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Source: [Anuj Batra, Jaiganesh Balakrishnan, Anand Dabak, et al.] Company [Texas Instruments]

Address [12500 TI Blvd, MS 8649, Dallas, TX 75243]
Voice:[214-480-4220], FAX: [972-761-6966], E-Mail:[batra@ti.com]

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 TI physical layer proposal for IEEE 802.15 TG3a.]

Purpose: [For discussion by IEEE 802.15 TG3a.]

TI Physical Layer Proposal: Time-Frequency Interleaved OFDM

Anuj Batra, Jaiganesh Balakrishnan, Anand Dabak
Ranjit Gharpurey, Paul Fontaine, Jerry Lin
Jin-Meng Ho, Simon Lee, Michel Frechette
Steven March, Hirohisa Yamaguchi

Texas Instruments
12500 TI Blvd, MS 8649
Dallas, TX

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Outline

- Overview of OFDM: History, strengths, worldwide compliance.
- Optimal operating bandwidth.
- Details about Time-Frequency Interleaved OFDM (TFI-OFDM).
- Performance Results:
  - Link budget.
  - System performance in multi-path.
  - Simultaneously operating piconets and robustness to coexistence.
  - Complexity.
- Summary and Conclusions.

History of OFDM

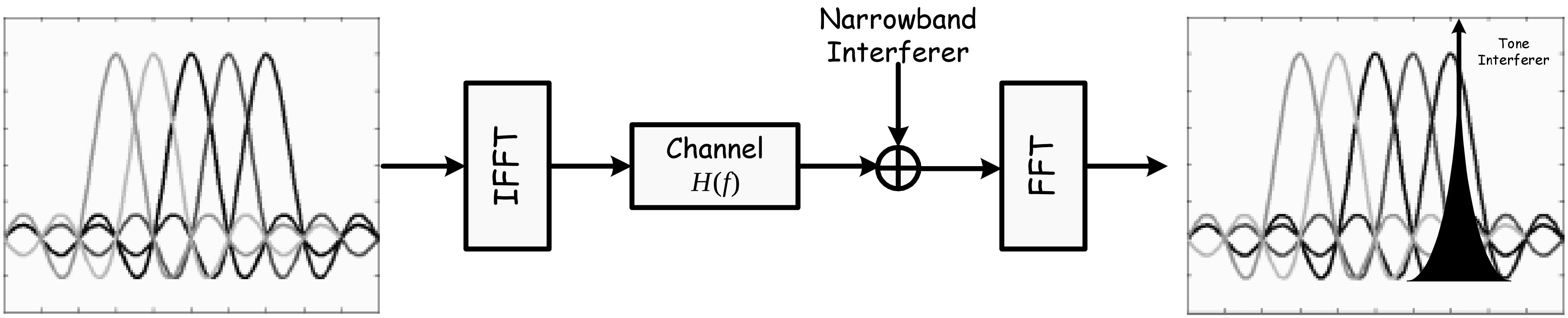
- OFDM was invented more than 40 years ago.

- OFDM has been adopted by several standards:
  - Asymmetric Digital Subscriber Line (ADSL) services.
  - IEEE 802.11a/g.
  - IEEE 802.16a.
  - Digital Audio Broadcast (DAB).
  - Digital Terrestrial Television Broadcast:
    - DVB in Europe and ISDB in Japan.

- Because OFDM is suitable for high data-rate systems, it is being considered for the following standards:
  - Fourth generation (4G) wireless services.
  - IEEE 802.11n, IEEE 802.16, and IEEE 802.20.

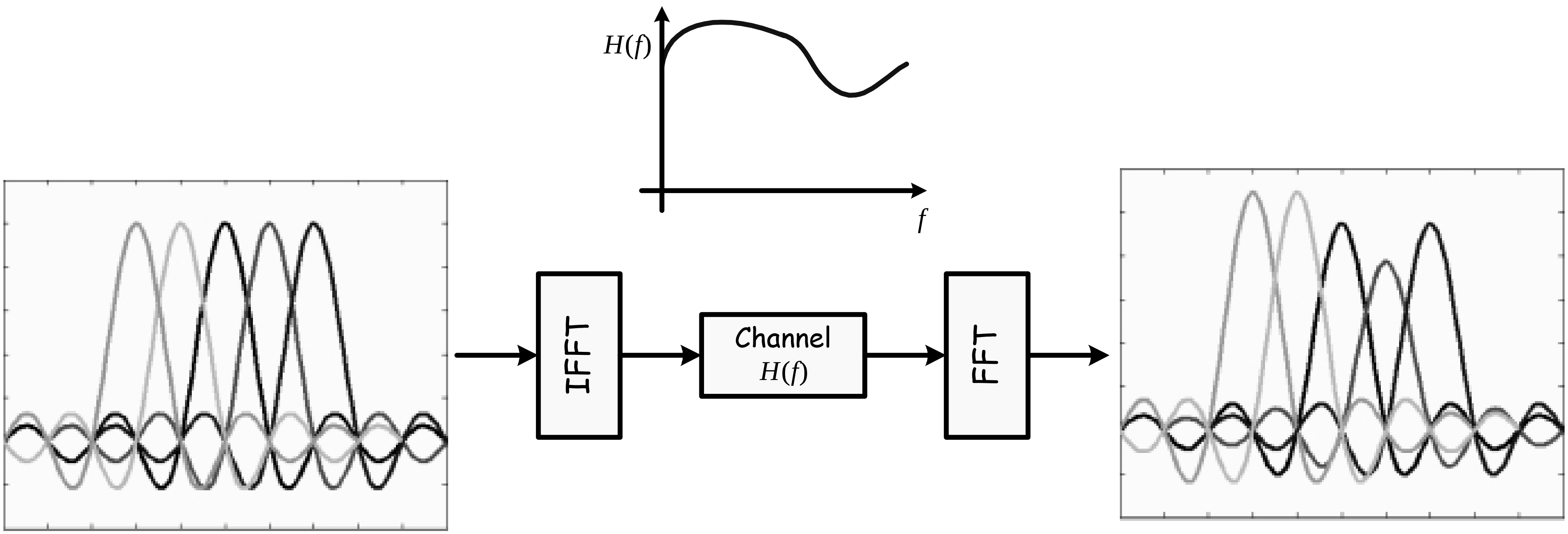
Strengths of OFDM (1)

- 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-carrier 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 now unreliable. Use FECs to recover the lost information.



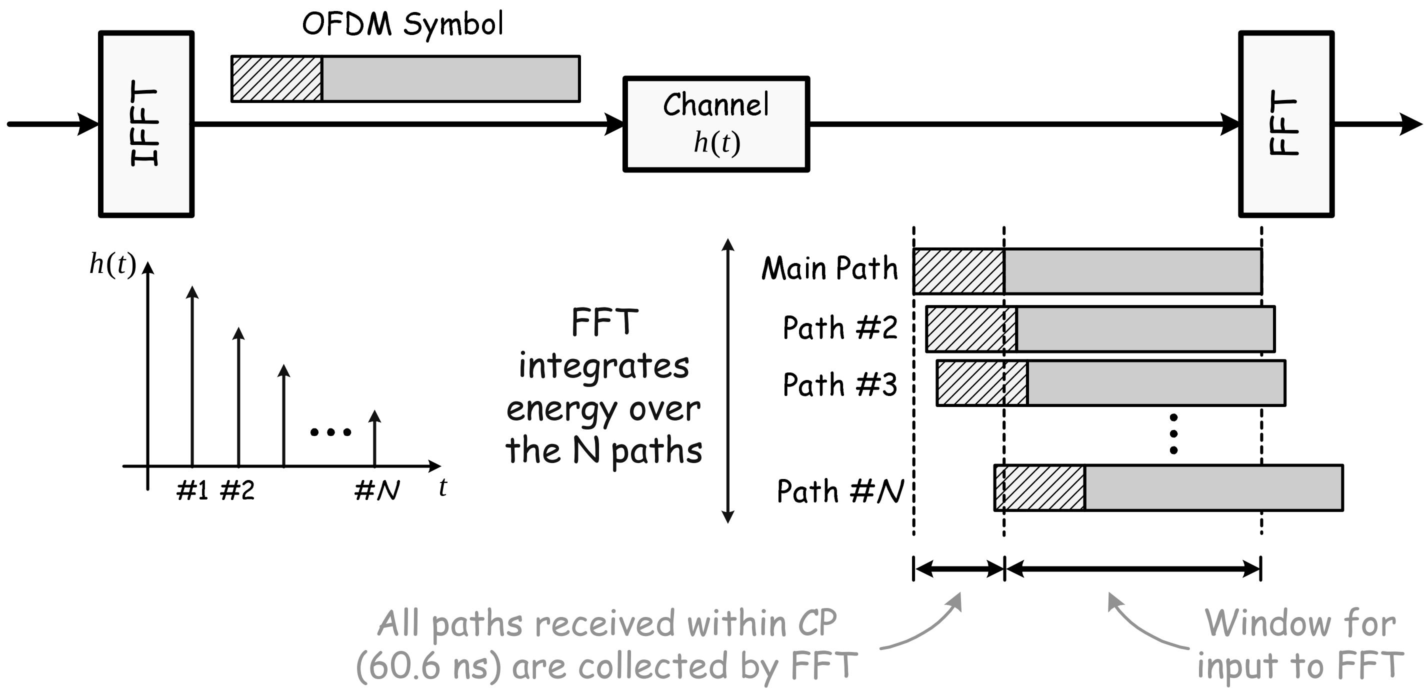
Strengths of OFDM (2)

- OFDM has excellent robustness in multi-path environments.
  1. Cyclic prefix preserves orthogonality between sub-carriers.



Strengths of OFDM (3)

- OFDM has excellent robustness in multi-path environments:
  2. Allows receiver to capture multi-path energy more efficiently.



Worldwide Compliance (1)

- Example: Ministry of Public Management, Home Affairs, Posts, and Telecommunications in Japan has set aside seven bands for radio-astronomy.
  1. 3260.0 – 3267.0 MHz (used for line spectral measurement)
  2. 3332.0 – 3339.0 MHz (same as above)
  3. 3345.8 – 3352.5 MHz (same as above)
  4. 4825.0 – 4835.0 MHz (same as above)
  5. 4950.0 – 4990.0 MHz
  6. 4990.0 – 5000.0 MHz
  7. 6650.0 – 6675.2 MHz

- The Ministry has taken measures to ensure that these services will be free of interference.

