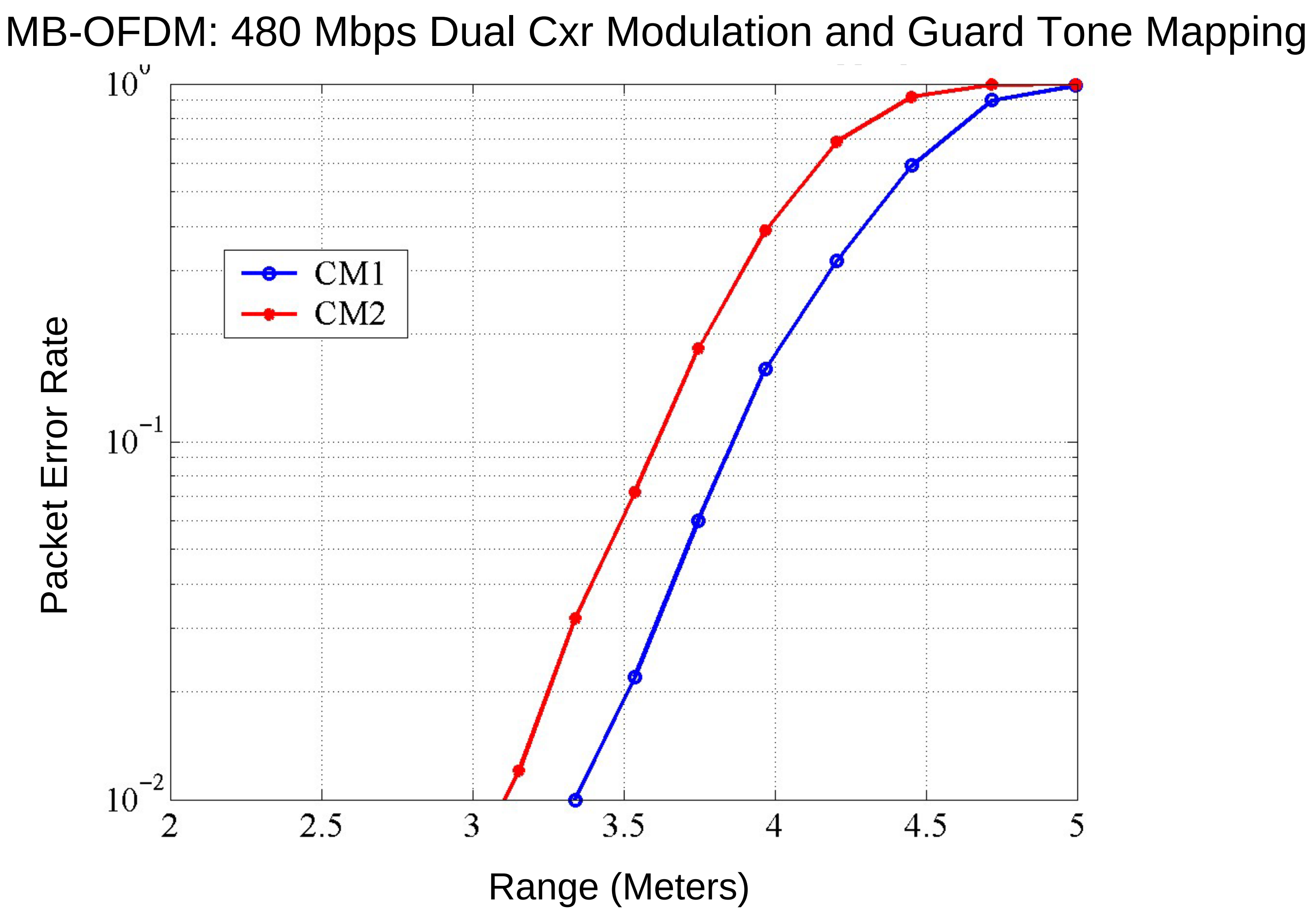




Simulation Parameters

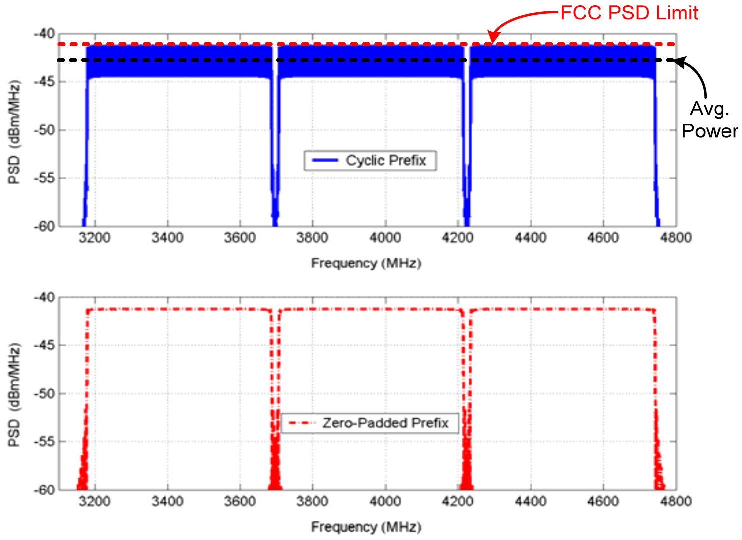
- Assumptions:
  - Clipping at the DAC (PAR = 9 dB).
  - Finite precision ADC (4 bits for 110, 200 Mbps and 5 bits for 480 Mbps).
  - DCM for 320, 400, 480 Mbps.
  - No attenuation on the Guard Tones.
- Degradations incorporated:
  - Front-end filtering.
  - Multi-path degradation.
  - Shadowing.
  - Clipping at the DAC.
  - Finite precision ADC.
