Multi-Band OFDM:

Achieving High Speed Wireless Communications

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August 22, 2004

Acknowledgements

- We would like to thank the authors of Texas Instruments' UWB proposal: Time-Frequency Interleaved (TFI) OFDM proposal.
  - *TFI-OFDM proposal served as the foundation of the MB-OFDM proposal.*
- Authors:
  - Jaiganesh Balakrishnan
  - Anand Dabak
  - Ranjit Gharpurey
  - Paul Fontaine
  - Jerry Lin
  - Simon Lee
- In addition, we would especially like to thank Nathan Belk for all his efforts and advice concerning design issues for the UWB radio.

Outline

- Motivation for Ultra-wideband Systems.
- Challenges for Designing Ultra-wideband Systems:
  - Overlay of UWB spectrum with licensed and unlicensed bands.
  - Operating bandwidth for initial devices.
  - Worldwide compliance.
- Overview of Multi-band OFDM:
  - Transmitter and receiver architectures.
  - Systems parameters and system details.
  - Band plan and frequency synthesis.
  - Link budget and system performance.
  - Complexity.
- Conclusions.

Exploiting Shannon's Theorem

- Shannon's Theorem:

$$C = W \log_2(1 + S/N)$$

- **High** S/N **:** $C \cong W \log_2(S/N)$
- IEEE 802.11a 54 Mbps mode needs ~26 dB of SNR.
- Channels are fixed to 20 MHz bandwidth.
- To achieve higher data rates (= 100 Mbps) with a single antenna, need to increase constellation size (*need larger SNR*) or use advanced coding (*complexity*).

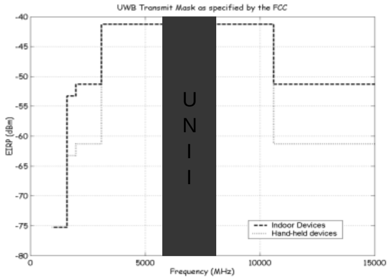
- **Low** S/N **:** $C \cong W (S/N)$
- Because of the constraints imposed by FCC, UWB systems operates at relatively low SNRs (0 – 4 dB).
- One way to achieve high data rates (= 100 Mbps) in the low SNR regime is to increase bandwidth.
- *Hence, the interest at looking at systems that use = 500 MHz.*

Promise of UWB

- Data rates:
  - *Scalable data rates from 55 Mb/s to 480 Mb/s.*
  - *110 Mb/s at 10 meters in realistic multi-path environments.*
  - *200 Mb/s at greater than 4 meters in realistic multi-path environments.*
  - *480 Mb/s at 2 meters in realistic multi-path environments.*
- Low cost solutions.
- Low power PHY solutions:
  - *TX ≤ 130 mW*
  - *RX ≤ 160 mW.*
- Integrated CMOS solution ⇒ Single chip solutions.
  - Small form factors.
- Coexistence with current and future devices.

Challenges for Design of UWB Systems

- On Feb. 14, 2002, FCC issued a Report and Order for UWB devices:
  - FCC amended the Part 15 rules to allow operation of devices incorporating UWB technology.
  - ***Unprecedented allocation of spectrum.***
  - Indoor and handheld devices must operate in the frequency band 3.1 – 10.6 GHz.
  - Maximum average TX power is below unintentional radiation limit of –41.25 dBm/MHz.



- Challenges: *coexistence with previous allocated users*!
  - Example: UWB spectrum cuts across the U-NII band (IEEE 802.11a).

What Operating Bandwidth to Use?

- Given that we have 7.5 GHz to use, what should the operating bandwidth be?
- Look at: Received Power = TX Power – Path Loss, as a function of upper frequency.
- Assume that the TX signal occupies the BW from f_L to f_U.
  - Assume that f_L is fixed at 3.1 GHz. Vary upper frequency f_U between 4.8–10.6 GHz.
  - Assume that the transmit spectrum is flat over entire bandwidth.
  - TX power = –41.25 dBm + 10log10($f_U - f_L$).
- IEEE 802.15.3a has specified a free-space propagation model:

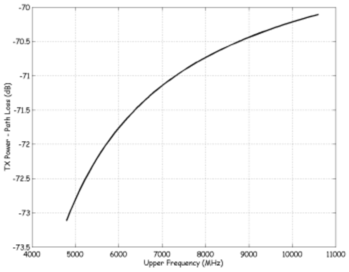
$$P_L(d) = 20\log_{10}\left[\frac{4\pi f_g d}{c}\right] \ \text{(dB)}$$