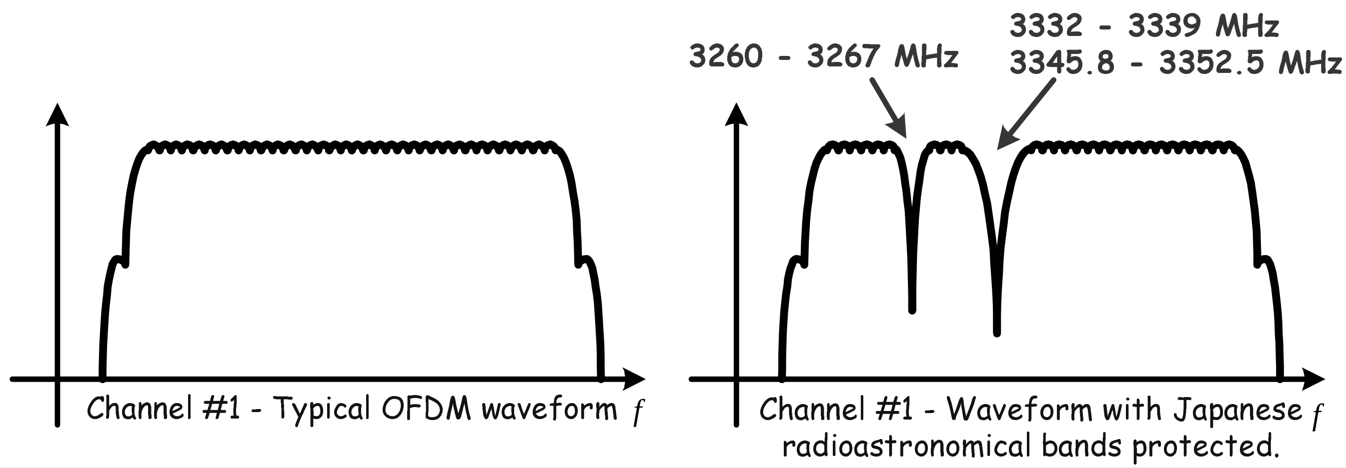
- With OFDM, these services can be protected by turning off the tones near these particular frequencies.

Worldwide Compliance (2)

- Example: consider a TFI-OFDM systems, which uses 3 channels.
  - Channel #1: 3168 – 3696 MHz.
  - Channel #2: 3696 – 4224 MHz.
  - Channel #3: 4224 – 4752 MHz.

- Only need to protect the first 3 radio astronomy bands. No modifications are required in order to protect the other 4 bands.

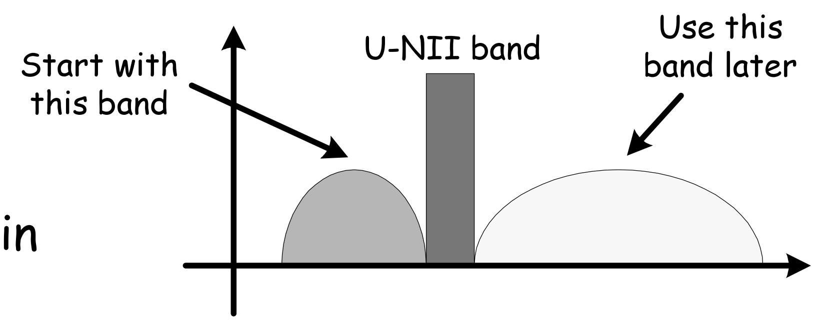
- Solution: Zero out tones near these frequencies to protect these 3 bands.



Optimal Operating Bandwidth (1)

- Only incremental gains (less than 1 dB) can be realized by using frequencies above 4.8 GHz.
- Start with the frequency band from 3.1 to 4.8 GHz:
  - Simplifies the front-end design: LNA and mixers (CMOS friendly).
  - Avoids the U-NII band entirely.

⇒ Quicker time to market!

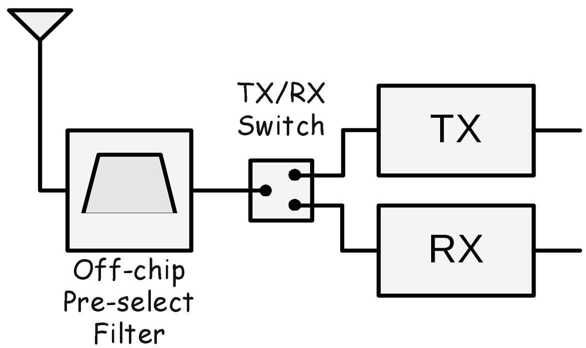


- As the RF technology improves, can start using the higher band in addition to the lower band.
- Using the upper band (adding more channels) will increase the multiple piconet performance

Optimal Operating Bandwidth (2)

- Another reason for avoiding frequencies higher than 4.8 GHz is to simplify the design of off-chip filters.
  - Avoid the U-NII band entirely.
  - Pre-select filter only needs to span the frequencies: 3.1 – 4.8 GHz.

- Block diagram of standard pre-select filter:

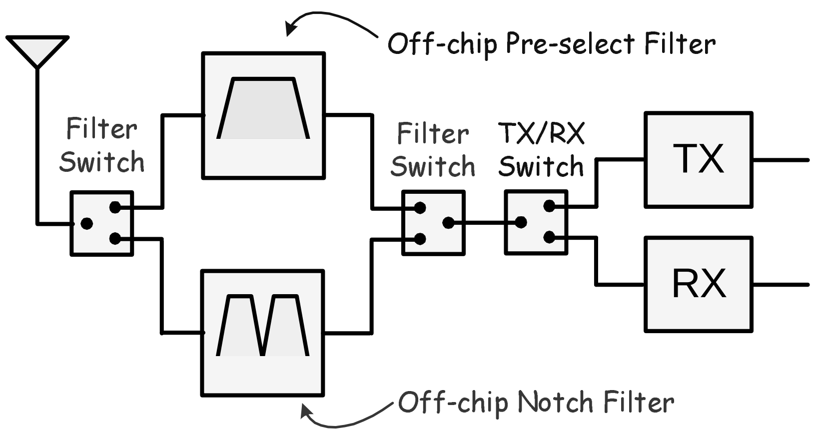


- Pre-select serves 4 purposes:
  - Selects the desired band.
  - Limits out of band noise.
  - Suppresses out-of-band interference (U-NII and ISM).
  - Relaxes the filtering requirements for the remainder of the analog chain (ex. channel select filter).

Optimal Operating Bandwidth (3)

- If the operating BW includes the U-NII band, then interference mitigation strategies have to be included in the receiver design to prevent analog front-end saturation.

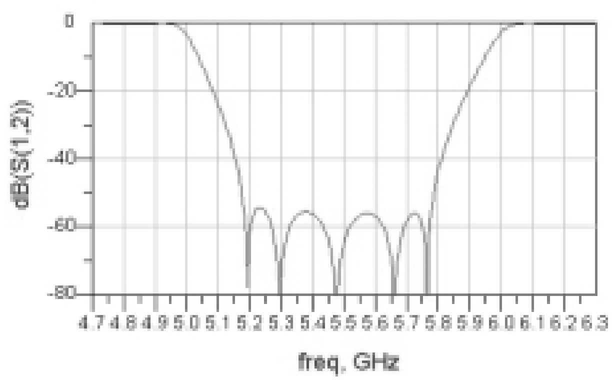
- Example: Switchable filter architecture.
  - When no U-NII interference is present, use standard pre-select filter.
  - When U-NII interference is present, pass the receive signal through a different filter (notch filter) that suppresses the entire U-NII band.

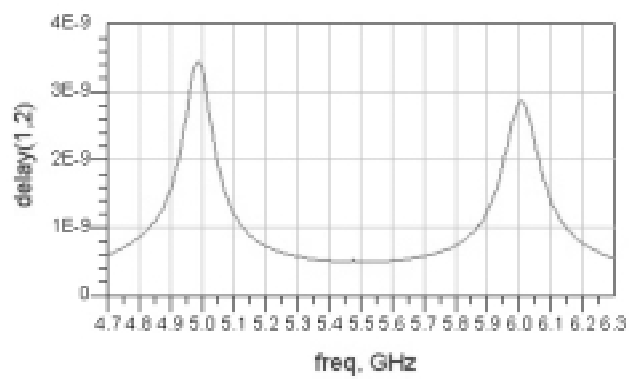


- Problems with this approach:
  - Extra switches ⇒ more insertion loss in RX/TX chain.
  - More external components ⇒ higher BOM cost.
  - More testing time.

Design of a Notch Filter

- Design of a "relatively" narrowband notch filter is a challenging problem:
  - Need greater than 30 dB of rejection (03/142) over the entire U-NII band to meet desired criteria.
  - Transition region is ~150 MHz on either side of the band.
  - Example filter design using ideal components (5th-order equal-ripple elliptic):





  - Problem: Frequencies between 5.05 – 5.95 GHz are no longer usable.
  - Problem: Significant group delay variations at the edge of the notch filter.

- May be possible to design 3 individual notch filters that remove just the Lower, Middle U-NII bands, the Upper U-NII band, and the Japanese U-NII band.

- Incorporating these off-chip filters into the design will require even more switches ⇒ even more insertion loss in the RX/TX chains.

Proposed System:

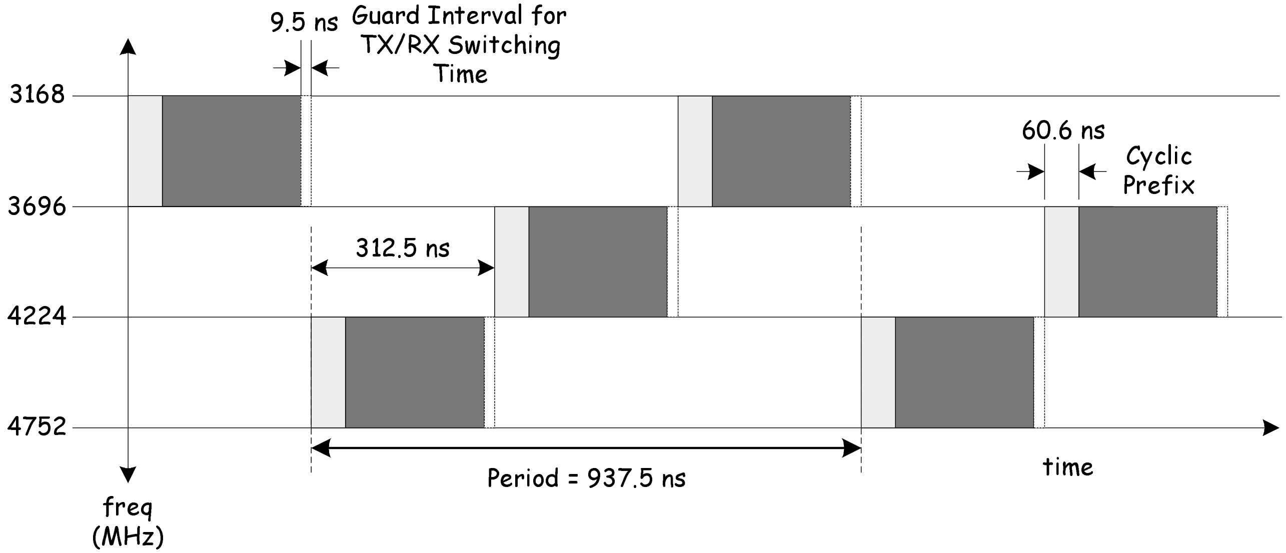
Time Frequency Interleaved OFDM

Time-Frequency Interleaved OFDM

- Basic idea: divide spectrum (3.1 – 4.8 GHz) into 3 sub-bands, where each band is 528 MHz wide.
- Information is transmitted using OFDM modulation on each band.
  - OFDM carriers are efficiently generated using an 128-point IFFT/FFT.
  - Internal precision is reduced by limiting constellation size to QPSK.
- Information bits are interleaved across all the three bands (3 OFDM symbols) to exploit frequency diversity and provide robustness against multi-path and interference.
- 60.6 ns cyclic prefix provides robustness against multi-path even in the worst channel environments.
- 9.5 ns guard interval provides sufficient time for switching between bands.

