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

Submission Title: [XtremeSpectrum CFP Presentation]
Date Submitted: [July 2003]
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Re: [Response to Call for Proposals, document 02/372r8]

Abstract: []

Purpose: [Summary Presentation of the XtremeSpectrum proposal. Details are presented in document 03/154 along with proposed draft text for the standard.]

Certification Rules For UWB Frequency Hoppers Is Very Significant To This Committee

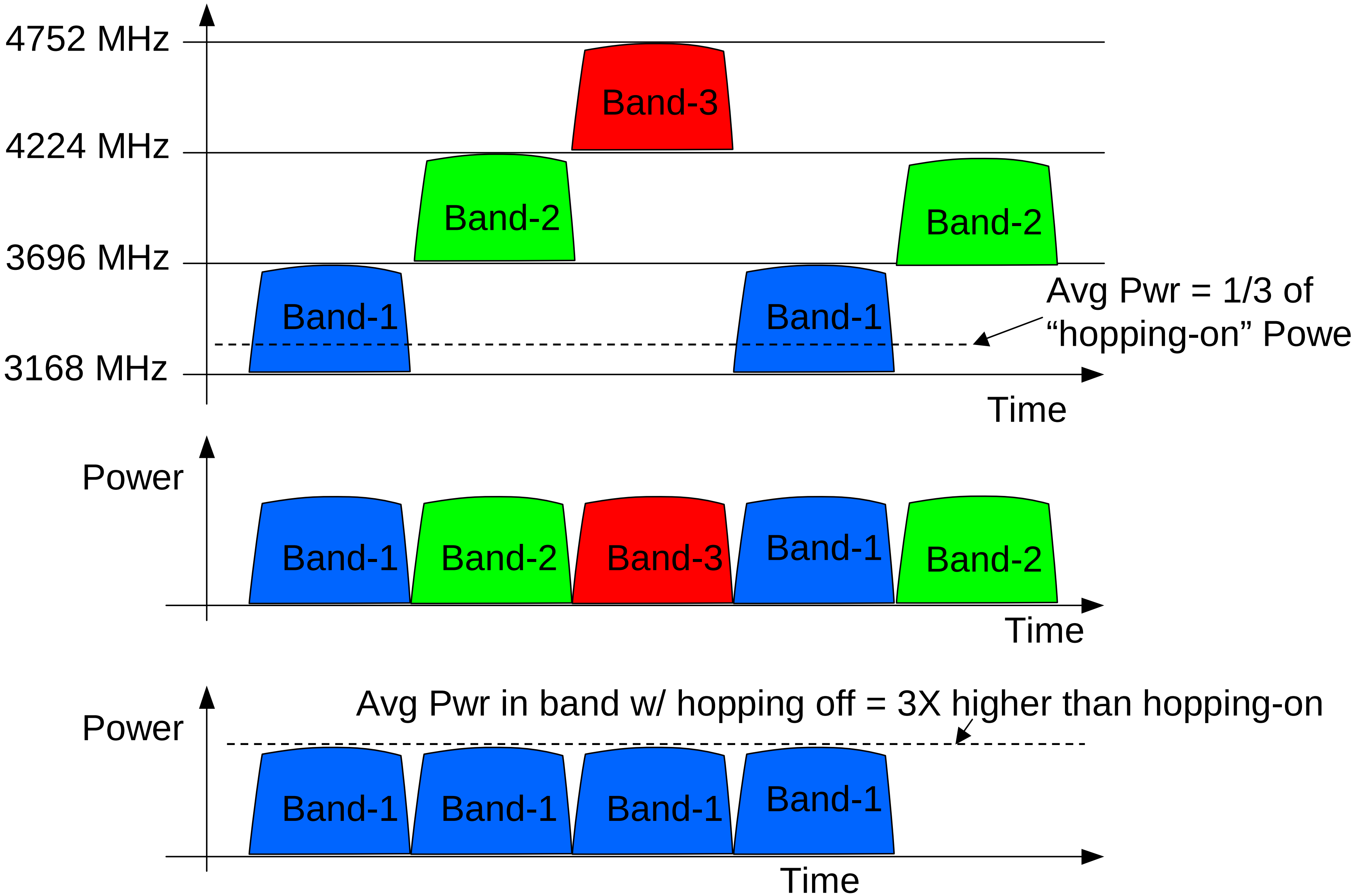
- Summary of FCC's Part 15 rules on UWB
  - A UWB frequency hopper must be tested for compliance with the ***hopping turned off*** and the signal "parked" or held stationary at one band of frequencies. (First R&O at para. 32.)
  - The bandwidth must be at least 500 MHz with the hopping turned off.
  - The device must comply with all emissions limits with the hopping turned off.
- Therefore
  - A hopper is NOT allowed to put as much energy as a non-hopper (both covering the same total range of frequencies)
  - The maximum permitted power is reduced in proportion to the number of hops
- ***Therefore the performance of FH systems is seriously degraded.***
  - N=number of hops
  - Range is reduced by $1/\sqrt{N}$ assuming $1/R^2$ propagation
  - Data-rate is reduced by 1/N assuming all else is equal.
  - Example - 10 m range is reduced to 5.8 m range using three hops
- ***None of the submissions proposing Multiband OFDM have factored this reduction into their performance analysis.***

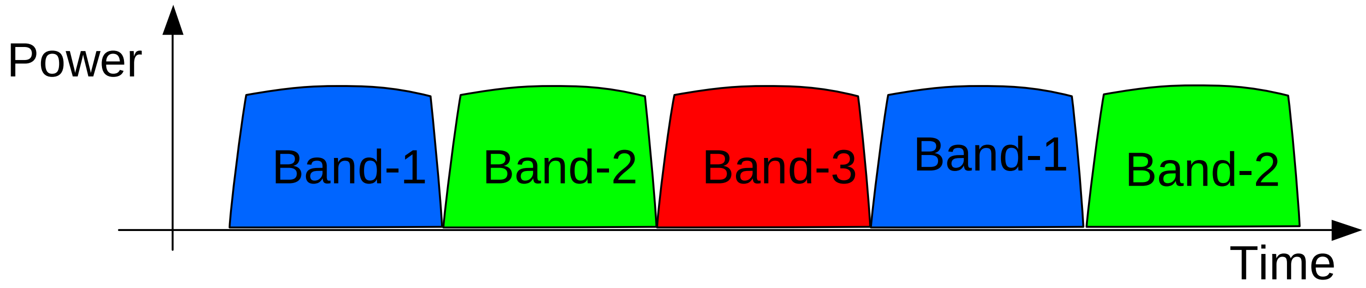
Frequency Hoppers *and* FCC UWB Rules

- The issue today is NOT whether or not there is more or less interference
- The issue is, ***what are the rules***.
  - Side interest is WHY did NTIA and FCC specifically write rules for frequency hoppers
- The next issues regard changing the rules
  - What is the process for the rules to be changed
  - How long would this process typically take

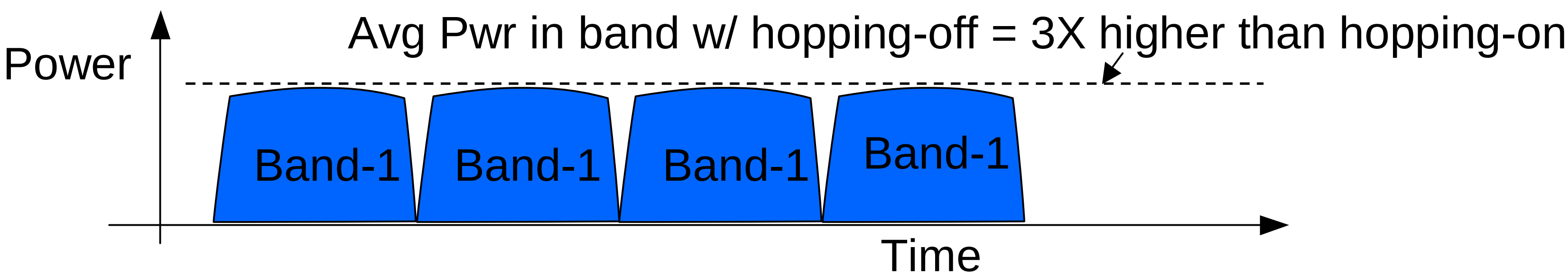
What do FCC documents say about ***why*** FH systems are have specifically different rules?

- The WB R&O states “The current measurement procedures require that measurements of swept frequency devices be made with the frequency sweep stopped. The sweep is stopped because no measurement procedures have been proposed or established for swept frequency devices nor has the interference aspects of swept frequency devices been evaluated …. Similarly, measurements on a stepped frequency or frequency hopping modulated system are performed with the stepping sequence or frequency hop stopped.
See 47 C.F.R. §15.31(c).