  - f_g is the Geometric mean of lower/upper frequencies (10-dB points)
  - d is the UWB transmitter-receiver separation distance (assume d = 10 m)
  - c is the speed of light

Small Gains From Increasing Upper Frequency

- Let’s look at the problem from a link budget perspective:

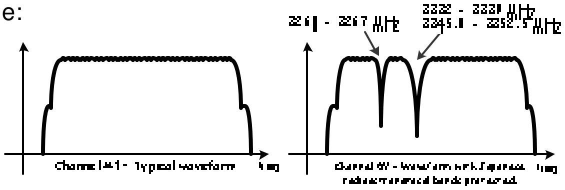
	f_u = 7.5 GHz	f_u = 10.6 GHz
RX Power Gain	+ 2.0 dB	+3.0 dB
N_F Increase	-1.0 dB	-2.0 dB
Result	+1.0 dB	+1.0 dB



- Note: using frequencies > 4.8 GHz increases the overall link margin by *at most* 1.0 dB with the current RF technology, but at the cost of higher complexity and power consumption.
- Conclusion: only minimal gains can be realized in the link budget by using frequencies above 4.8 GHz.
- Note: using larger operating BW is useful for multiple access.

Worldwide Compliance

- UWB regulations are ONLY set in the United States.
- Europe, Japan, Korea are currently in the process of allocating UWB spectrum.
  - In these countries, UWB proponents may have to negotiate with current spectrum holders in order to obtain appropriate power levels for UWB transmissions.
  - Example: Japanese administration has suggested the need for protecting radio astronomy bands.
- It is important that UWB devices are designed with the ability to arbitrarily shape the spectrum.
- Example:



Overview of Multi-band OFDM

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Authors and Supporters of Multi-band OFDM

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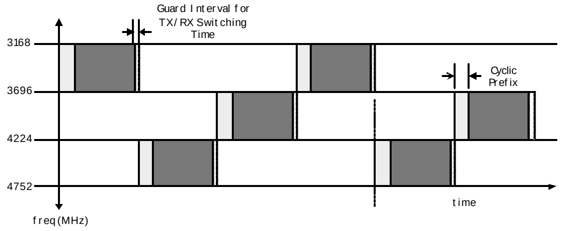
Overview of Multi-band OFDM

- Basic idea: divide the spectrum into bands that are 528 MHz wide.
- Interleave OFDM symbols across all bands to exploit frequency diversity and provide robustness against multi-path and interference.
- Transmitter and receiver process smaller bandwidth signals (528 MHz).
- Prefix provides robustness against multi-path even in the worst case channel environments.
- Insert a guard interval between OFDM symbols in order to allow sufficient time to switch between channels.



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The Benefits of OFDM

- OFDM was invented almost 50 years ago.
- OFDM is a mature technology
- Currently used in several products available today:
  - ADSL, 802.11a/g, 802.16, European Digital TV, Digital Audio Broadcast
- OFDM is also being considered in the following technologies:
  - 4G, 802.11n, 802.16a/e, 802.20
- High spectral efficiency
- Excellent robustness against multi-path
- Robustness against narrowband interferers

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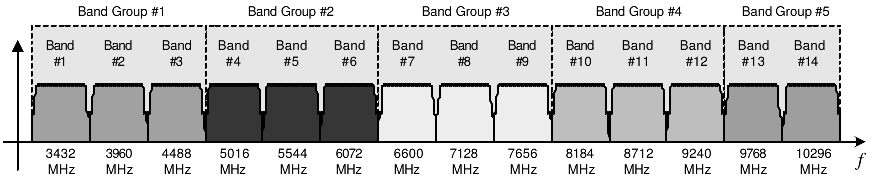
Band Plan

- Group the 528 MHz bands into 5 distinct groups.