TFI-OFDM Physical Layer

- Interleave OFDM symbols across sub-bands.
- Transmitter and receiver process smaller bandwidth signals (528 MHz).
- Insert a guard interval between OFDM symbols in order to allow sufficient time to switch between channels.
- TFI-OFDM needs only a single TX/RX chain for all data rates and all channel environments.

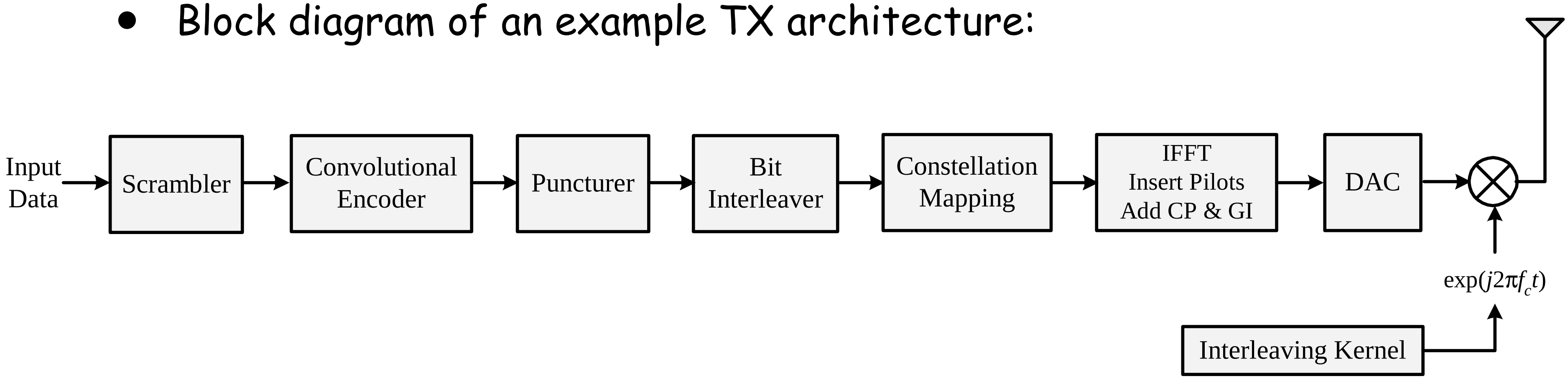


Details of the TFI-OFDM System

*More details about the TFI-OFDM system can be found in the latest version of 03/142.

TFI-OFDM: Example TX Architecture

- Block diagram of an example TX architecture:



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

- For a given superframe, the interleaving pattern is specified in the beacon by the PNC. The interleaving pattern is rotated across multiple superframes to mitigate multi-piconet interference.

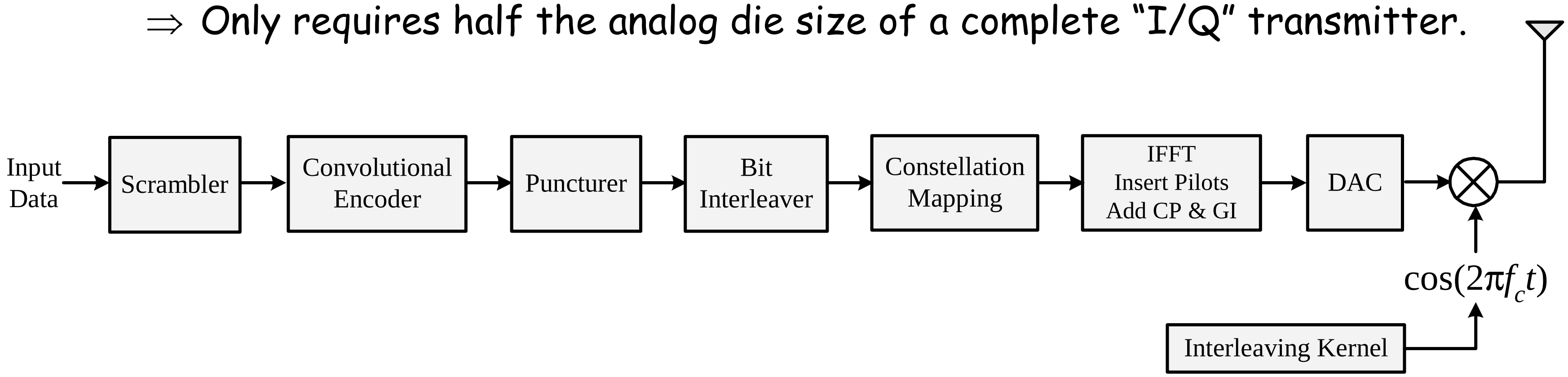
TFI-OFDM System Parameters

- System parameters for rates specifically mentioned in selection criteria document:

Info. Data Rate	110 Mbps	200 Mbps	480 Mbps
Modulation/Constellation	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK
FFT Size	128	128	128
Coding Rate (K=7)	R = 11/32	R = 5/8	R = 3/4
Spreading Rate	2	2	1
Information Tones	50	50	100
Data Tones	100	100	100
Info. Length	242.4 ns	242.4 ns	242.4 ns
Cyclic Prefix	60.6 ns	60.6 ns	60.6 ns
Guard Interval	9.5 ns	9.5 ns	9.5 ns
Symbol Length	312.5 ns	312.5 ns	312.5 ns
Channel Bit Rate	640 Mbps	640 Mbps	640 Mbps
Frequency Band	3168 – 4752 MHz	3168 – 4752 MHz	3168 – 4752 MHz
Multi-path Tolerance	60.6 ns	60.6 ns	60.6 ns

Simplified TX Analog Section

- For rates up to 200 Mb/s, the input to the IFFT is forced to be conjugate symmetric (for spreading gains ≥ 2).
  - ⇒ Output of the IFFT is REAL.
- The analog section of TX can be simplified when the input is real:
  - ⇒ Need to only implement the "I" portion of DAC and mixer.
  - ⇒ Only requires half the analog die size of a complete "I/Q" transmitter.



- For rates > 200 Mb/s, need to implement full "I/Q" transmitter.

More Details on the OFDM Parameters

- By using a contiguous set of orthogonal carriers, the transmit spectrum will always occupy a bandwidth greater than 500 MHz.
- Total of 128 tones:
  - 100 data tones used to transmit information (constellation: QPSK).
  - 12 pilot tones used for carrier and phase tracking.
  - 10 user-defined pilot tones.
  - Remaining 6 tones including DC are NULL tones.
- User-defined pilot tones:
  - Carry no useful information.
  - Energy is placed on these tones to ensure that the spectrum has a bandwidth greater than 500 MHz.
  - Can trade the amount of energy placed on tones for relaxing analog filtering specifications.
  - Ultimately, the amount of energy placed on these tones is left to the implementer. Provides a level of flexibility for the implementer.

Potential Coding Schemes

- Several different potential coding schemes:
  - Convolutional codes.
  - Block codes.
  - Concatenated codes – block codes plus convolutional codes.
  - Turbo codes.

- There are trade-offs in selecting any of these codes.

	Advantages	Disadvantages
Convolutional Code	Well understood.	Requires a Viterbi decoder.
Block Code	Well understood.	Requires a large interleaver (> 10 μs).
Concatenated Code	At very low BERs (< 10^{-9}), the required Eb/N0 is a lower than that of either convolutional or block codes.	Provides very minor coding gains at target BERs of 10^{-5}. Requires both a Viterbi decoder and a block decoder (larger complexity).
Turbo Code	Coding gains near the Shannon limit.	High computational complexity.

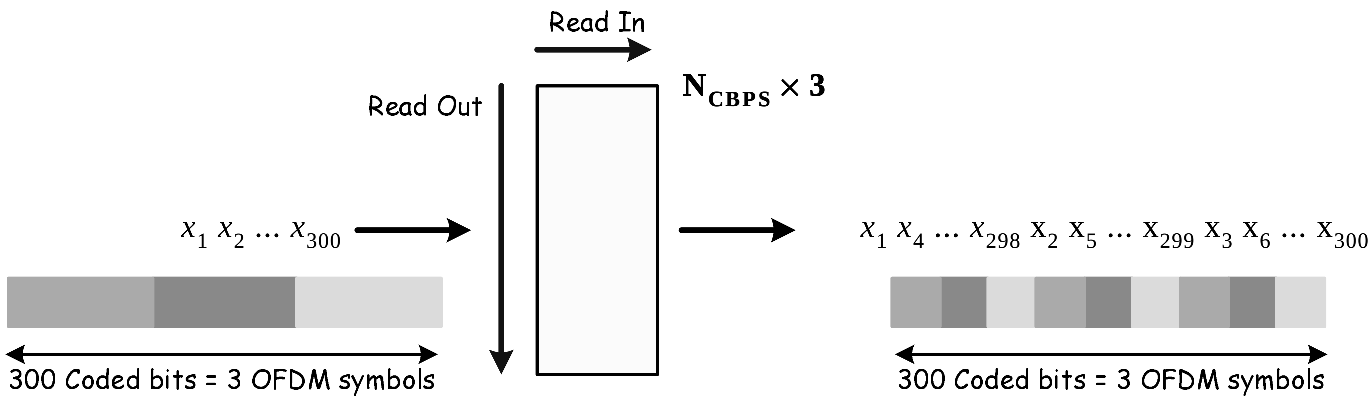
- The proposal uses convolutional codes, which provides the best trade-off in terms of performance and complexity for a target BER = 10^{-5}.