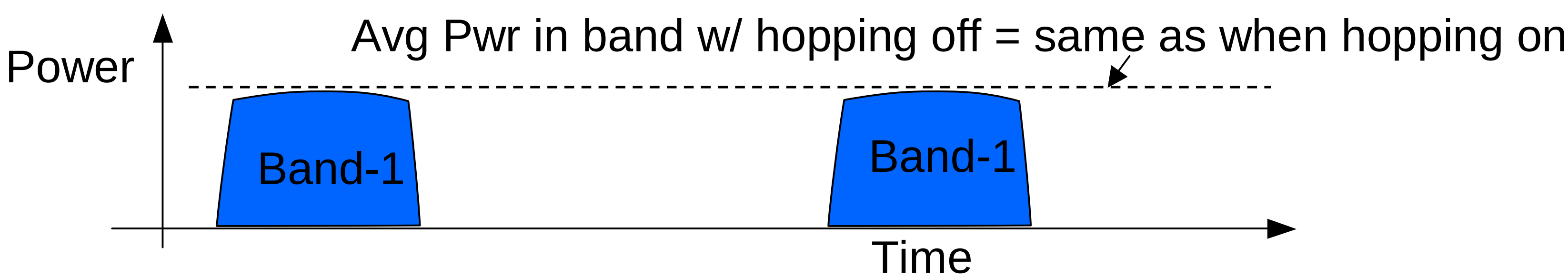

4752 MHz
4224 MHz
3696 MHz
3168 MHz
Band-3
Band-2
Band-2
Band-1
Band-1
Avg Pwr = 1/3 of
“hopping-on” Power
Time
Power
Band-1
Band-2
Band-3
Band-1
Band-2
Time
Power
Avg Pwr in band w/ hopping off = 3X higher than hopping-on
Band-1
Band-1
Band-1
Band-1
Time



Which way should this be measured if the requirement is to have “hopping stopped”? Is it (A) this way:



Or is it (B) this way:



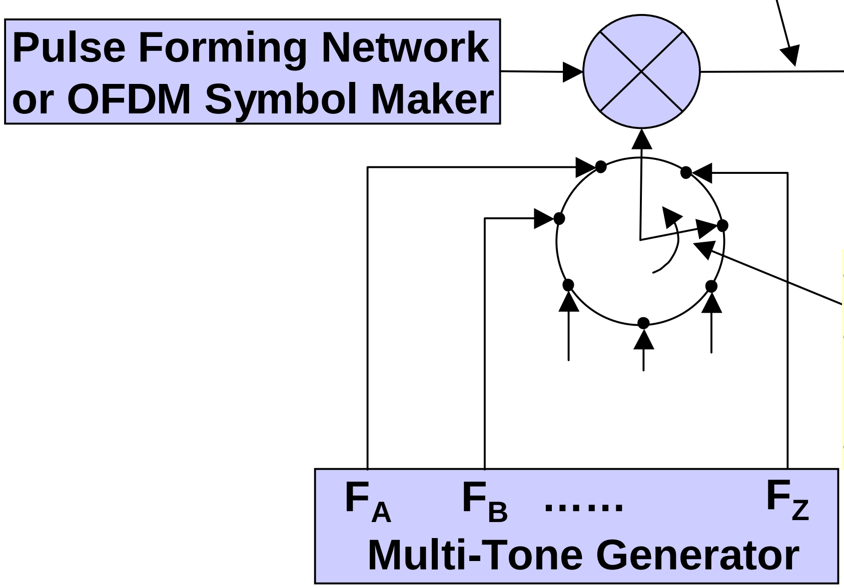
- UWB is a highly unusual regulation as it allows devices to radiate in bands specifically allocated to other services
- As a result, the proceeding was one of the most contentions in the history of the FCC (having over 1000 filings).
- FCC and NTIA (representing DOD, DOT, FAA etc) through-out the proceeding specifically addressed FH as being a different class device
- The specific rules were clearly intended to change the certification measurement result.
  - Any interpretation that makes the measurement come out the same regardless of whether hopping is turned on or off, would make the language superfluous, which was clearly not the intent of the language.

- Examples of FH systems that the FH rules could have been meant to addresses include:
  – Random hopping - which could put too much energy in a particular band.
  – Hopping where the hop-bands overlap – which could put too much energy into an overlap region
  – Hopping where sidelobe energy of neighboring hops could put too much energy into a band.
- The FCC does not have separate rules or measurement procedures to address hoppers with orthogonal pulses, hoppers with overlapping pulses, hoppers with sequential/periodic pulses, or hoppers with pseudo-random pulses, or combinations of these.
- All frequency hoppers must follow the same rule: measurements “are performed with the stepping sequence or frequency hop stopped.“

Illustration of how to test a compliant UWB FH radio

With Hopping turned OFF:

1. Bandwidth here must meet FCC UWB definition of > 500 MHz bandwidth; AND
2. W/MHz emissions must be within all emission limits defined in the rules



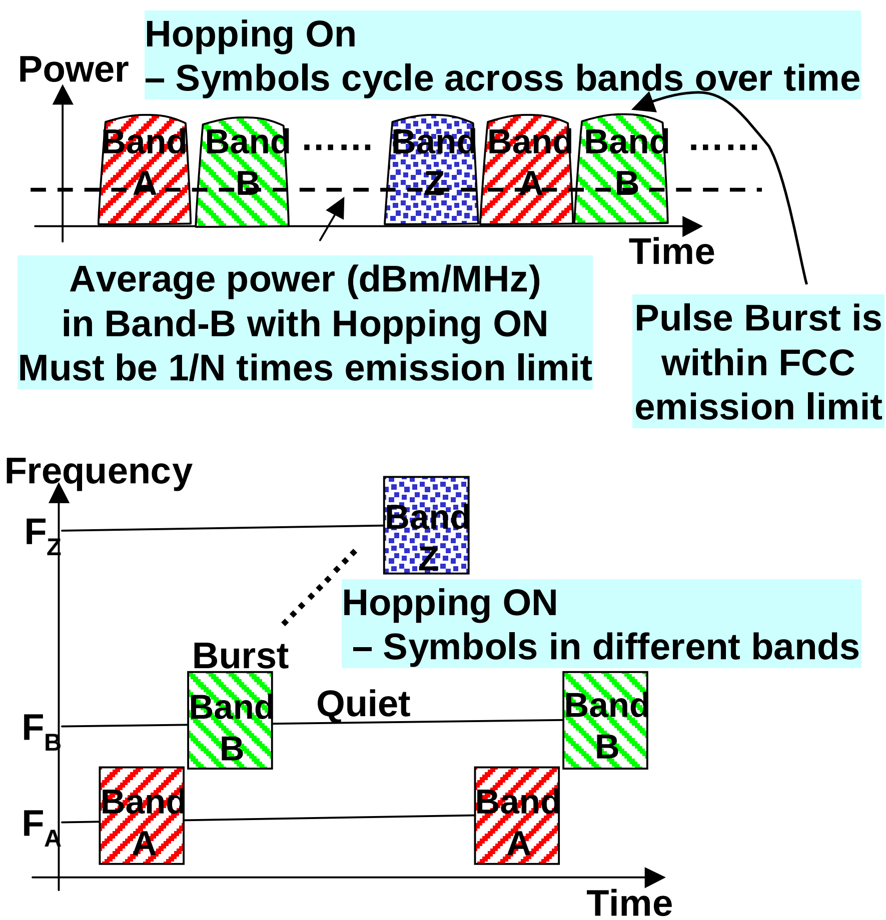
- Pulses/Symbols always come out at same rate
- The total average power is the same with or without hopping stopped
- With hopping stopped all power is concentrated in one band instead of N bands

- Switch is synchronized to the PFN/symbol maker
- Switch rotates to hop the >500 MHz bandwidth pulse (or symbol) to a different center frequency
- Switch stops rotating to stop hopping

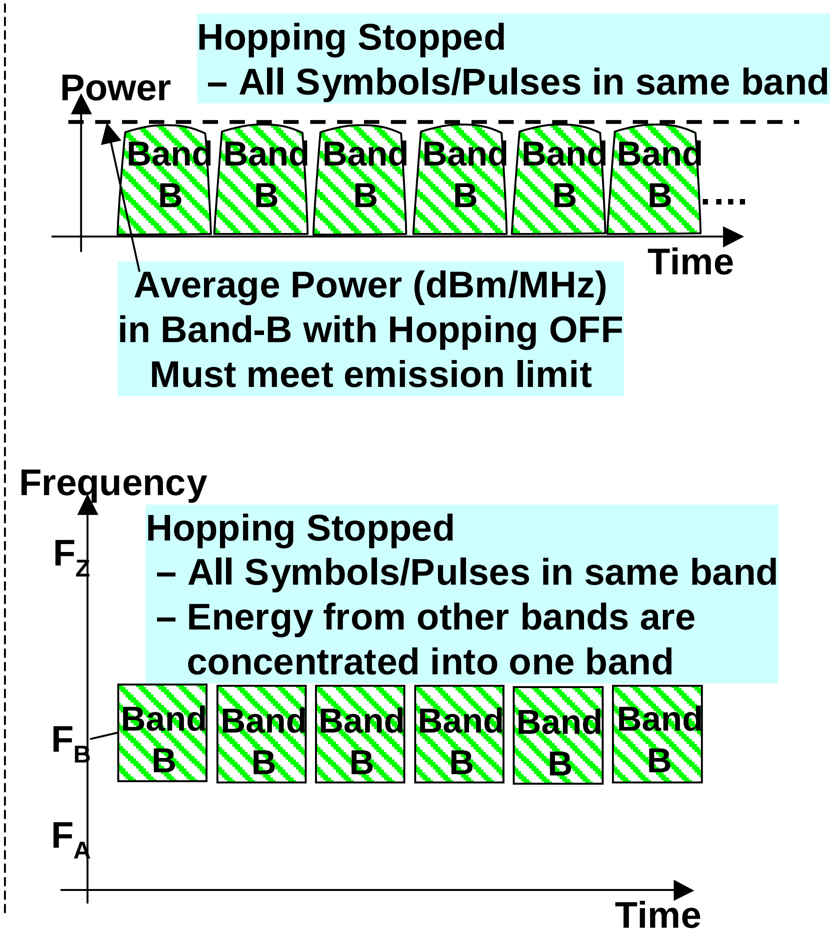
A compliant FH system has only 1/N th the power of a non-hopping system so that it meets the emission limits with hopping turned off