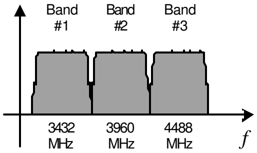
- Band Group #1: Intended for 1st generation devices (3.1 – 4.9 GHz).
- Band Group #2 – #5: Reserved for future use.
- Because of path loss, the range that is supported by each Band Group will be different, i.e.,

$$R_{max,1} > R_{max,2} > R_{max,3} > R_{max,4} > R_{max,5}$$

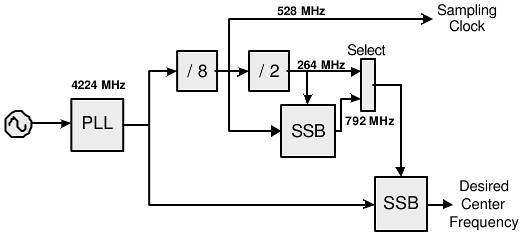
- Range differential turns out to be an advantage!
  - Can use range differential to help address multiple access.
  - Example: for applications, such as DVD to HDTV, use Band Group #1 or #2.
  - Example: for applications, such as DSC to laptop, use Band Group #3 or #4.

Frequency Synthesis (1)

- Center frequencies for the sub-bands:
  - $f_1 = 4224 - 792 = 3432$ MHz
  - $f_2 = 4224 - 264 = 3960$ MHz
  - $f_3 = 4224 + 264 = 4488$ MHz

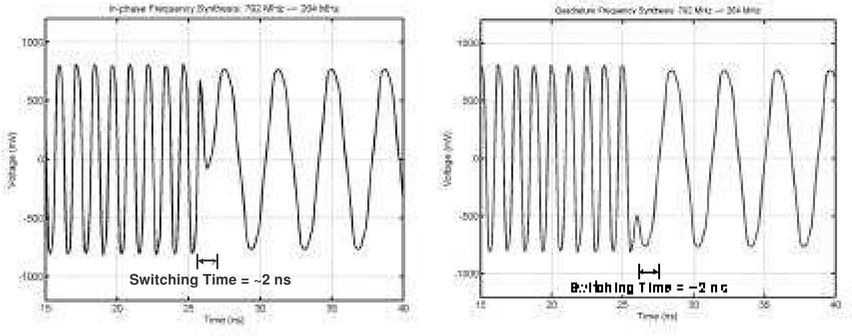


- Example: Frequency synthesis circuit for Band Group #1:



Frequency Synthesis (2)

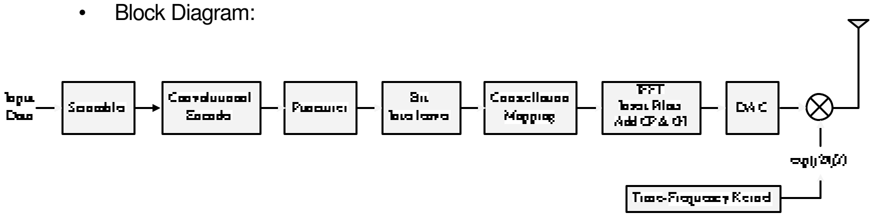
- Circuit-level simulation of frequency synthesis:



- Nominal switching time = ~2 ns.
- Need to use a slightly larger switching time to allow for process and temperature variations.

Multi-band OFDM Transmitter Architecture

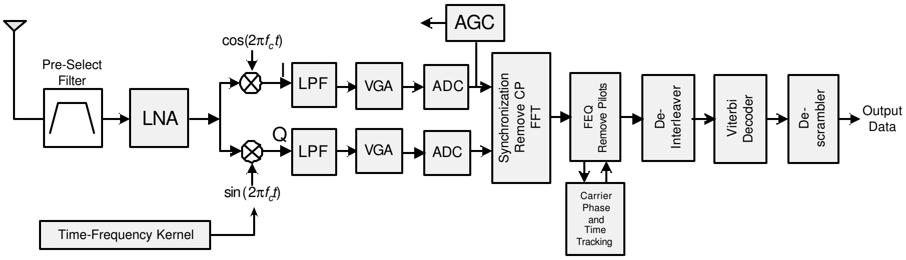
- Block Diagram:



- Architecture is similar to that of a conventional and proven OFDM system.
- Major Differences:
  - Time-Frequency kernel specifies the frequency for next OFDM symbol.
  - Constellation size is limited to QPSK (limits size of IFFT/FFT, DAC/ADC).
  - For rates less than 80 Mb/s, we force the input to the IFFT to be conjugate symmetric.
    - Need to only implement the “I” portion of TX analog chain.
    - As a result, only half the analog die size of a full “I/Q” transmitter is needed.
  - Zero-padded prefix limits power back-off at the transmitter.