Bit Interleaver (1)

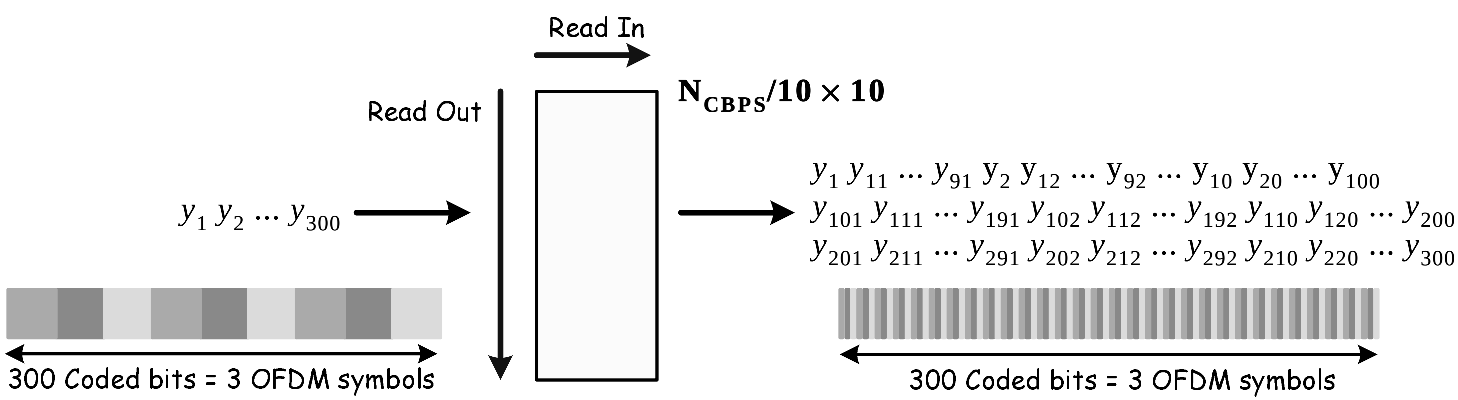
- Bit interleaving is performed across the bits within an OFDM symbol and across at most three OFDM symbols.
  - Exploits frequency diversity.
  - Randomizes any interference $\Rightarrow$ interference looks nearly white.
  - Latency is less than 1 μs.
- Bit interleaving is performed in three stages:
  - First, $3N_{CBPS}$ coded bits are grouped together.
  - Second, the coded bits are interleaved using a $N_{CBPS}\times 3$ block symbol interleaver.
  - Third, the output bits from 2nd stage are interleaved using a $(N_{CBPS}/10)\times 10$ block tone interleaver.
  - The end results is that the $3N_{CBPS}$ coded bits are interleaved across 3 symbols and within each symbol.
- If there are less than $3N_{CBPS}$ coded bits, which can happen at the end of the header or near the end of a packet, then the second stage of the interleaving process is skipped.

Bit Interleaver (2)

- Ex: Second stage (symbol interleaver) for a data rate of 110 Mbps



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



Channelization

- The relationship between f_c and channel number n_{ch} is

$$f_c(n_{ch}) = 2904 + 528 \times n_{ch} \quad \text{(MHz)}$$

- Initially, only the first 3 channels will be defined.

CHNL_ID (n_{ch})	Center Frequency (f_c)
1	3432 MHz
2	3960 MHz
3	4488 MHz

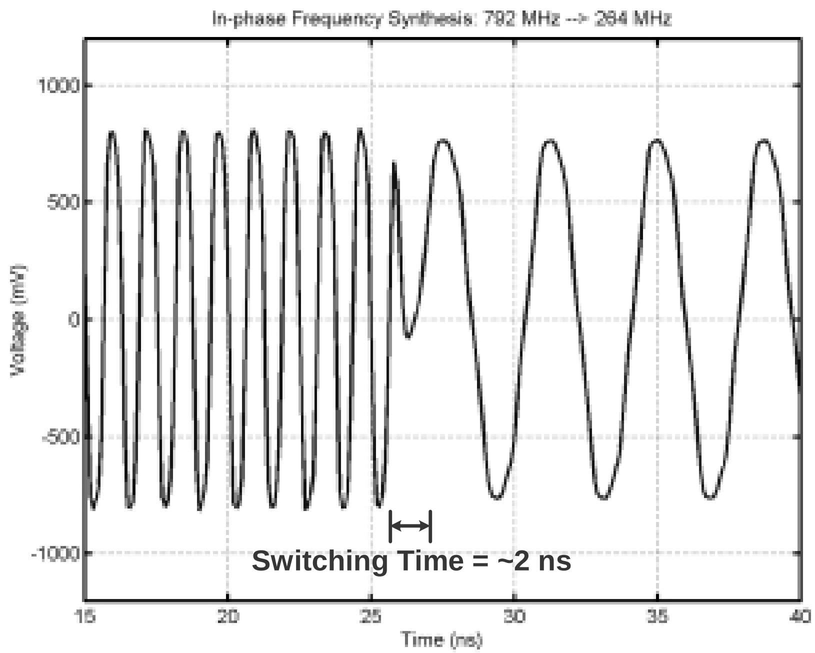
- More channels can be added as RF technology improves.

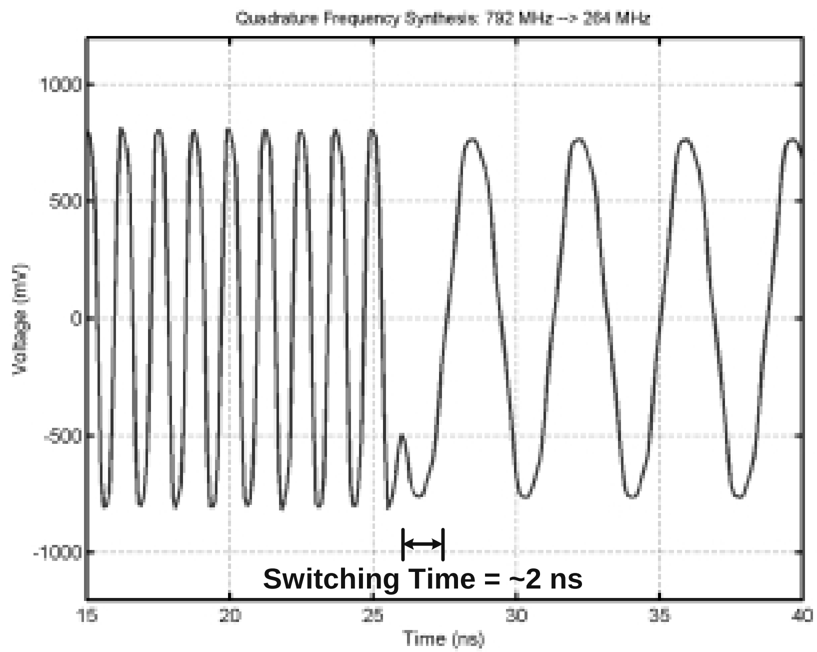
Frequency Synthesis (1)

- All three frequencies can be generated rapidly using the single-sideband (SSB) generation principle:
  - $\mathrm{Cos}(\omega_1 t) \times \mathrm{Cos}(\omega_2 t) - \mathrm{Sin}(\omega_1 t) \times \mathrm{Sin}(\omega_2 t) = \mathrm{Cos}[(\omega_1 + \omega_2)t]$
  - $\mathrm{Cos}(\omega_1 t) \times \mathrm{Sin}(\omega_2 t) + \mathrm{Sin}(\omega_1 t) \times \mathrm{Cos}(\omega_2 t) = \mathrm{Sin}[(\omega_1 + \omega_2)t]$
- Let the VCO center frequency = 4224 MHz
- Divide by 4 $\Rightarrow$ 1056 MHz and Divide by 16 $\Rightarrow$ 264 MHz
- Center frequencies for individual sub-bands:
  - Channel #1: 4224 – 1056 + 264 MHz = 3432 MHz.
  - Channel #2: 4224 – 264 MHz = 3960 MHz.
  - Channel #3: 4224 + 264 MHz = 4488 MHz.

Frequency Synthesis (2)

- Circuit-level simulation of frequency synthesis:

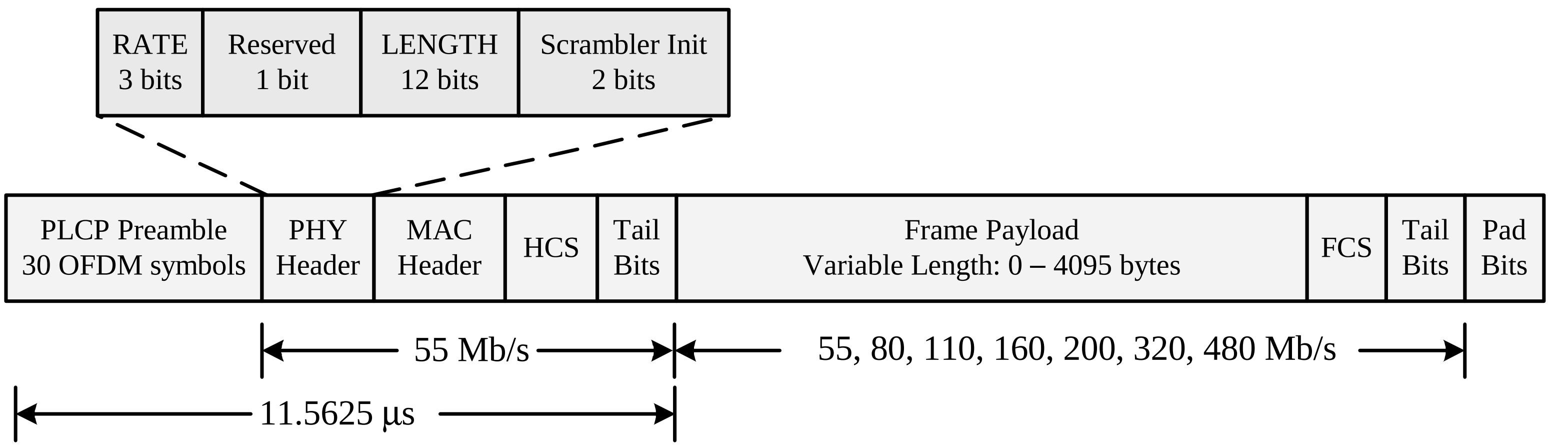




- Nominal switching time = ~2 ns.
- Need to use a slightly larger switching time to allow for process and temperature variations.