Timing versus Power and Frequency Diagrams for frequency hoppers

Hopping on (normal operation)



Hopping off (for compliance testing)



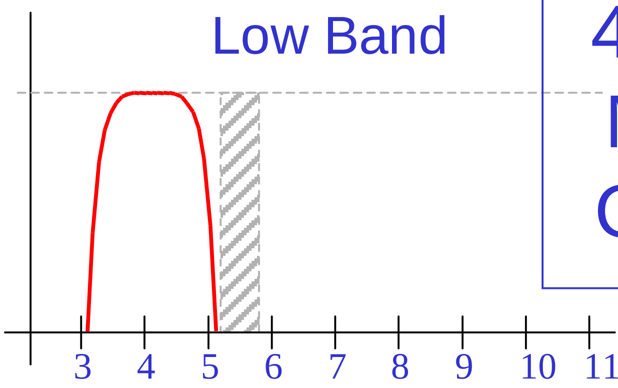
Conclusion

Turning hopping off concentrates the energy so a compliant FH system has only 1/N th the power of a non-hopping system

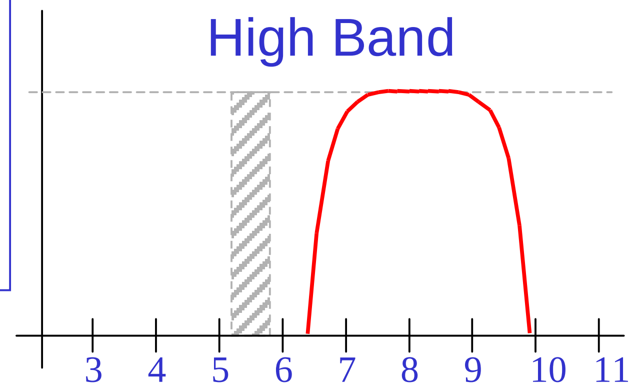
The Multi-Band OFDM Association Proposal Will Require A Reduction In Performance To Be Compliant

Split Band DS-CDMA

4 Spectral Modes of Operation

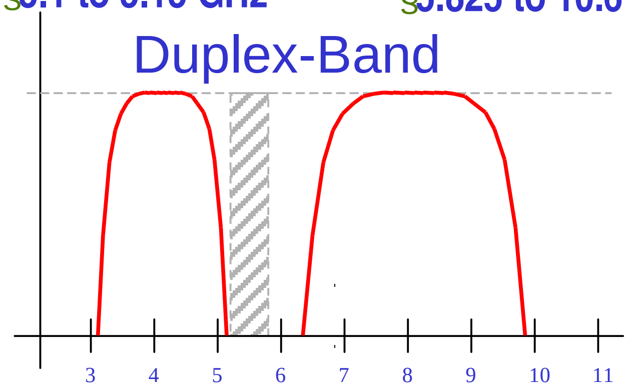


- Low Band (3.1 to 5.15 GHz)
  - 28.5 Mbps to 400 Mbps



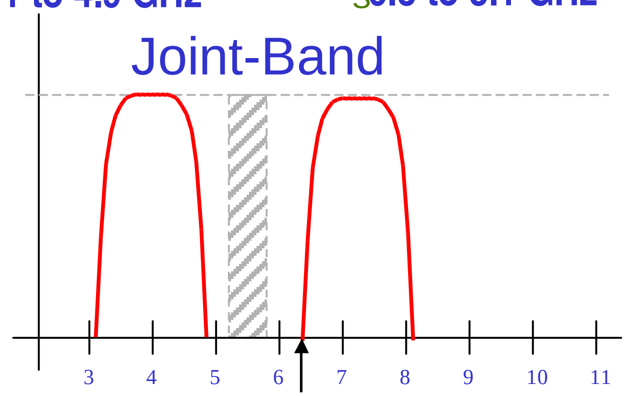
- High Band (5.825 to 10.6 GHz)
  - 57 Mbps to 800 Mbps

- 3.1 to 5.15 GHz
- 5.825 to 10.6 GHz



- Up to 1.2 Gbps
- Independent data in each band

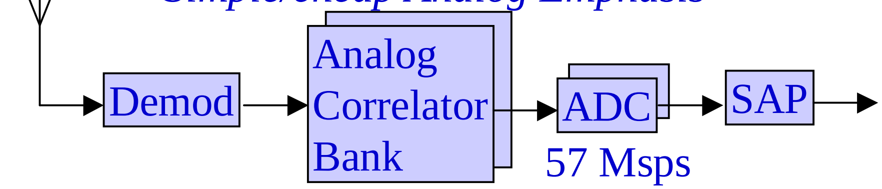
- 3.1 to 4.9 GHz
- 6.3 to 8.1 GHz



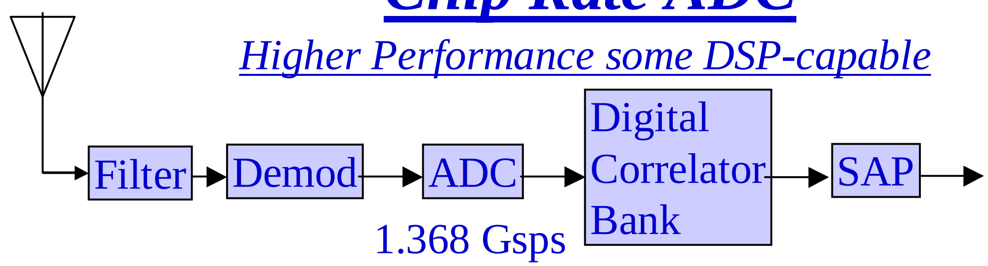
RX Implementation Considerations
(Analog vs. Digital)

Scaleable power/cost/performance
Adaptable to broad application classes

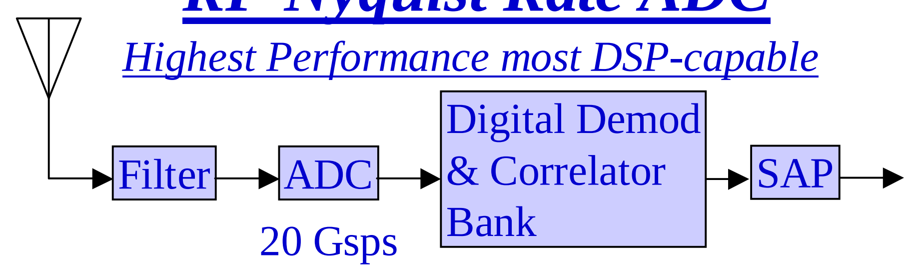
Symbol Rate ADC
Simple/cheap Analog Emphasis



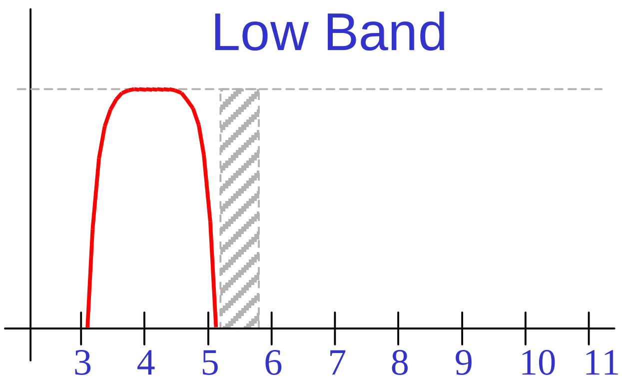
Chip Rate ADC
Higher Performance some DSP-capable