Multi-band OFDM Receiver Architecture

- Block diagram:



- Architecture is similar to that of a conventional and proven OFDM system.
- Can leverage existing OFDM solutions for the development of the Multi-band OFDM physical layer.

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	400 Mbps	480 Mbps
Modulation/Constellation	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK
FFT Size	128	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 = 5/8	R = 3/4
Frequency-domain Spreading	Yes	Yes	No	No	No	No	No	No
Time-domain Spreading	Yes	Yes	Yes	Yes	Yes	No	No	No
Data Tones	100	100	100	100	100	100	100	100
Zero-padded Prefix	60.6 ns	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	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	312.5 ns
Channel Bit Rate	640 Mbps	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	60.6 ns

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

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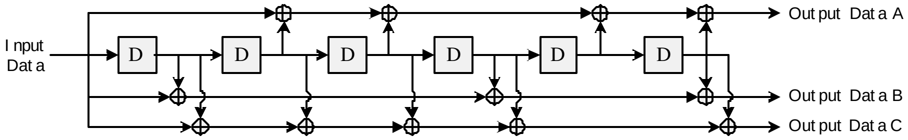
Convolutional Encoder

- Assume a mother convolutional code of R = 1/3, K = 7. Having a single mother code simplifies the decoder implementation.

- Generator polynomial: $g_0 = [133_8]$, $g_1 = [165_8]$, $g_2 = [171_8]$.



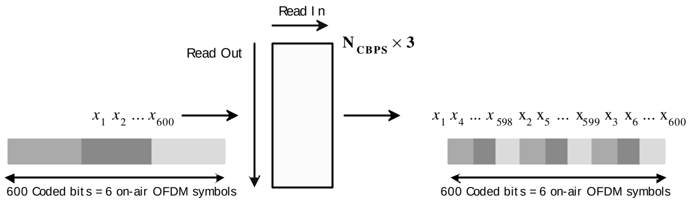
- Higher rate codes are achieved by optimally puncturing the mother code. Code rates supported via puncturing are: 11/32, 1/2, 5/8, 3/4.

Bit Interleaver

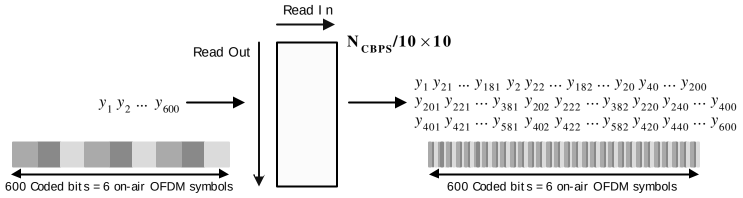
- Bit interleaving is performed across the bits within an OFDM symbol and across six OFDM symbols.
  - Exploits frequency diversity.
  - Randomizes any interference ⇒ interference looks nearly white.
  - Latency is less than 2 μs.
- Bit interleaving is performed in three stages:
  - Initially, $(6/T_{SF})N_{CBPS}$ coded bits are grouped together.
  - First stage: the coded bits are interleaved using $N_{CBPS} \times (6/T_{SF})$ block symbol interleaver.
  - Second stage: the output bits from 1st stage are interleaved using $(N_{CBPS}/10) \times 10$ block tone interleaver.
  - The end results is that the data is spread across 6 on-air OFDM symbols; spanning three different frequency bands.
- If there are less than $(6/T_{SF})N_{CBPS}$ coded bits, the data is padded out to align with the interleaver boundary.

Bit Interleaver

- Ex: Second stage (symbol interleaver) for a data rate of 110 Mbps (T_{SF} = 2).

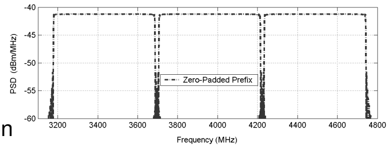


- Ex: Third stage (tone interleaver) for a data rate of 110 Mbps.