TFI-OFDM: PLCP Frame Format

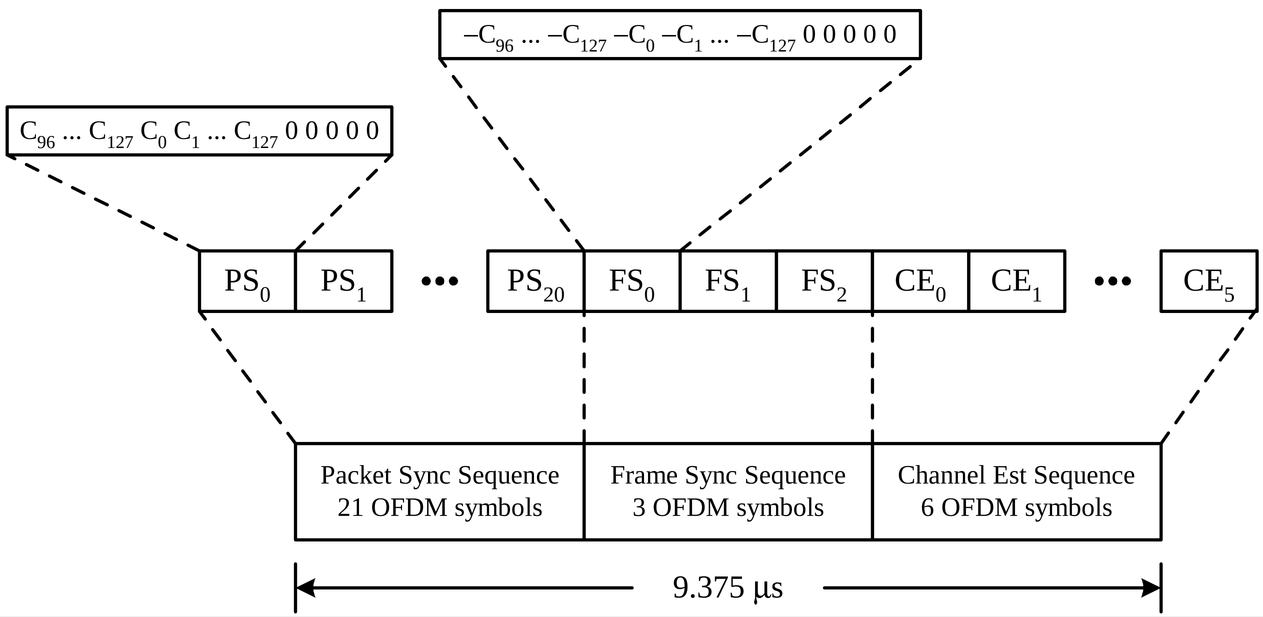
- PLCP frame format:



- Rates supported: 55, 80, 110, 160, 200, 320, 480 Mb/s. Support for 55, 110, and 200 Mb/s is mandatory.
- Preamble length = 9.38 µs. Burst preamble length = 4.69 µs.
- For the sake of robustness, the PLCP header, MAC header, HCS, and tail bits are always sent at the information data rate of 55 Mb/s.
- PLCP header + MAC header + HCS + tail bits = 2.19 µs.
- Maximum frame payload supported is 4095 bytes.

PLCP Preamble (1)

- Preamble is divided into 3 distinct and separate sections:
  - Packet synchronization sequence (21 symbols).
  - Frame synchronization sequence (3 symbols).
  - Channel estimation sequence (6 symbols).



PLCP Preamble (2)

- Packet synchronization sequence:
  - Time-domain sequence is a hierarchical sequence.
  - Correlators using these sequences can be implemented efficiently, i.e., with low power and low complexity.
  - Designed this portion of the preamble to be more robust than the header.
- Frame synchronization sequence:
  - This sequence is 180° out of phase with the packet sync sequence.
  - Provides a clean and detectable boundary between the two sequences.
- Channel estimation sequence:
  - Sequence is used for frequency-domain channel estimation.

Link Budget and Receiver Sensitivity

- Assumption: AWGN and 0 dBi gain at TX and 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
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

- The distance at which the TFI-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	11.5 m	10.9 m	11.6 m	11.0 m
200 Mbps	14.1m	6.9 m	6.3 m	6.8 m	5.0 m
480 Mbps	7.8 m	2.9 m	2.6 m	N/A	N/A

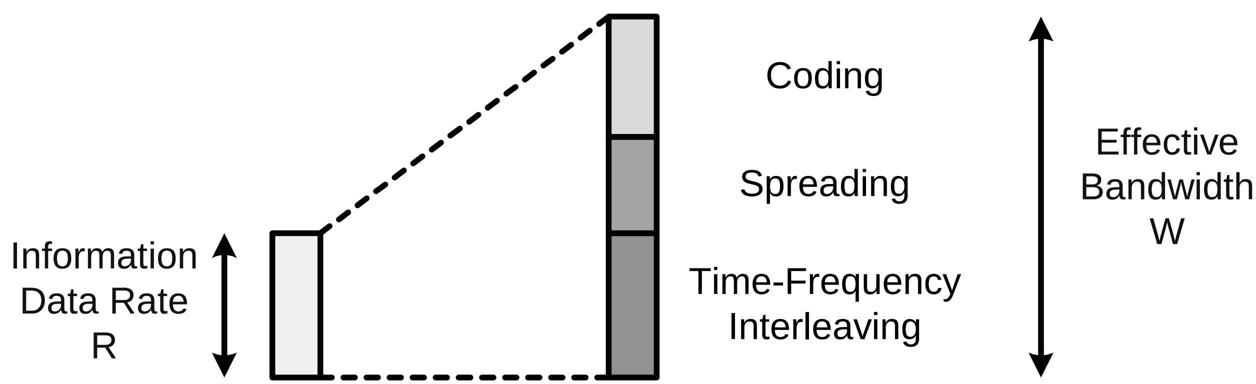
* Includes losses due to front-end filtering, clipping at the DAC, ADC degradation, multi-path degradation, channel estimation, carrier tracking, packet acquisition, etc.

** Results obtained using new channel model. *All results incorporate shadowing.*

Simultaneously Operating Piconets (1)

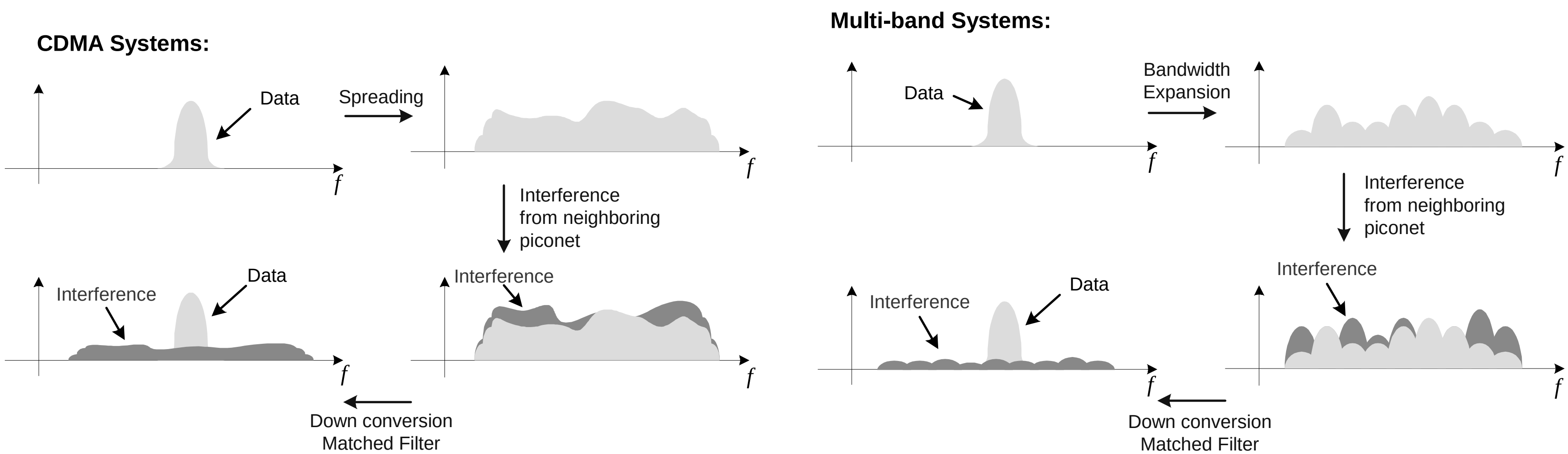
- Bandwidth expansion refers to using a signaling bandwidth that is much larger than the information data rate.

- Bandwidth expansion can be achieved using any of the following techniques or combination of techniques:
  - Spreading, Time-frequency interleaving, Coding
  - Ex: TFI-OFDM obtains its BW expansion by using all three techniques.



Simultaneously Operating Piconets (2)

- However, multi-path and asynchronicity between piconets ensures that spreading sequences and TF codes will never be truly orthogonal.
  - $\Rightarrow$ Can never have perfect isolation between piconets.



- Multiple piconet performance is governed by SIR = (P_{sig}/P_{int}) (W/R). Note that SIR is directly related to bandwidth expansion (W/R).
- In realistic multi-path, real-world conditions: "BW expansion is all that matters".
  - $\Rightarrow$ Systems with same BW expansion have similar multiple piconet capability.

Simultaneously Operating Piconets (3)

- Assumptions:
  - As specified in 03/031r9, d_{ref} = 10.0 meters for all tests.

- Single piconet (N= 1) interferer separation distance as a function of the reference and interfering multipath channel environments:

Test Link \ Interferer Link	CM1	CM2	CM3	CM4
CM1 (d_{int}/d_{ref})	10.5 m (1.05)	9.5 m (0.95)	10.9 m (1.09)	10.4 m (1.04)
CM2 (d_{int}/d_{ref})	9.8 m (0.98)	8.9 m (0.89)	10.3 m (1.03)	9.7 m (0.97)
CM3 (d_{int}/d_{ref})	9.8 m (0.98)	9.1 m (0.91)	10.3 m (1.03)	9.8 m (0.98)

  - Results for N = 2 and N = 3 interferers as well as FDMA can be found in 03/142r2.

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.

Interferer	Value
IEEE 802.11b @ 2.4 GHz	$d_{int} \leq$ 0.2 meter
IEEE 802.11a @ 5.3 GHz	$d_{int} \leq$ 0.2 meter
Modulated interferer	SIR ≥ -3.6 dB
Tone interferer	SIR ≥ -5.6 dB

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

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	85.1 Mb/s	130.4 Mb/s	211.4 Mb/s
5	95.2 Mb/s	155.6 Mb/s	286.4 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	102.3 Mb/s	175.9 Mb/s	362.4 Mb/s
5	105.7 Mb/s	186.3 Mb/s	409.2 Mb/s

Complexity (1)

- 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:

	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.

- Power consumption (analog plus digital):

	TX @ 110 Mb/s	RX @ 110 Mb/s	TX @ 200 Mb/s	RX @ 200 Mb/s	Deep Sleep
90 nm	93 mW	155 mW	93 mW	169 mW	15 μW
130 nm	117 mW	205 mW	117 mW	227 mW	18 μW

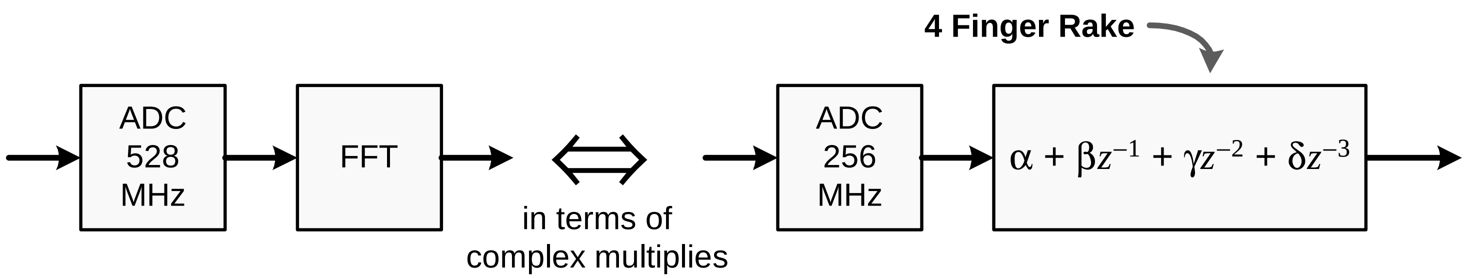
Complexity (2)

- Manufacturability:
  - Leveraging standard CMOS technology results in a straightforward development effort.
  - OFDM solutions are mature and have been demonstrated in ADSL and 802.11a/g solutions.
- Time to market: the earliest complete CMOS PHY solutions would be ready for integration is 2005.
- Size: Solutions for PC card, compact flash, memory stick, SD memory in 2005.