RF Nyquist Rate ADC
Highest Performance most DSP-capable



Split Band DS-CDMA



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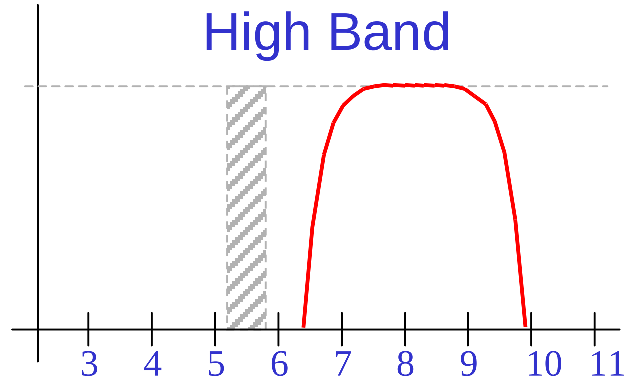
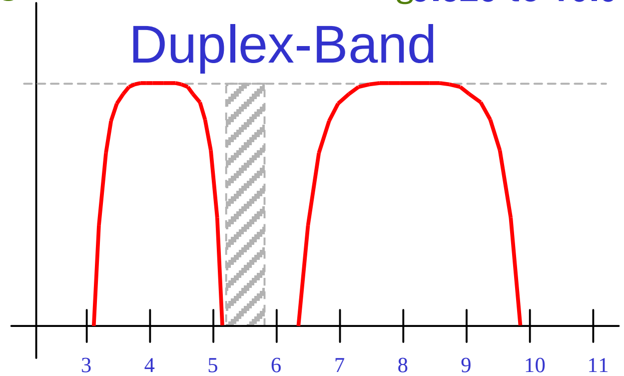


- High Band (5.825 to 10.6 GHz)
  - 57 Mbps to 800 Mbps

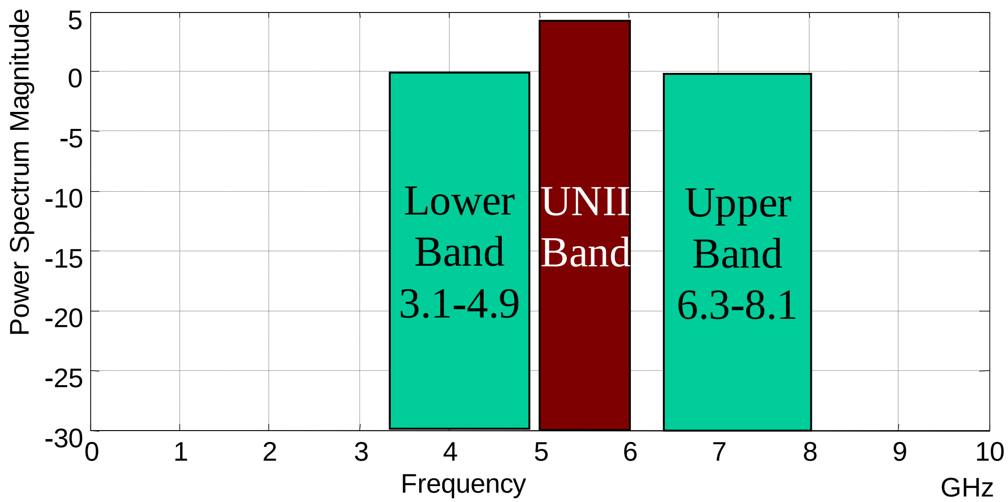
3 Modes Span Analog and Digital Implementations

- 3.1 to 5.15 GHz
- 5.825 to 10.6 GHz



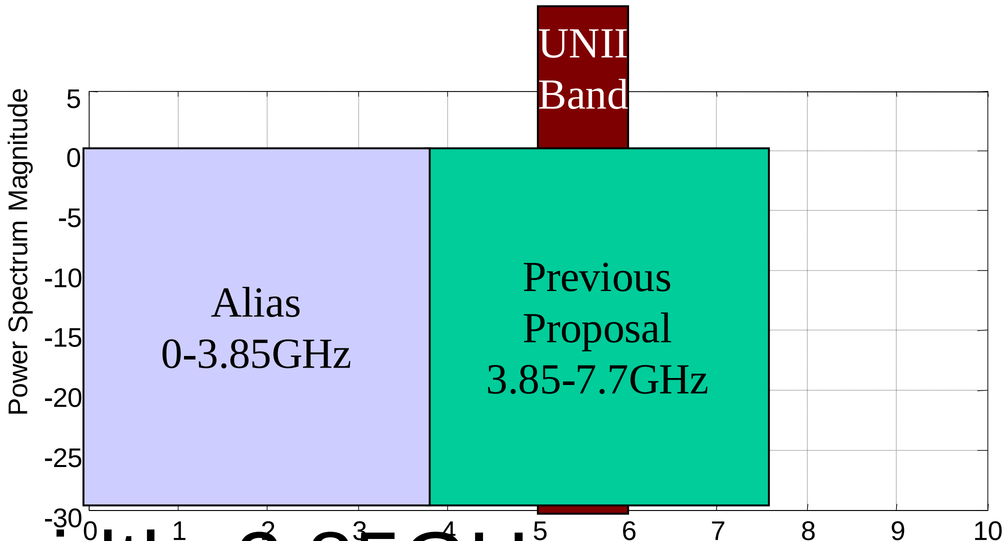
- Up to 1.2 Gbps
- Independent data in each band

New Joint-band Spectrum



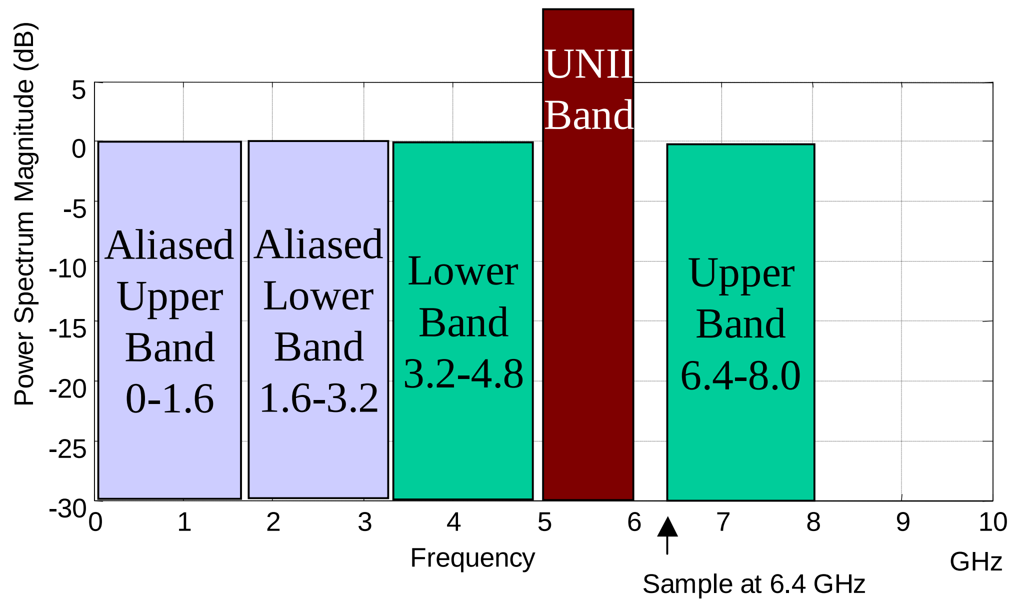
- Bandwidth: 3.2GHz
- 1m Receive level: -52.9dBm
- Sample Rate 7.7GHz

Previous ParthusCeva Proposal



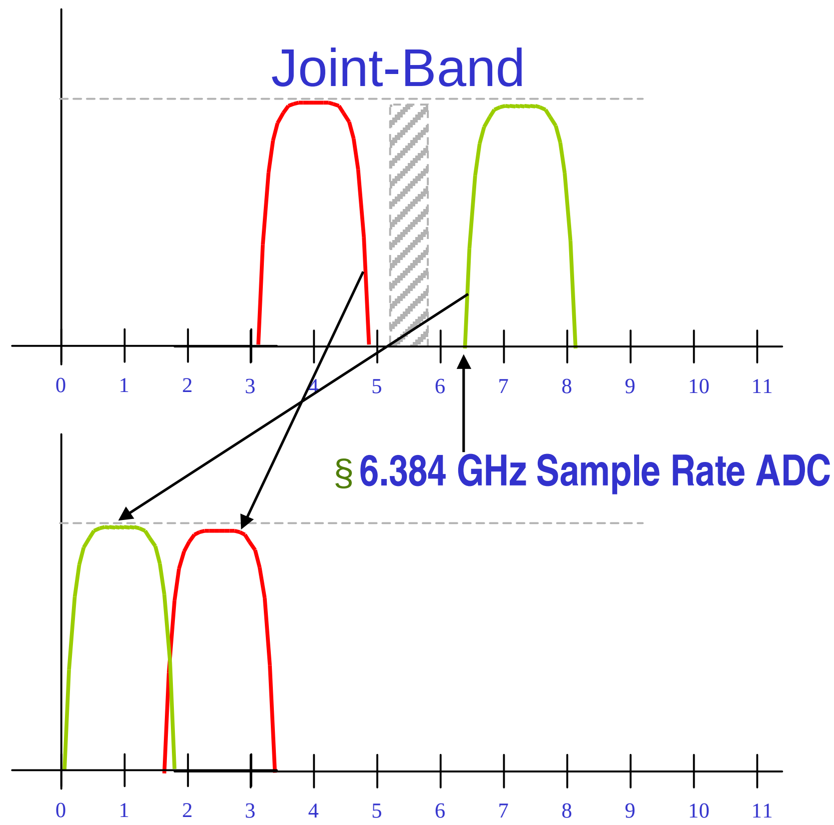
- Bandwidth: 3.85GHz
- 1m Receive level: -53dBm
- Sample Rate: 7.7GHz