Zero-Padded Prefix (1)

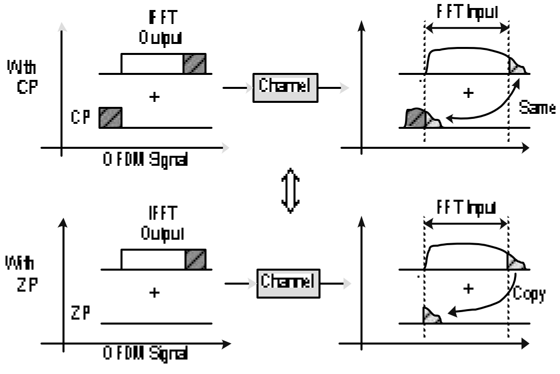
- In conventional OFDM system, a cyclic prefix is added to provide multi-path protection.
- Cyclic prefix introduces structure into the transmitted waveform ⇒ structure in the transmitted waveform produces ripples in the PSD.
- In an peak PSD-limited system, any ripples in the transmitted waveform will results in back-off at the transmitter (reduction in range).
- Ripple in the transmitted spectrum can be eliminated by using a zero-padded prefix.
  - Zero-padded prefix eliminates redundancy in the transmitted waveform.
  - Results in almost no ripple in PSD.
  - Provides the same multi-path protection if a cyclic prefix were present.



- Using a zero-padded (ZP) prefix instead of a cyclic prefix is a well-known and well-analyzed technique.

Zero-Padded Prefix (2)

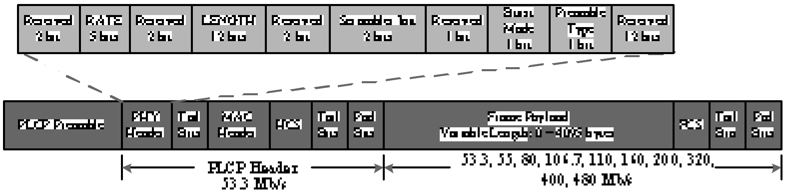
- A Zero-Padded Multi-band OFDM has the same multi-path robustness as a system that uses a cyclic prefix (60.6 ns of protection).
- The receiver architecture for a zero-padded multi-band OFDM system requires ONLY a minor modification (less than < 200 gates).



- Added flexibility to implementer: multi-path robustness can be dynamically controlled at the receiver, from 1.9 ns up to 60.6 ns.

Multi-band OFDM: PLCP Frame Format

- PLCP frame format:



- Rates supported: 55, 80, 110, 160, 200, 320, 400, 480 Mb/s.
  - Support for 55, 110, and 200 Mb/s is mandatory.
- Preamble + Header = 13.125 ms.
- Burst preamble + Header = 9.375 ms.
- Header is sent at an information data rate of 55 Mb/s.
- Maximum frame payload supported is 4095 bytes.

PLCP Preamble (1)

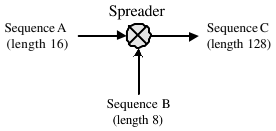
- Multi-band OFDM preamble is composed of 3 sections:
  - Packet sync sequence: used for packet detection.
  - Frame sync sequence: used for boundary detection.
  - Channel estimation sequence: used for channel estimation.
- Packet and frame sync sequences are constructed from the same hierarchical sequence.
- Correlators for hierarchical sequences can be implemented efficiently:
  - Low gate count.
  - Extremely low power consumption.
- Sequences are designed to be the most robust portion of the packet.

PLCP Preamble (2)

- In the multiple overlapping piconet case, it is desirable to use different hierarchical preambles for each of the piconets .
- Basic idea: define 4 hierarchical preambles, with low cross-correlation values.
- Preambles are generated by spreading a length 16 sequence by a length 8 sequence.

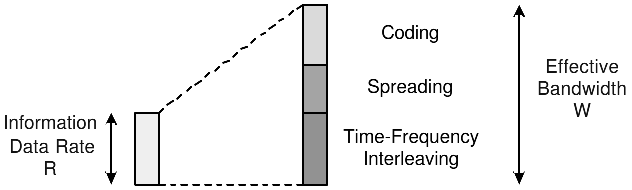
Preamble Pattern	Sequence A															
1	1	1	1	1	-1	-1	1	1	-1	-1	1	-1	1	-1	1	1
2	1	-1	-1	-1	-1	-1	1	-1	1	-1	-1	1	1	-1	-1	1
3	1	1	-1	-1	-1	1	-1	-1	-1	1	-1	-1	1	-1	1	1
4	1	-1	-1	1	-1	1	-1	-1	1	1	-1	-1	-1	-1	-1	1

Preamble Pattern	Sequence B							
1	1	-1	-1	-1	1	1	-1	1
2	1	-1	1	1	-1	-1	-1	1
3	1	1	-1	1	1	-1	-1	-1
4	1	1	1	-1	-1	1	-1	-1



Multiple Access (1)

- Bandwidth expansion refers to using a signaling bandwidth that is much larger than the information data rate.
- Bandwidth expansion can be achieved using any of the following techniques or combination of techniques:
  - Typical methods: Spreading, Coding, Time-Frequency Coding
  - Ex: MB-OFDM obtains its BW expansion (= W/R) by using all three techniques.