FFT/IFFT Complexity

- Number of complex multipliers and complex adders needed per clock cycle for a 128 point FFT.

Clock	Complex Multipliers / clock cycle	Complex Adders / clock cycle
102.4 MHz	10	28
128 MHz	8	22.4



$\Rightarrow$ OFDM efficiently captures multi-path energy with lower complexity!

- 128-point FFT is realizable in current CMOS technology.
  - A technical contribution (03/213) by Roger Bertschmann (SiWorks, Inc.) shows that they have a 128-point IFFT/FFT core which can be used in a TFI-OFDM system.
  - The synthesized core has a gate count of approximately 70K gates in a 130 nm TSMC process.

Comparison of OFDM Technologies

- Qualitative comparison between TFI-OFDM and IEEE 802.11a OFDM:

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

1. Assumes a 256-point FFT for IEEE 802.11a.
2. Assumes a 128-point FFT for IEEE 802.11a.

TFI-OFDM Advantages (1)

- Suitable for CMOS implementation (all components).
- Only one transmit and one receive chain at all times, even in the presence of multi-path.
- Antenna and pre-select filter are easier to design (can possibly use off-the-shelf components).

$\Rightarrow$ Early time to market!

- Low cost, low power, and CMOS integrated solution leads to:

$\Rightarrow$ Early market adoption!

TFI-OFDM Advantages (2)

- Inherent robustness in all the expected multipath environments.
- Excellent robustness to ISM, U-NII, and other generic narrowband interference.
- Ability to comply with world-wide regulations:
  - Channels and tones can be dynamically turned on/off to comply with changing regulations.
- Coexistence with current and future systems:
  - Channels and tones can be dynamically turned on/off for enhanced coexistence with the other devices.
- Scalability:
  - More channels can be added as the RF technology improves.
  - Digital section complexity/power scales with improvements in technology nodes (Moore's Law).
  - Analog section complexity/power scales poorly with technology node.

Summary

- The proposed system is specifically designed to be a *low power, low complexity all CMOS solution*.
- Expected range for 110 Mb/s: 20.5 meters in AWGN, and greater than 11 meters in multipath environments.
- Expected power consumption for 110 Mb/s:
  - 90 nm process: 93 mW (TX), 155 mW (RX), 15 μW (deep sleep).
  - 130 nm process: 117 mW (TX), 205 mW (RX), 18 μW (deep sleep).
- TFI-OFDM is coexistence friendly and complies with world-wide regulations.
- PHY solution are expected to be ready for integration in 2005.
- TFI-OFDM offers the best trade-off between the various system parameters.

Backup slides

Self-evaluation Matrix (1)

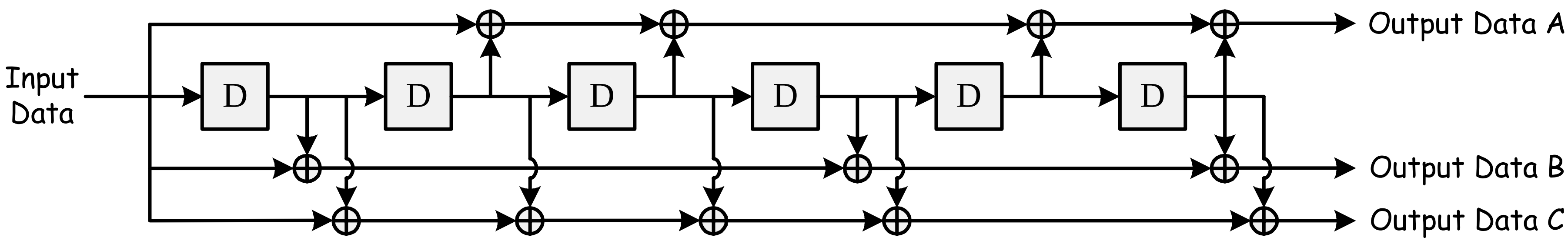
	REF.	*IMPORTANCE LEVEL*	*PROPOSER RESPONSE*
Unit Manufacturing Complexity (UMC)	3.1	B	+
Signal Robustness			
Interference And Susceptibility	3.2.2	A	+
Coexistence	3.2.3	A	+
Technical Feasibility			
Manufacturability	3.3.1	A	+
Time To Market	3.3.2	A	+
Regulatory Impact	3.3.3	A	+
Scalability (i.e. Payload Bit Rate/Data Throughput, Channelization – physical or coded, Complexity, Range, Frequencies of Operation, Bandwidth of Operation, Power Consumption)	3.4	A	+
Location Awareness	3.5	C	0
CRITERIA	*REF.*	*IMPORTANCE LEVEL*	*PROPOSER RESPONSE*
MAC Enhancements And Modifications	4.1.	C	+

Self-evaluation Matrix (2)

CRITERIA	*REF.*	*IMPORTANCE LEVEL*	*PROPOSER RESPONSE*
Size And Form Factor	5.1	B	+
PHY-SAP Payload Bit Rate & Data Throughput			
Payload Bit Rate	5.2.1	A	+
Packet Overhead	5.2.2	A	+
PHY-SAP Throughput	5.2.3	A	+
Simultaneously Operating Piconets	5.3	A	+
Signal Acquisition	5.4	A	+
System Performance	5.5	A	+
Link Budget	5.6	A	+
Sensitivity	5.7	A	+
Power Management Modes	5.8	B	+
Power Consumption	5.9	A	+
Antenna Practicality	5.10	B	+

Convolutional Encoder

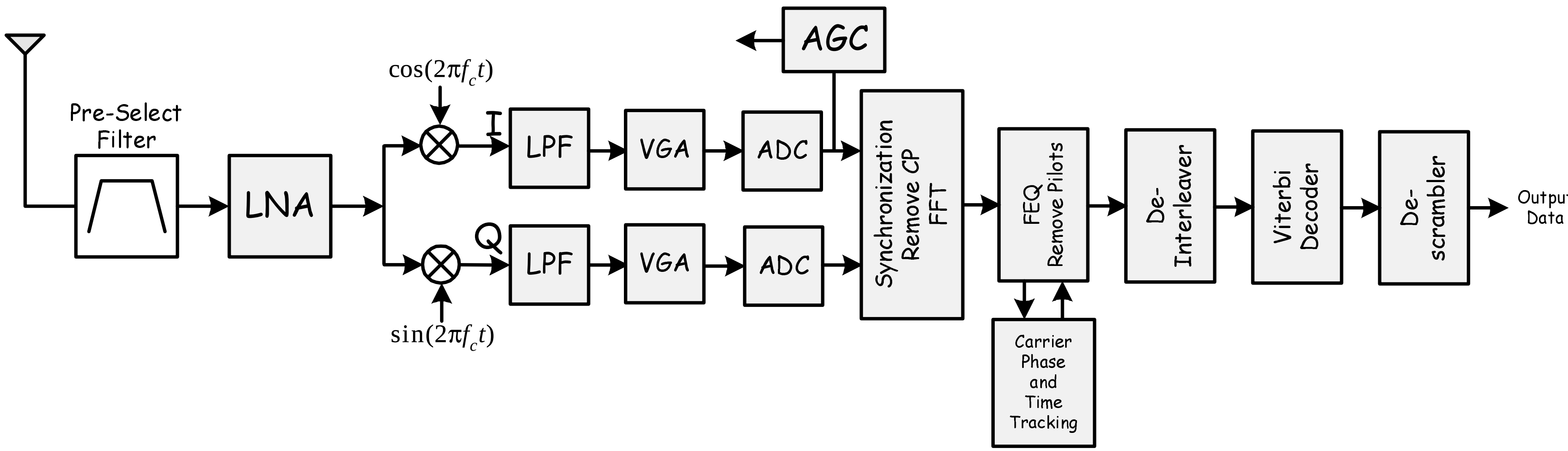
- Assume a mother convolutional code of R = 1/3, K = 7. Having a single mother code simplifies the implementation.
- Generator polynomial: g_0 = [133_8], g_1 = [145_8], g_2 = [175_8].



- Higher rate codes are achieved by puncturing the mother code. Puncturing patterns are specified in latest revision of 03/142.

TFI-OFDM: Example RX Architecture

- Block diagram of an example RX architecture:



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

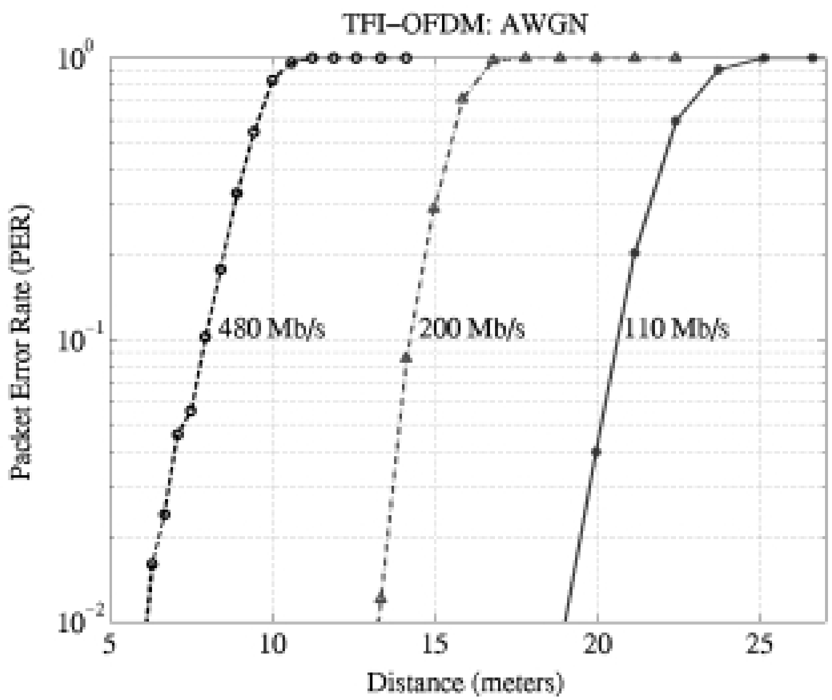
Simulation Parameters

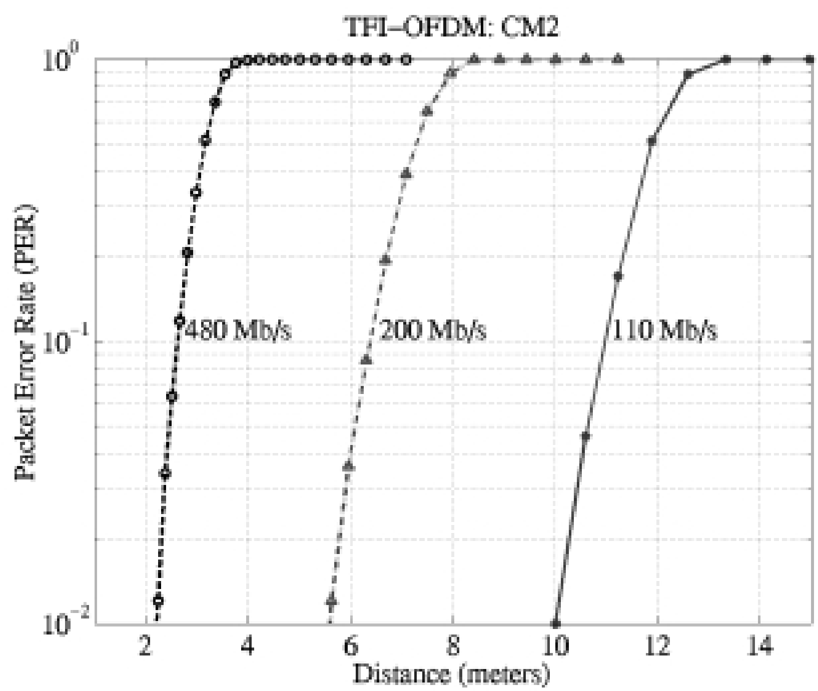
- Assumptions:
  - System as defined in 03/142.
  - Clipping at the DAC (PAR = 9 dB).
  - Finite precision ADC (4 bits @ 110/200 Mbps).

- Degradations incorporated:
  - Front-end filtering.
  - Multi-path degradation.
  - Clipping at the DAC.
  - Finite precision ADC.
  - Crystal frequency mismatch (±20 ppm @ TX, ±20 ppm @ RX).
  - Channel estimation.
  - Carrier offset recovery.
  - Carrier tracking.
  - Packet acquisition.

System Performance (1)

- PER as a function of distance and information data rate in an AWGN and CM2 environment* (90% link success probability).

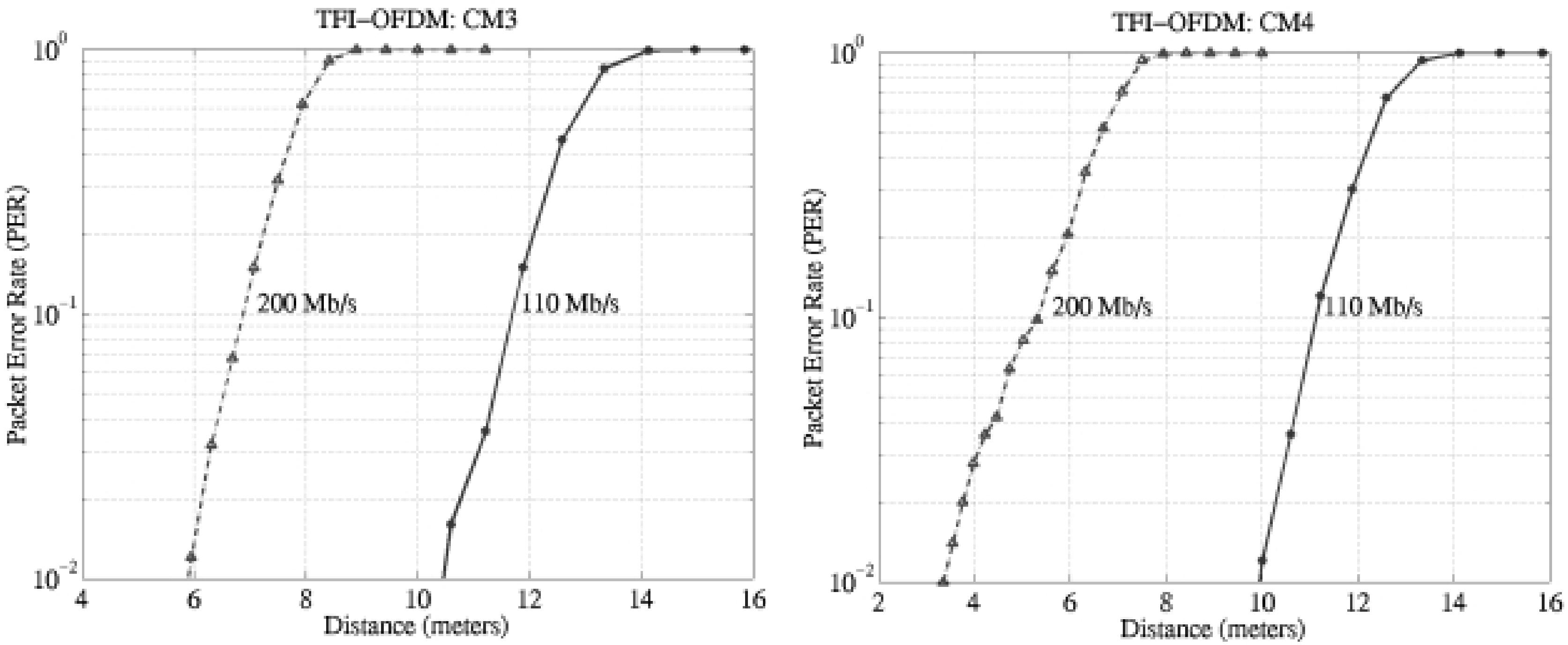




* Results obtained using new channel model. *All results incorporate shadowing.*

System Performance (2)

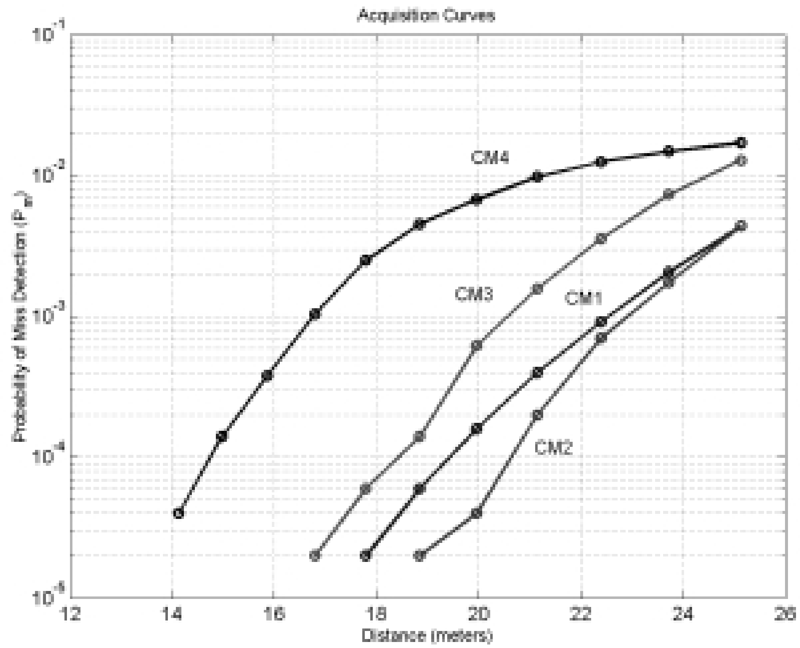
- PER as a function of distance and information data rate in an CM3 and CM4 environment* (90% link success probability).



* Results obtained using new channel model. *All results incorporate shadowing.*

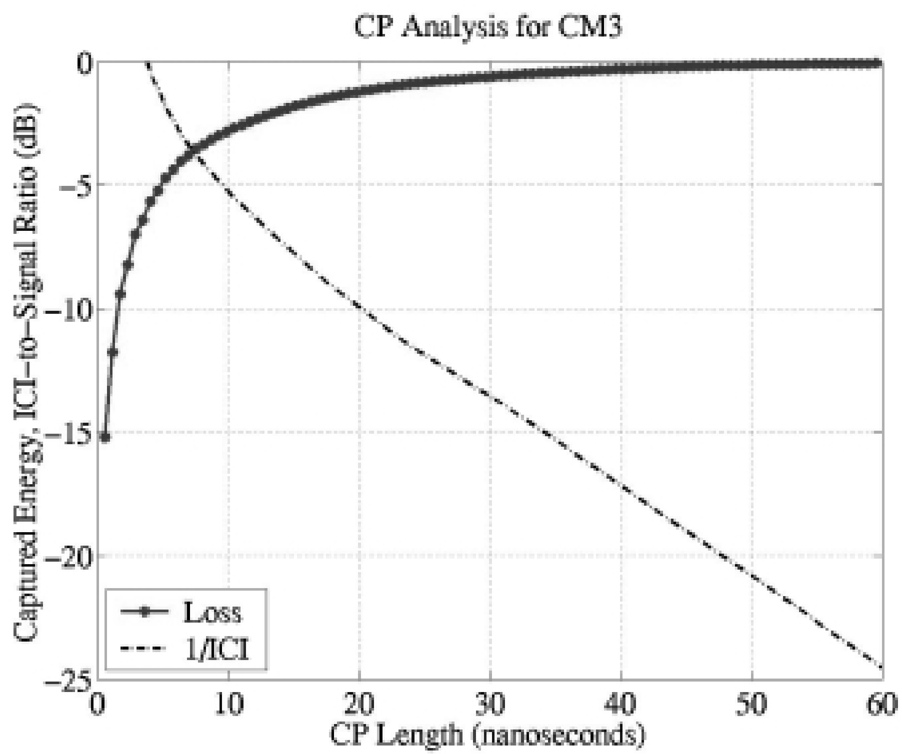
Signal Acquisition

- Preamble was designed to be robust and work at 3 dB below sensitivity for 55 Mbps.
- Prob. of false detect (P_f) = 6.2 x 10^{-4}.
- The results for prob. of miss detect (P_m) vs. distance @ 110 Mb/s was averaged over 500 noise realization for 100 channels in each channel environment:
- The start of a valid OFDM transmission at a receiver sensitivity level ≥ -83.5 dBm shall cause CCA to indicate busy with a probability > 90% in 4.69 μs.