  - Crystal frequency mismatch (±20 ppm @ TX, ±20 ppm @ RX).
  - Channel estimation.
  - Carrier/timing offset recovery.
  - Carrier tracking.
  - Packet acquisition.

Simulation Results for DCM + GT



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.

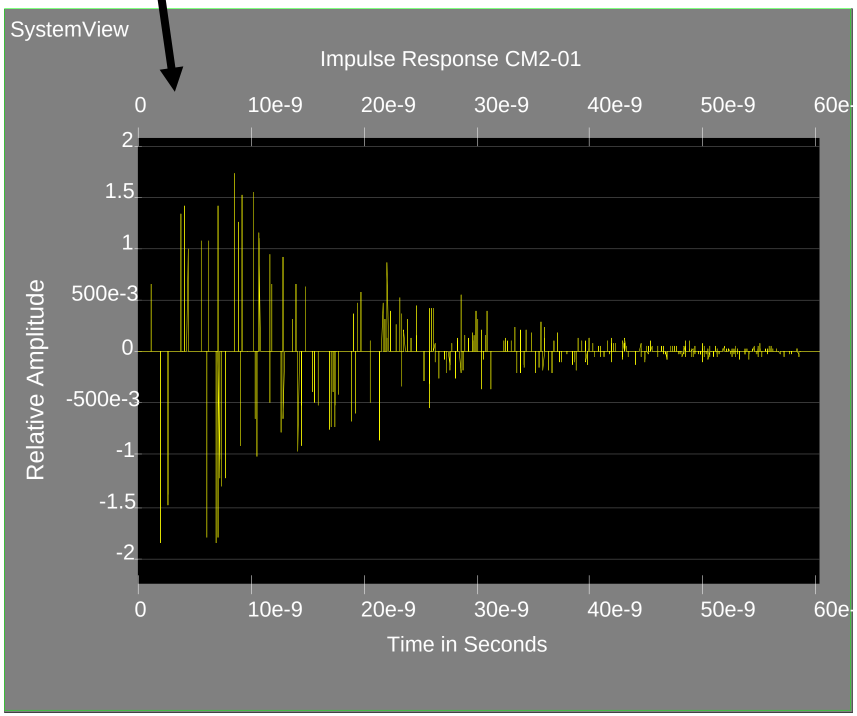
- A Zero-Padded Prefix provides the same multi-path robustness as a cyclic prefix (60.6 ns of protection).

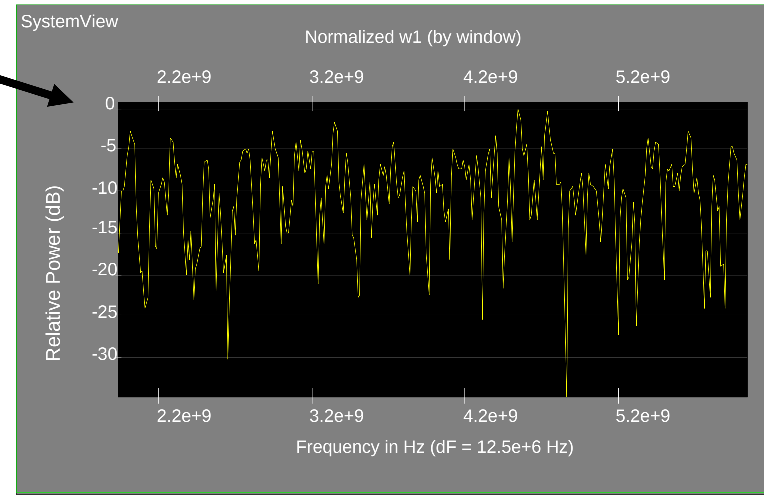
Multipath – The Engineer's Nightmare & Opportunity