Multiple Access (2)

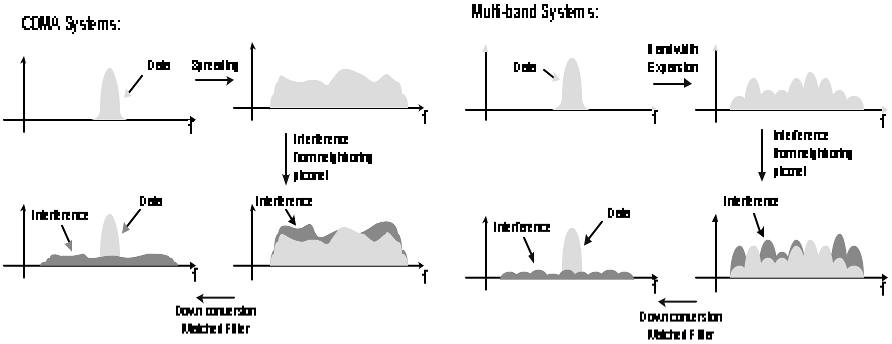
- Time-Frequency (TF) Codes:

Channel Number	Preamble Pattern	Mode 1 DEV: 3-band Length 6 TFC					
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

- Time-Frequency Codes were designed such that (on average) only 1/3 of the symbols would collide.
  - Since the transmitted information is spread over 6 OFDM symbols, the FEC code can compensate for the collisions.
- Even if the TF codes were designed to be perfectly orthogonal, *multi-path* and *asynchronicity between piconets* would destroy the orthogonality:
  - Similar phenomena occurs with spreading sequences in CDMA systems.
- Conclusion: *Can never have perfect isolation between piconets.*

Multiple Access (3)

- Example:



- Performance is governed by $SIR = (P_{sig}/P_{int})\ (W/R)$.
  - In realistic multi-path, real-world conditions: “BW expansion is all that matters”.
  - *Systems with same BW expansion have similar multiple piconet capability.*

Link Budget and Receiver Sensitivity

- Assumption: 3-band Device, AWGN, and 0 dBi gain at TX/RX antennas.

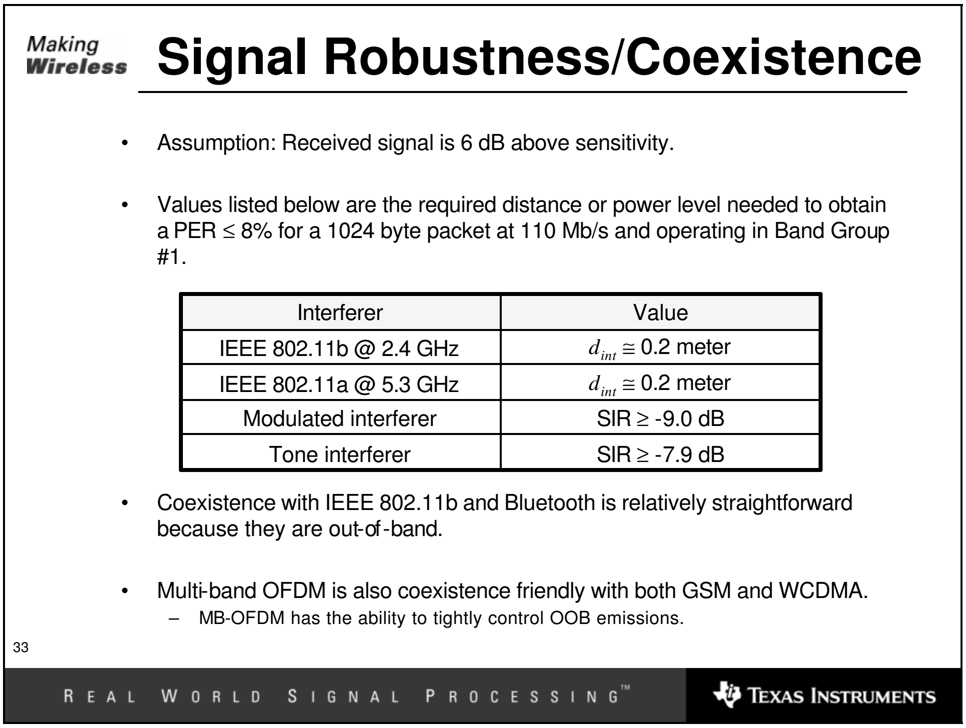
Parameter	Value	Value	Value
Information Data Rate	110 Mb/s	200 Mb/s	480 Mb/s
Average TX Power	-10.3 dBm	-10.3 dBm	-10.3 dBm
Total Path Loss	64.2 dB (@ 10 meters)	56.2 dB (@ 4 meters)	50.2 dB (@ 2 meters)
Average RX Power	-74.5 dBm	-66.5 dBm	-60.5 dBm
Noise Power Per Bit	-93.6 dBm	-91.0 dBm	-87.2 dBm
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