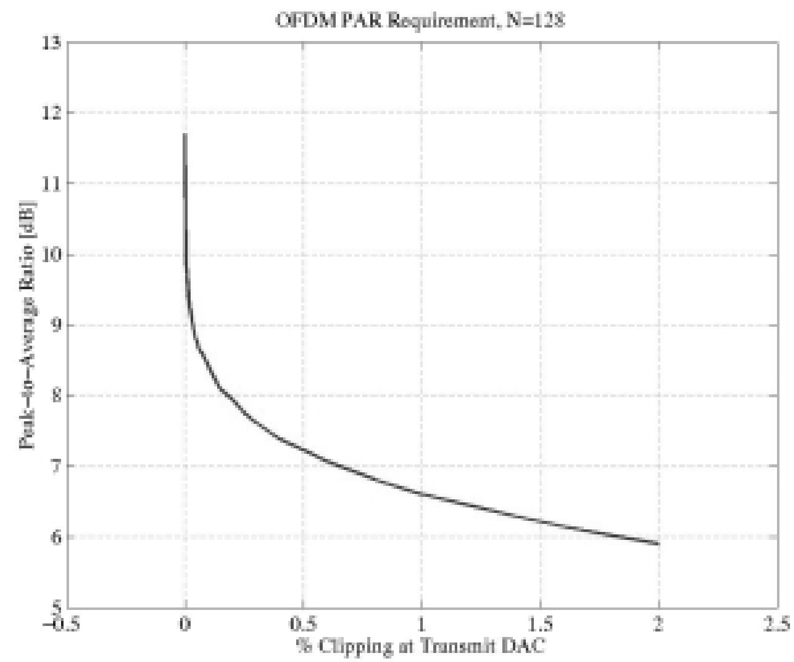
Is Cyclic Prefix (CP) Sufficient?

- For a data rate of 110 Mb/s, studied effect of CP length on performance.
- Curves were averaged over 100 realizations of CM3.
- For a CP length of 60 ns, the average loss in collected multi-path energy is approx. 0.1 dB.
- Inter-carrier interference (ICI) due to multi-path outside the CP is approximately 24 dB below the signal.



Peak-to-Average Ratio (PAR) for TFI-OFDM

- Average TX Power = –9.5 dBm (this value includes pilot tones)
- PAR of 9 dB results in:
  - Impact of clipping at TX DAC is negligible.
  - Results in a performance loss of less than 0.1 dB in AWGN.
  - Results in a performance loss of less than 0.1 dB in all multipath environments.
- Peak TX power ≤ 0 dBm.
- Implication: TX can be built completely in CMOS.



MAC Enhancements

- Add a time-frequency interleaving information element (TFI IE) to the beacon:
  - TFI IE contains parameters for synchronizing DEVs using TFI-OFDM PHY.
  - IE payload contains Interleaving Sequence (IS) and Rotation Sequence (RS) parameters.

Octets: 1	1	1	1
Element ID	Length	Interleaving Sequence	Rotation Sequence

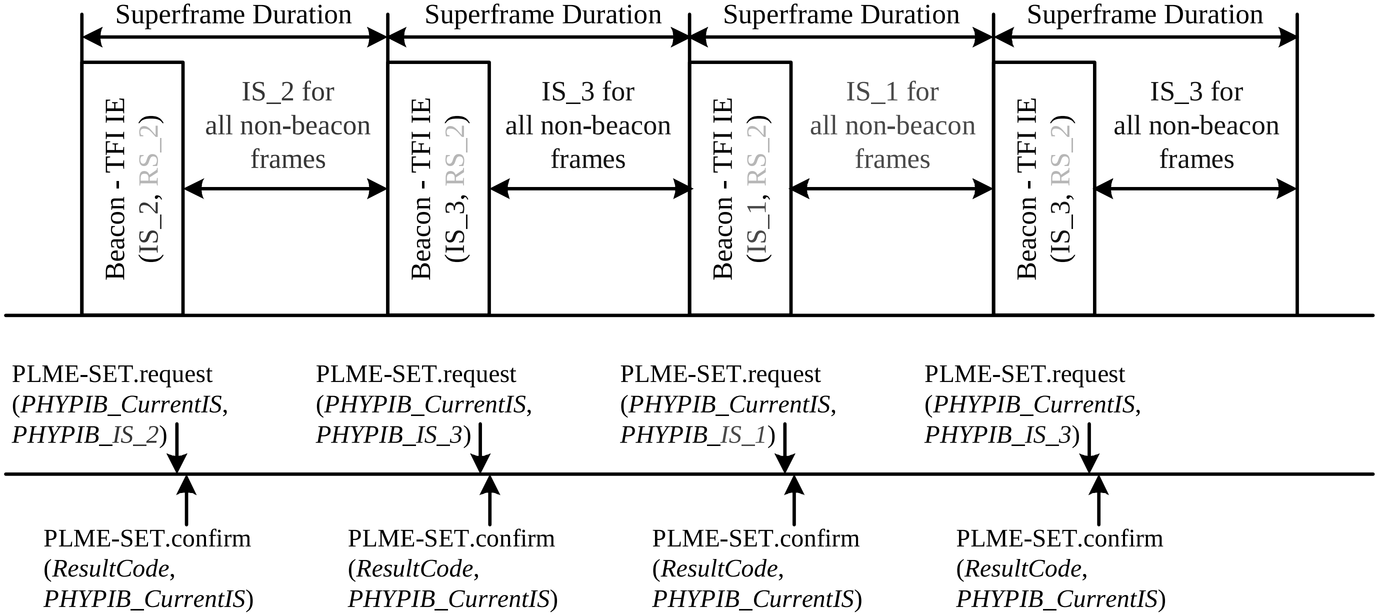
  - IS field specifies the current pattern for interleaving over the channels.
  - RS field specifies the current rotation pattern for the interleaving sequences.

- PNC updates the IS parameter in the beacon for each superframe according to the RS parameter.
  - DEVs that miss the beacon can determine the IS based on the definition of the RS in the last beacon received.

- PNC may change the RS parameter by applying the piconet parameter change procedure specified in the IEEE 802.15.3 draft standard.
  - Reuse “New Channel Index” as “New Channel Index/RS Number”.

MAC Controlled Rules for Interleaving

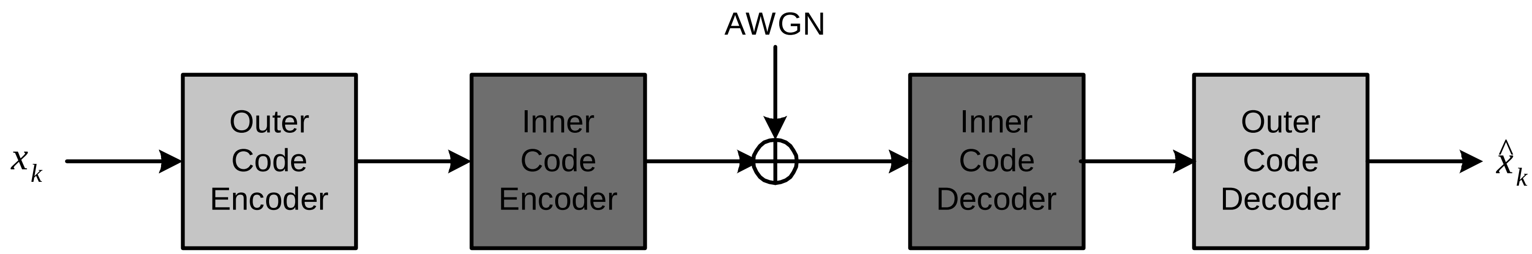
- Piconet #1:
  - Ex: RS_2 = {IS_2, IS_3, IS_1, IS_3, IS_2, IS_1, Repeat}
  - Ex: IS_1 = {Chan_2, Chan_1, Chan_3, Chan_1, Chan_2, Chan_3, Repeat}



- Piconet #2:
  - Ex: RS_2 = {IS_1, IS_3, IS_2, IS_1, IS_2, IS_3, Repeat}

Coding Gains for Concatenated Codes (1)

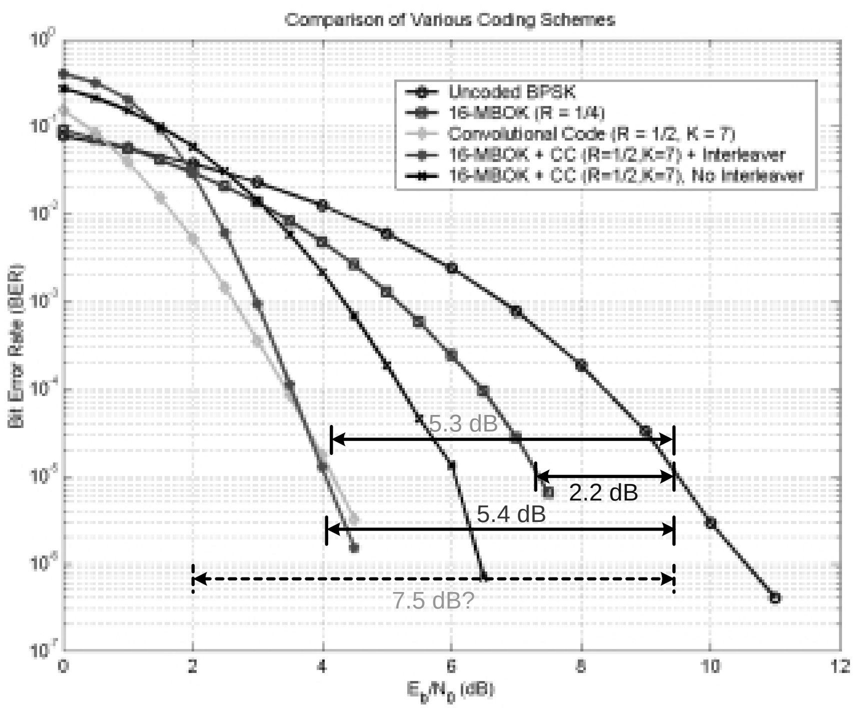
- Consider a system that uses both an inner and an outer code.
- Example:
  - Outer code: R = ½, K = 7 Convolutional Code (coding gain = G_{outer})
  - Inner code: 16-BOK based on Walsh functions (coding gain = G_{inner})



- Let $G_{overall}$ = coding gain of overall system.
- Does $G_{overall} = G_{inner} + G_{outer}$ at a given BER? Short answer is NO.
- See example on next slide.

Coding Gains for Concatenated Codes (2)

- Simulated the coding gains for 16-BOK, Convolutional Code, 16-BOK + Convolutional Code with and without an interleaver.
- Assumption: Coding gain is measured at a BER = 10^{-5}.
- Assumption: Independent decoders for both the inner and outer codes.
- Gains: G_{inner} = 2.2 dB, G_{outer} = 5.3 dB.
- Common mistake is to expect an overall coding gain of 7.5 dB.
- In reality, $G_{overall}$ = 5.4 dB when there is an interleaver present between the two codes.



Simultaneously Operating Piconets

- 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.

$\Rightarrow$ Systems that have the same BEF have similar multiple piconet capability.

Mailing Address:

Texas Instruments
Post Office Box 655303
Dallas, Texas 75265