After sampling at 6.4GHz



- Bandwidth: 3.2GHz
- 1m Receive level: -52.9dBm

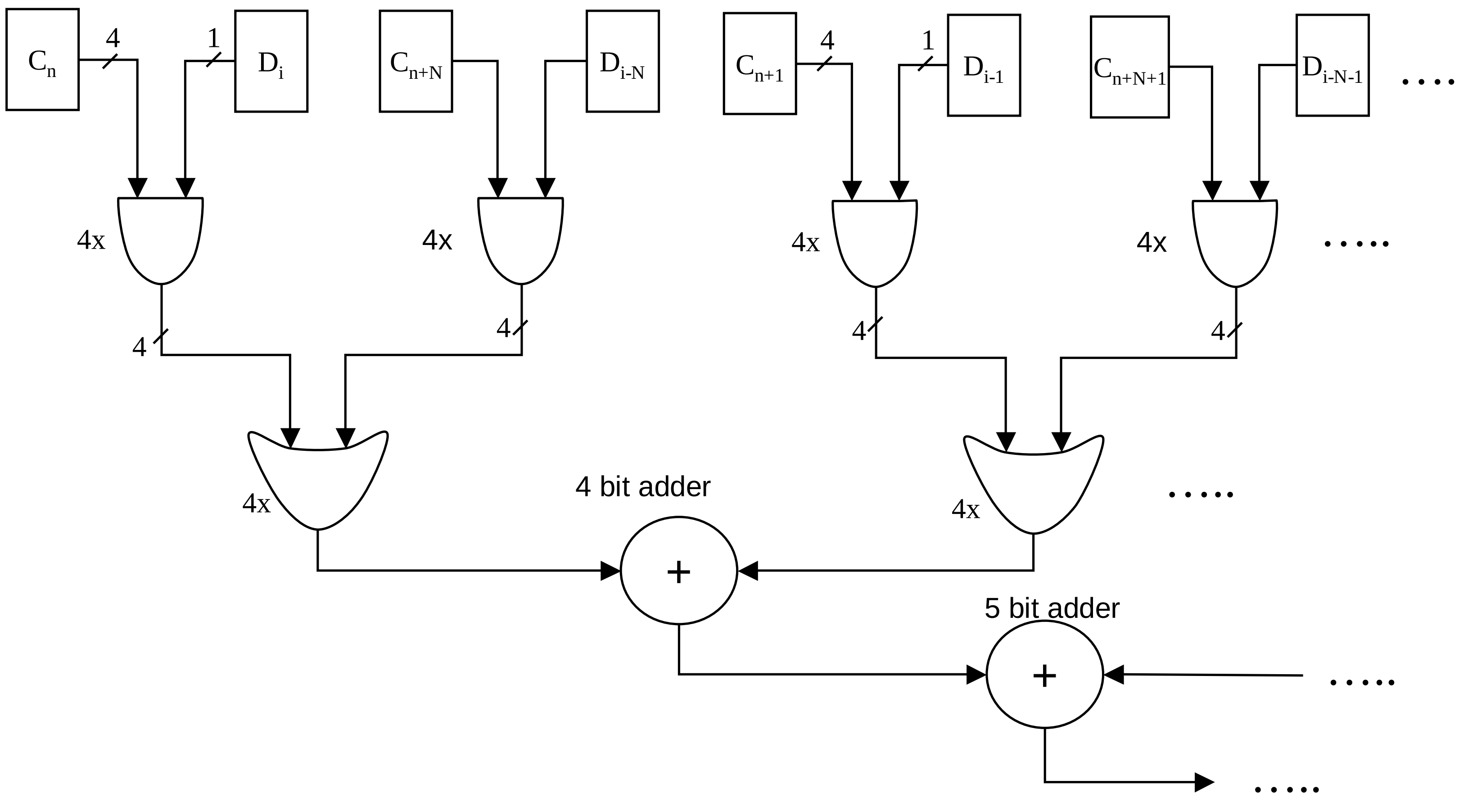
Joint Band Reception on Single ADC



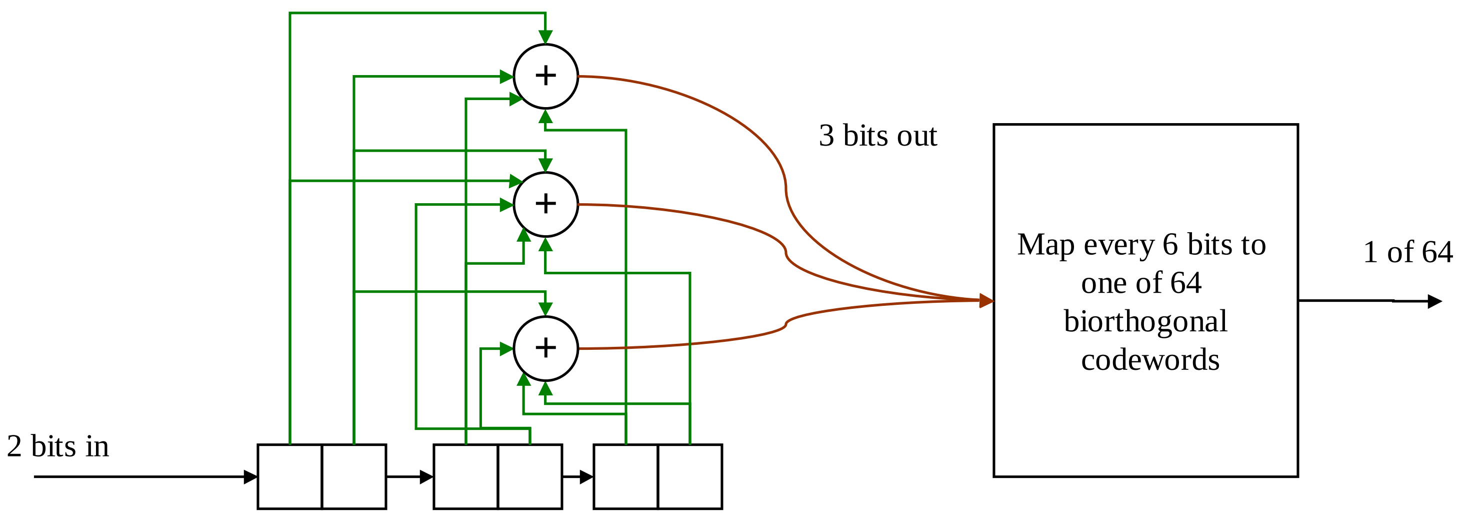
Joint-Band Benefits

	Single Band	Dualband
Rx Power	-54dBm	-53.9dBm
Bandwidth	3.85GHz	3.2GHz
Filter Rate	7.7GHz	6.4GHz
Relative Complexity	100%	70%
Relative Power	100%	70%