System Performance (3-band)

- 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	LOS: 0 – 4 m CM1	NLOS: 0 – 4 m CM2	NLOS: 4 – 10 m CM3	RMS Delay Spread: 25 ns CM4
110 Mbps	20.5 m	11.4 m	10.7 m	11.5 m	10.9 m
200 Mbps	14.1 m	6.9 m	6.3 m	6.8 m	4.7 m
480 Mbps	8.9 m	2.9 m	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.

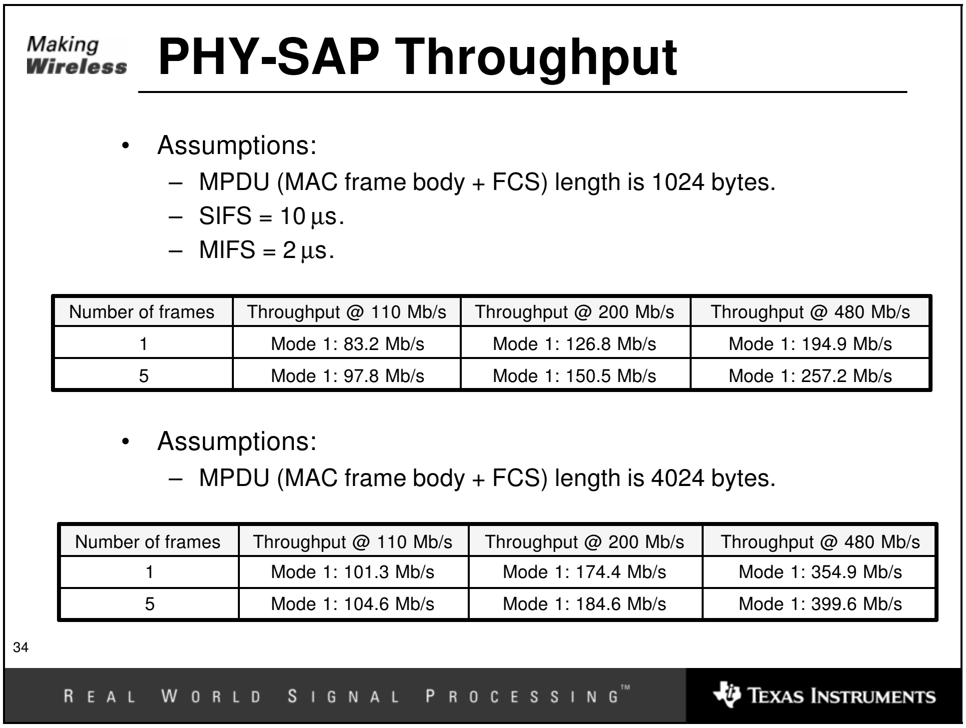


Signal Robustness/Coexistence

- Assumption: Received signal is 6 dB above sensitivity.
- Values 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 operating in Band Group #1.

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 IEEE 802.11b and Bluetooth is relatively straightforward because they are out-of-band.
- Multi-band OFDM is also coexistence friendly with both GSM and WCDMA.
  - MB-OFDM has the ability to tightly control OOB emissions.



PHY-SAP Throughput

- Assumptions:
  - MPDU (MAC frame body + FCS) length is 1024 bytes.
  - SIFS = 10 µs.
  - MIFS = 2 µs.