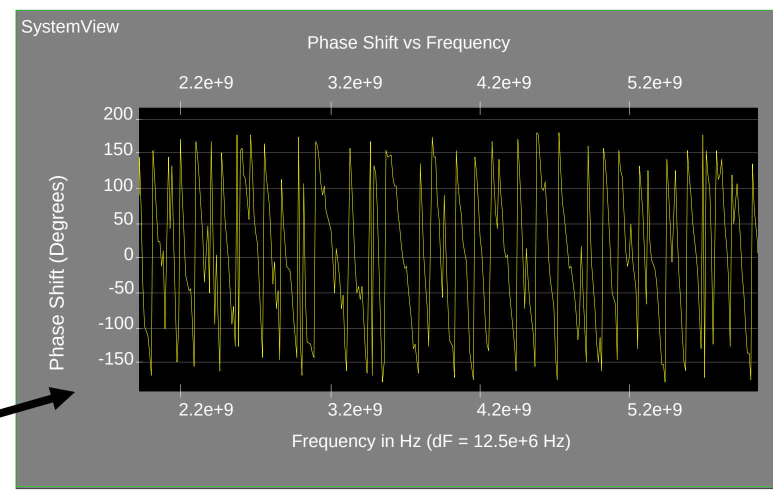
Typical UWB Channel Impulse Response

Time

Frequency







Phase

MB-OFDM Contributors (1)

Roberto Aiello	Staccato Communications
Anand Anandakumar	Jaalaa
Naiel Askar	General Atomics
Jaiganesh Balakrishnan	Texas Instruments
Anuj Batra	Texas Instruments
Nathan Belk	Texas Instruments
Roger Bertschmann	SiWorks
Dagnachew Birru	Philips
Leo Bogod	Nokia
Chuck Brabenac	Intel
Vern Brethour	Alereon
Stephan ten Brink	Realtek Semiconductors
Sujai Chari	Tzero
Jonathon Cheah	Femto Devices
Francois Chin	Institute for Infocomm Research
Anand Dabak	Texas Instruments
Joe Decuir	MCCI
Yossi Erlich	Infineon
Eran Fishler	Infineon
Jeff Foerster	Intel
Paul Fontaine	Texas Instruments

Vasanth Gaddam	Philips
Miki Genossar	Adimos
Ranjit Gharurey	University of Michigan
Manish Goel	Texas Instruments
Sorin Goldenberg	Wisair
Danielle Griffith	Texas Instruments
Assaf Gurevitz	Infineon
Jin-Meng Ho	Texas Instruments
Dale Hocevar	Texas Instrements
Eyal Hochdorf	Infineon
Srinath Hosur	Texas Instruments
Osamu Inagawa	NEC Electronics
Daryl Kaiser	Tzero
Joy Kelly	Alereon
HaeSik Kim	Samsung Advanced Institute of Technology
YongSuk Kim	Samsung Advanced Institute of Technology
Noam Kogos	Adimos
Rajeev Krishnamoorthy	Tzero
Nishant Kumar	Staccato Communications
Haim Kupershmidt	Wisair
Do-Hoon Kwon	Samsung Advanced Institute of Technology
Torbjorn Larsson	Staccato Communications

MB-OFDM Contributors (2)

Joe Lauer	Broadcom
Simon Lee	Texas Instruments
David Leeper	Intel
Jerry Lin	Texas Instruments
Susan Lin	General Atomics
Srinivas Lingam	Texas Instruments
Steve Lo	Tzero
Ian Macnamara	Nokia
David Magee	Texas Instruments
Ravishankar Mahadevappa	Realtek Semiconductors
Tom Matheney	Alereon
Dan Meacham	Staccato Communications
Suzuki Mitsuhiro	Sony
Shaomin Mo	Panasonic
Andreas F. Molisch	Mitsubishi Electric Research Laboratories
Lars Mucke	Staccato Communications
Yves-Paul Nakache	Mitsubishi Electric Research Laboratories
Hideo Ohba	NEC Electronics
Eric Ojard	Broadcom
Philip Orlik	Mitsubishi Electric Research Laboratories
SeungYoung Park	Samsung Advanced Institute of Technology
Shrenik Patel	Alereon
Xiaoming Peng	Institute for Infocomm Research
Sridhar Rajagopal	WiQuest
Pekka Ranta	Nokia
Yaron Rashi	Infineon
Charles Razzell	Philips
Jaeho Roh	Samsung Advanced Institute of Technology
Ebrahim Saberinia	University of Nevada, Las Vegas
Tomoki Saito	NEC Electronics
Yasufumi Sasaki	NEC Electronics
Assaf Sella	Wisair
Kevin Shelby	Alereon
Matthew Shoemake	WiQuest
Gadi Shor	Wisair
Srinivasa Somayazulu	Intel
Robert Sutton	TDK R&D
Kazuhisa Takamura	Sony
Nir Tal	Texas Instruments
Jun Tang	University of Minnesota
Larry Taylor	Staccato Communications
John Terry	WiQuest
Ahmed Tewfik	University of Minnesota
Takashi Usui	Sony
Hirohisa Yamaguchi	Texas Instruments
Jin Zhang	Mitsubishi Electric Research Laboratories
Anat Zilber	Adimos