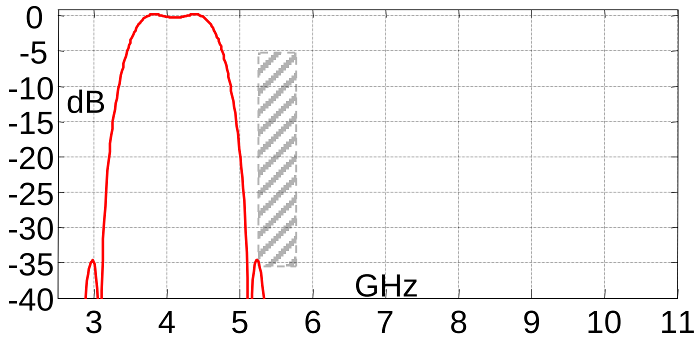
Matched Filter configuration



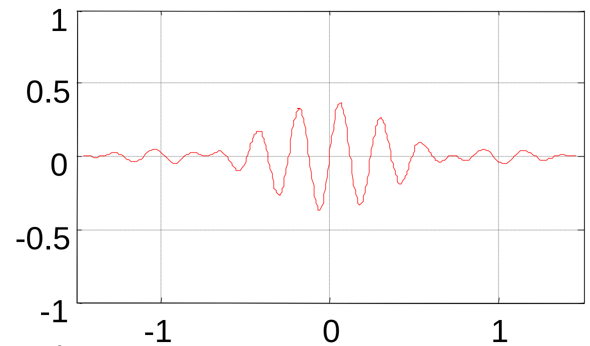
Rate 4/6 Convolutional coder

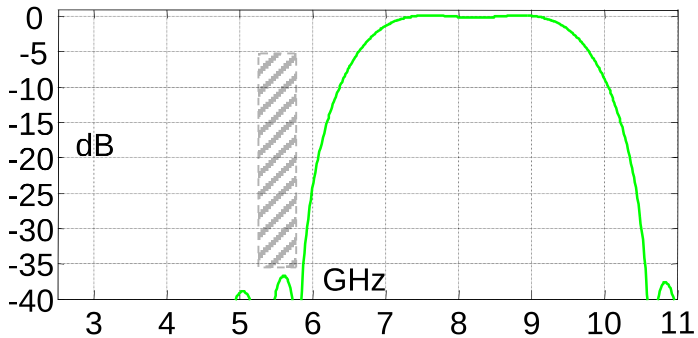


Joint Time Frequency Wavelet Family

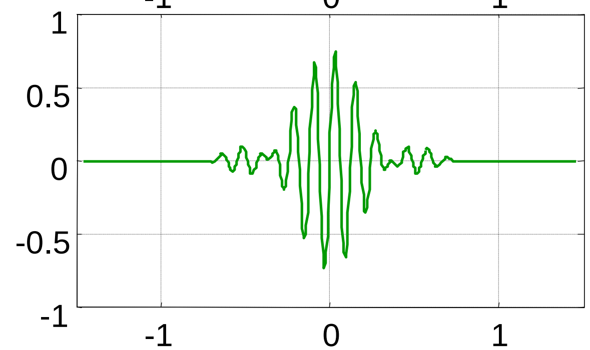


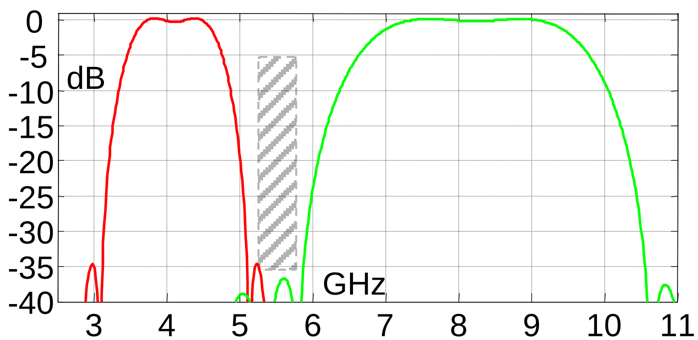
Long Wavelet



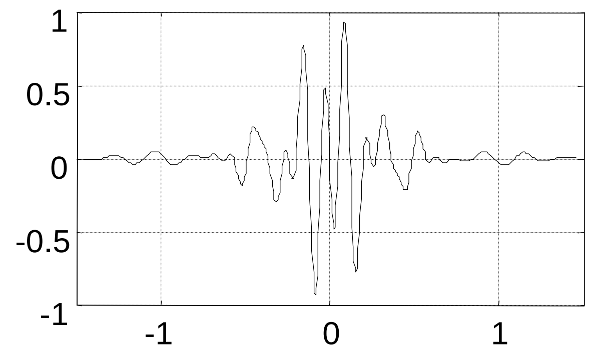


Mid Wavelet



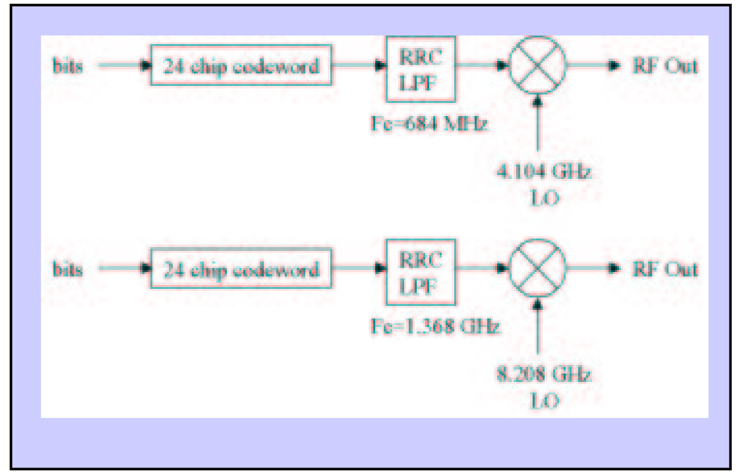


Example Duplex Wavelet

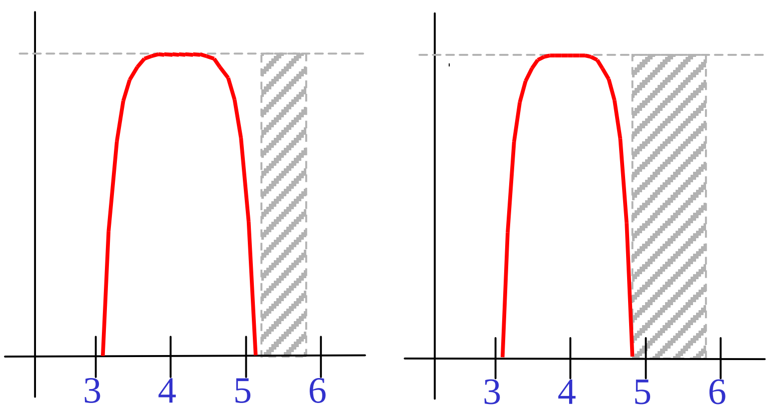


Spectral Flexibility and Scalability

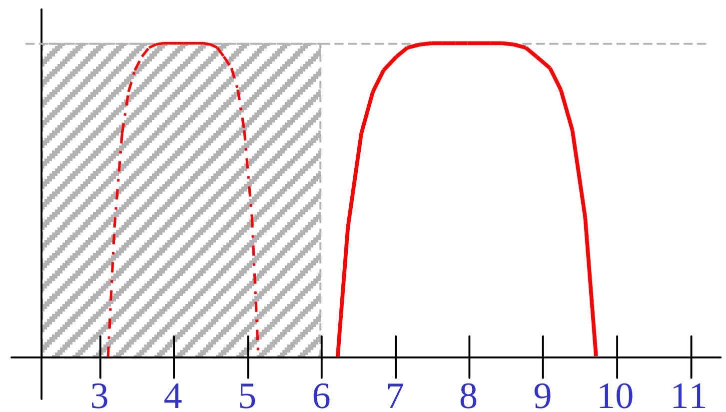
- PHY Proposal accommodates alternate spectral allocations
  - Center frequency and bandwidth are adjustable
  - Supports future spectral allocations
  - Maintains UWB advantages (i.e. wide bandwidth for multipath resolution)
  - **No changes to silicon**



Example 1: Modified Low Band to include protection for 4.9-5.0 GHz WLAN Band



Example 2: Support for hypothetical "above 6 GHz" UWB definition



Note 1: Reference doc IEEE802.15-03/211

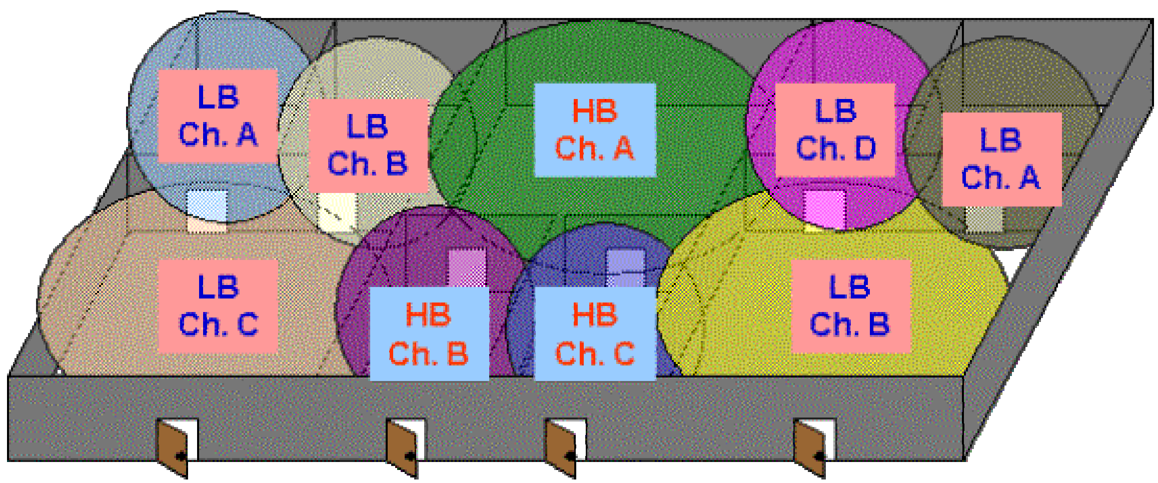
Multiple Access: A Critical Choice

Multi-piconet capability via:

- FDM (Frequency)
  - Choice of one of two operating frequency bands
  - Alleviates severe near-far problem
- CDM (Code)
  - 4 CDMA code sets available within each frequency band
  - Provides a selection of logical channels
- TDM (Time)
  - Within each piconet the 802.15.3 TDMA protocol is used

Legend:

LB Ch. X	**Low Band (FDM) Channel X (CDM) 802.15.3a piconet (TDM/TDMA)**
HB Ch. X	**High Band (FDM) Channel X (CDM) 802.15.3a piconet (TDM/TDMA)**



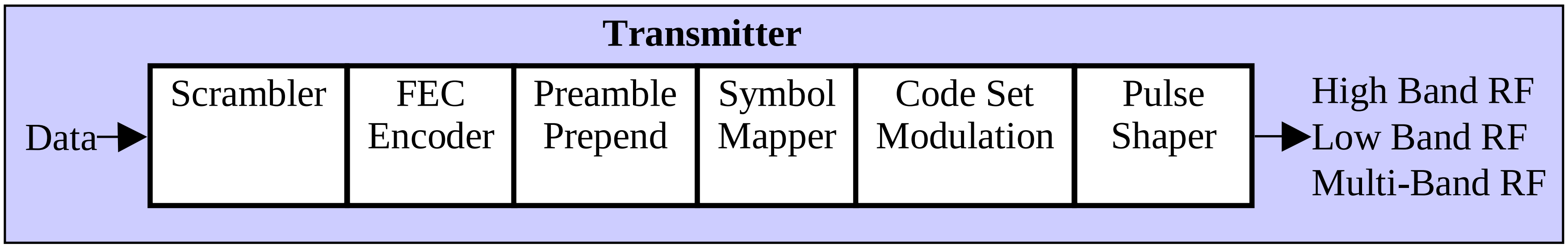
An environment depicting multiple collocated piconets

Why a Multi-Band CDMA PSK Approach?