Number of frames	Throughput @ 110 Mb/s	Throughput @ 200 Mb/s	Throughput @ 480 Mb/s
1	Mode 1: 83.2 Mb/s	Mode 1: 126.8 Mb/s	Mode 1: 194.9 Mb/s
5	Mode 1: 97.8 Mb/s	Mode 1: 150.5 Mb/s	Mode 1: 257.2 Mb/s

- Assumptions:
  - MPDU (MAC frame body + FCS) length is 4024 bytes.

Number of frames	Throughput @ 110 Mb/s	Throughput @ 200 Mb/s	Throughput @ 480 Mb/s
1	Mode 1: 101.3 Mb/s	Mode 1: 174.4 Mb/s	Mode 1: 354.9 Mb/s
5	Mode 1: 104.6 Mb/s	Mode 1: 184.6 Mb/s	Mode 1: 399.6 Mb/s

PHY 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 the PHY (RF+basbeband) operating in Band Group #1:

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

* Analog Component area.

- Active CMOS power consumption for the PHY (RF+baseband) operating in Band Group #1 :

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

Comparison of OFDM Technologies

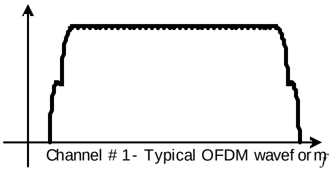
- Qualitative comparison between Multi-band OFDM and IEEE 802.11a OFDM:

Criteria	Multi-band OFDM Strong Advantage	Multi-band OFDM Slight Advantage	Neutral	802.11a Slight Advantage	802.11a Strong Advantage
PA Power Consumption	✓				
ADC Power Consumption	✓[3]				
FFT Complexity			✓[1]	✓[2]	
Viterbi Decoder Complexity				✓	
Band Select Filter Power Consumption		✓			
Band Select Filter Area		✓			
ADC Precision	✓				
Digital Precision		✓			
Phase Noise Requirements	✓				
Sensitivity to Frequency/Timing Errors	✓				
Design of Radio	✓				
Power / Mbps	✓				

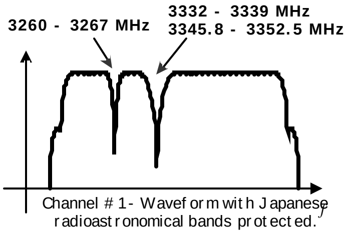
1. Assumes a 256-point FFT for IEEE 802.11a device.
2. Assumes a 128-point FFT for IEEE 802.11a device.
3. Even though the Multi-band OFDM ADC runs faster than the IEEE 802.11a ADC, the bit precision requirements are significantly smaller, therefore the Multi-OFDM ADC will consume much less power.

Conclusions (1)

- Inherent robustness to multi-path in all expected environments.
- Excellent robustness to U-NII and other generic narrowband interference.
- Ability to comply with worldwide regulations:
  - Channels and tones can be turned on/off dynamically to comply with changing regulations.
  - Can arbitrarily shape spectrum because the tones resolution is ~4 MHz.
- Example: Radio-astronomy bands 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.

Conclusions (2)

- Enhanced coexistence with current and future services:
  - Channels and tones can be turned on/off dynamically to coexist with other devices.
- Scalability:
  - More channels can be added as RF technology improves and as capacity requirements increase.
  - Multi-band OFDM is digital heavy. Digital section complexity and power scales with improvements in technology node (Moore's Law).
- MB-OFDM offers the best trade-off between the various system parameters.
- PHY solution are expected to be ready for integration in 2005.

Backup Slides

Multiple Access

- Total effective bandwidth (TEB) is given as:

$$\mathrm{TEB} = \begin{cases} (\#\text{ of bands}) \times (3\text{-dB BW}) & \text{For single-carrier systems} \\ \dfrac{(\#\text{ of bands}) \times (\#\text{ of data tones})}{\text{symbol duration}} & \text{For multi-carrier systems} \end{cases}$$

- Bandwidth Expansion Factor (BEF) is defined as follows:

$$\mathrm{BEF} = \frac{\text{Total effective bandwidth}}{\text{Data rate}} \left(= 9 \text{ for TFI-OFDM}\right)$$

- Interference suppression capability is directly related to the BEF.
- In terms of supporting multiple uncoordinated piconets, all that matters is a systems ability to suppress interference.

⇒ *Systems that have the same BEF have similar multiple piconet capability.*