- Support simultaneous full-rate piconets
- Low cost, low power
- Uses existing 802.15.3 MAC
  - No PHY layer protocol required
- Time to market
  - Silicon in 2003

Proven Technology

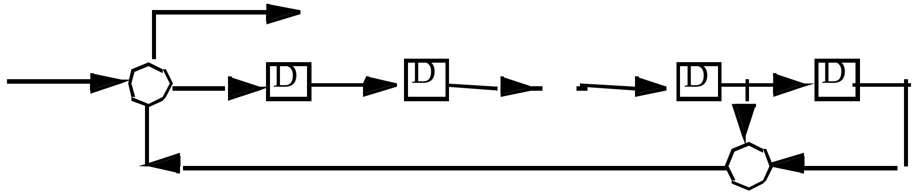
This PHY proposal is based upon proven and common communication techniques



- Multiple bits/symbol via MBOK coding
- Data rates from 28.5 Mbps to 1.2 Gbps
- Multiple access via ternary CDMA coding
- Support for CCA by exploiting higher order properties of BPSK/QPSK
- Operation with up to 8 simultaneous piconets

Scrambler and FEC Coding

- Scrambler (15.3 scrambler)
  - Seed passed as part of PHY header



$g(D)=1+D^{14}+D^{15}$

- Forward error correction options
  - Rate 2/3 trellis code for operation with 64 BOK
  - Convolutional FEC code (<200 Mbps – 2002 technology)
    - ½ rate K=7, (171, 133) with 2/3 and 3/4 rate puncturing
    - Convolutional interleaver
  - Reed-Solomon FEC code (high rates)
    - RS(255, 223) with byte convolutional interleaver
  - Concatenated FEC code (<200 Mbps – 2002 technology)

Pulse Shaping and Modulation

- Approach uses tested direct-sequence spread spectrum techniques
- Pulse filtering/shaping used with BPSK/QPSK modulation
  - 50% excess bandwidth, root-raised-cosine impulse response
- Harmonically related chipping rate, center frequency and symbol rate
  - Reference frequency is 684 MHz

	RRC BW	Chip Rate	Code Length	Symbol Rate
Low Band	1.368 GHz	1.368 GHz (±1 MHz, ± 3 MHz)	24 chips/symbol	57 MS/s
High Band	2.736 GHz	2.736 GHz (±1 MHz, ± 3 MHz)	24 chips/symbol	114 MS/s
Joint Band		912 /1596 / 2128 MHz	24/32 chips/symbol	Various

Code Sets and Multiple Access

- CDMA via low cross-correlation *ternary* code sets (±1, 0)
- Four logical piconets per sub-band (8 logical channels over 2 bands)
- Up to 16-BOK per piconet (4 bits/symbol bi-phase, 8 bits/symbol quad-phase)
  - 1 sign bit and 3 bit code selection per modulation dimension
  - 8 codewords per piconet
- Total number of 24-chip codewords (each band): 4x8=32
  - RMS cross-correlation < -15 dB in a flat fading channel
- CCA via higher order techniques
  - Squaring circuit for BPSK, fourth-power circuit for QPSK
  - Operating frequency detection via collapsing to a spectral line
- Each piconet uses a unique center frequency offset
  - Four selectable offset frequencies, one for each piconet
    - +/- 3 MHz offset, +/- 9 MHz offset

4x8 Code Set

2-BOK uses code 1
4-BOK uses codes 1 & 2
8-BOK uses codes 1,2,3 &4
16-BOK uses all codes

PNC1 =

-1	1	-1	-1	1	-1	-1	1	-1	0	-1	0	-1	-1	1	1	1	-1	1	1	1	-1	-1	-1
0	-1	-1	0	1	-1	-1	1	-1	-1	1	1	1	1	-1	-1	1	-1	1	-1	1	1	1	1
-1	-1	-1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	1	0	-1	0	1	1
0	-1	1	1	1	-1	-1	-1	-1	-1	-1	-1	1	-1	1	-1	0	1	-1	1	1	-1	-1	1
-1	0	1	-1	-1	-1	1	1	0	1	1	1	1	-1	1	-1	1	1	1	-1	1	-1	-1	1
-1	0	-1	1	-1	1	-1	-1	0	1	1	1	1	-1	1	1	-1	-1	-1	1	1	-1	1	1
-1	-1	-1	-1	-1	-1	1	1	1	0	-1	-1	1	1	-1	1	-1	1	-1	1	1	-1	0	1
-1	1	-1	-1	-1	1	-1	-1	0	-1	1	-1	-1	1	-1	0	1	1	1	1	-1	-1	-1	1

PNC2 =

-1	-1	1	0	1	1	1	-1	-1	1	-1	1	1	-1	1	0	1	-1	-1	-1	1	-1	-1	-1
-1	-1	-1	1	-1	-1	-1	1	0	1	-1	1	1	-1	1	-1	-1	1	1	1	0	1	-1	-1
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-1	-1	-1	-1	-1	-1	1	1	1	0	-1	1	-1	1	-1	1	1	-1	-1	1	-1	0	1	-1

4x8 Code Set (Cont.)

PNC3 =

-1	1	-1	1	-1	-1	0	1	-1	-1	-1	1	-1	-1	1	0	-1	-1	-1	-1	1	1	1	1
-1	-1	1	1	-1	-1	-1	-1	-1	-1	1	1	0	1	-1	1	1	-1	1	-1	0	-1	1	-1
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-1	-1	-1	1	-1	1	-1	1	0	-1	-1	-1	1	1	1	1	-1	1	1	-1	0	1	-1	-1
-1	-1	-1	0	-1	-1	-1	-1	1	1	1	0	1	-1	-1	1	-1	1	-1	1	1	-1	-1	1
-1	1	-1	1	-1	1	1	0	1	1	1	0	-1	1	1	-1	1	1	-1	-1	-1	-1	1	1
-1	1	0	-1	1	-1	1	-1	-1	-1	1	-1	-1	0	1	-1	-1	1	1	1	1	-1	-1	-1

PNC4 =

-1	-1	1	1	1	-1	-1	-1	-1	-1	-1	0	-1	1	-1	1	-1	1	1	-1	1	1	-1	0
-1	-1	-1	1	-1	1	1	1	1	-1	1	1	-1	1	1	-1	-1	1	1	1	0	0	-1	1
-1	1	-1	1	1	1	1	0	-1	-1	-1	-1	1	-1	0	-1	-1	1	1	-1	-1	1	1	-1
0	-1	-1	-1	-1	-1	-1	1	1	0	-1	1	1	-1	1	-1	-1	1	1	-1	1	-1	1	-1
-1	-1	1	1	-1	-1	1	0	-1	1	1	1	1	-1	1	-1	1	-1	0	-1	1	1	1	1
-1	-1	1	-1	-1	1	-1	-1	0	-1	1	-1	1	1	-1	-1	-1	1	-1	0	-1	1	1	1
-1	1	0	1	-1	-1	-1	1	1	-1	0	-1	1	-1	-1	1	-1	-1	1	1	1	1	1	1
-1	-1	-1	-1	1	-1	1	0	-1	1	-1	1	1	1	0	1	-1	-1	1	1	-1	-1	1	1

4x8 Code Set Statistics

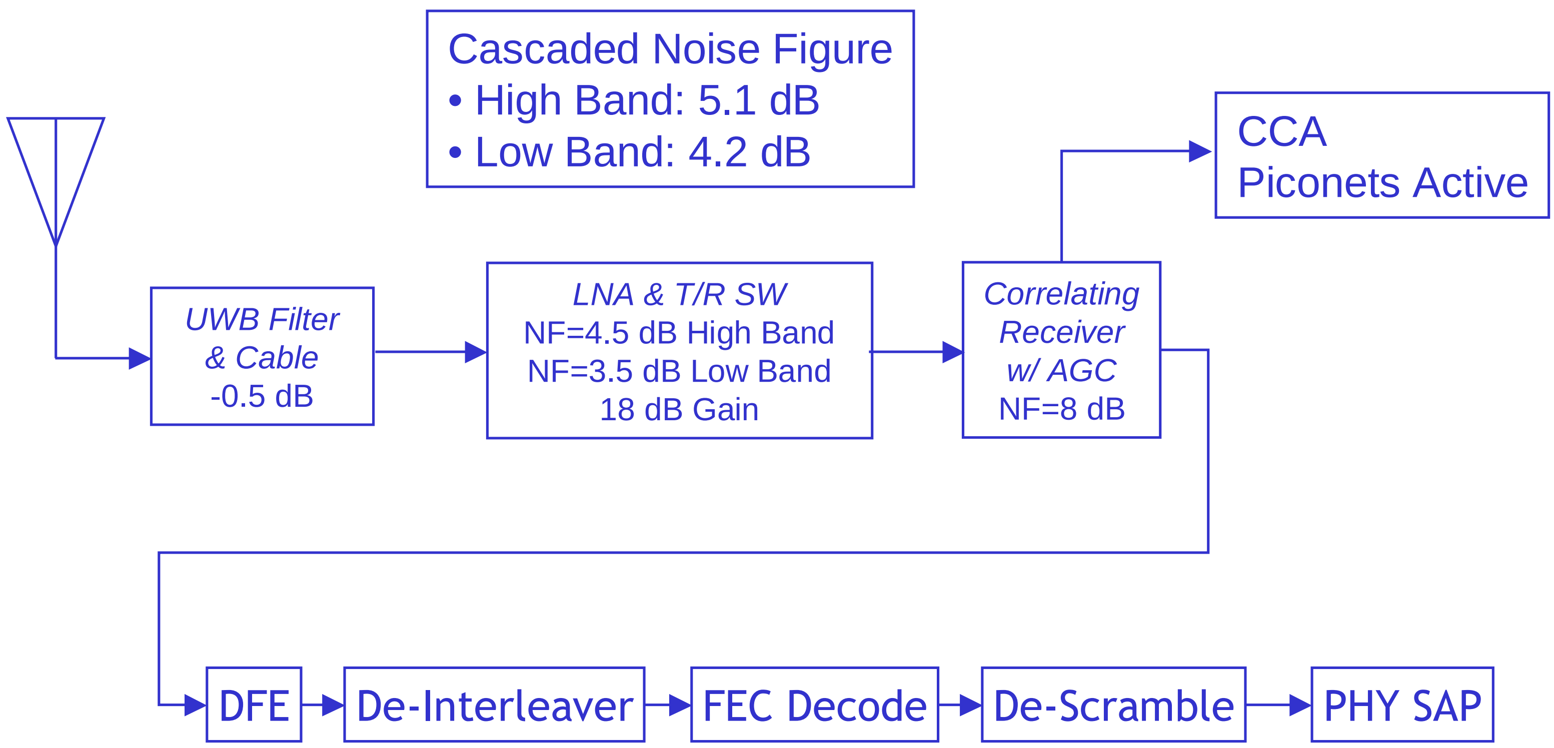
	2-BOK	4-BOK	8-BOK	16-BOK
Spectral Pk-to-Avg Backoff	2.2 dB	2.1 dB	1.7 dB	1.3 dB

Worst Case Synchronized Cross-correlation Coefficient within a group	2/22
Average RMS Cross Correlation between groups	channel dependent but generally looks like 10*log10(1/24) noise due to center frequency offset and chipping rate frequency offset

RX Link Budget Performance

- RX Link Budget (more detail in rate-range slides)
  - 114 Mbps @ 21.6 meters (Low Band in AWGN)
    - 6.7 dB margin at 10 meters
    - Acquisition range limited at 18.7 meters
    - RX Sensitivity of –82.7 dBm @ 4.2 dB noise figure
  - 200 Mbps @ 15.8 meters (Low Band in AWGN)
    - 4.0 dB margin at 10 meters
    - 11.9 dB margin at 4 meters
    - Not acquisition range limited
    - RX Sensitivity of –79.6 dBm @ 4.2 dB noise figure
  - 600 Mbps @ 4.9 meters (High Band in AWGN)
    - 1.7 dB margin at 4 meters
    - Not acquisition range limited
    - RX Sensitivity of –72.7 dBm @ 5.1 dB noise figure

Noise Figure Budget & Receiver Structure



Low Band Symbol Rates and Link Budget

Txpow=-9.9 dBm; Coded Eb/No=9.6 dB, 3 dB implementation loss, 0 dB RAKE gain, NF=4.2 dB, ½ rate code gain: 5.2 dB, 2/3 rate code gain: 4.7 dB, 3/4 rate code gain: 4 dB, RS code gain: 3 dB, concatenated gain: 6.3 dB, 8-BOK coding gain: 1.4 dB, 16-BOK coding gain: 2.4 dB, 2-BOK PSD Backoff: 2.2 dB, 4-BOK PSD Backoff: 2.1 dB, 8-BOK PSD Backoff: 1.7 dB, 16-BOK PSD Backoff: 1.3 dB

Rate	Modulation	CDMA Code Type	FEC	Fc GHz[1]	Range AWGN	Acquisition Range	10 meter margin	RX Sensitivity[2]
28.5 Mbps	BPSK	2-BOK (1 bits/symbol)	½ rate convolutional	4.0	36.8 meters	16.7 meters	11.3 dB	-87.9 dBm
57 Mbps	BPSK	4-BOK (2 bits/symbol)	½ rate convolutional	4.0	26.3 meters	16.9 meters	8.4 dB	-84.8 dBm
75 Mbps	BPSK	8-BOK (3 bits/symbol)	Concatenated	4.0	32.1 meters	17.7 meters	10.1 dB	-86.2 dBm
100 Mbps	BPSK	4-BOK (2 bits/symbol)	RS(255, 223)	4.0	15.5 meters	>15.5 meters	3.8 dB	-80.2 dBm
114 Mbps	BPSK	8-BOK (3 bits/symbol)	2/3 rate convolutional	4.0	21.6 meters	17.7 meters	6.7 dB	-82.7 dBm
200 Mbps (199.4 Mbps)	BPSK	16-BOK (4 bits/symbol)	RS(255, 223)	4.0	15.8 meters	>15.8 meters	4.0 dB	-79.6 dBm
400 Mbps (398.8 Mbps)	QPSK	16-BOK (8 bits/symbol)	RS(255, 223)	4.0	11.2 meters	>11.2 meters	1.0 dB	-76.6 dBm

[1] Center frequency determined as geometric mean in accordance with 03031r9, clause 5.6

[2] Based upon corrected Eb/No of 9.6 dB after application of all coding gain

Coding Gain References:
- http://www.intel.com/design/digital/STEL-2060/index.htm
- http://grouper.ieee.org/groups/802/16/tg1/phy/contrib/802161pc-00_33.pdf

Table is representative - there are about 28 logical rate combinations offering unique QoS in terms of Rate, BER and latency

High Band Symbol Rates and Link Budget

Txpow=-6.9 dBm; Coded Eb/No=9.6 dB, 3 dB implementation loss, 0 dB RAKE gain, NF=5.1 dB, ½ rate code gain: 5.2 dB, 2/3 rate code gain: 4.7 dB, 3/4 rate code gain: 4 dB, RS code gain: 3 dB, concatenated gain: 6.3 dB, 8-BOK coding gain: 1.4 dB, 16-BOK coding gain: 2.4 dB, 2-BOK PSD Backoff: 2.2 dB, 4-BOK PSD Backoff: 2.1 dB, 8-BOK PSD Backoff: 1.7 dB, 16-BOK PSD Backoff: 1.3 dB

Rate	Modulation	CDMA Code Type	FEC	Fc GHz	Range AWGN	Acquisition Range	4 meter margin	RX Sensitivity
100 Mbps	BPSK	4-BOK (2 bits/symbol)	Concatenated	8.1	14.2 meters	10.7 meters	11.0 dB	-82.6 dBm
114Mbps	BPSK	4-BOK (2 bits/symbol)	½ rate convolutional	8.1	11.7 meters	10.7 meters	9.3 dB	-80.9 dBm
200 Mbps (199.4 Mbps)	BPSK	4-BOK (2 bits/symbol)	RS(255, 223)	8.1	6.9 meters	>6.9 meters	4.7 dB	-76.3 dBm
300 Mbps (299.1 Mbps)	BPSK	8-BOK (3 bits/symbol)	RS(255, 223)	8.1	6.9 meters	>6.9 meters	4.8 dB	-75.9 dBm
400 Mbps (398.8 Mbps)	BPSK	16-BOK (4 bits/symbol)	RS(255, 223)	8.1	7.0 meters	>7.0 meters	4.9 dB	-75.7 dBm
600 Mbps (598.2 Mbps)	QPSK	8-BOK (6 bits/symbol)	RS(255, 223)	8.1	4.9 meters	>4.9 meters	1.7 dB	-72.9 dBm
800 Mbps (797.6 Mbps)	QPSK	16-BOK (8 bits/symbol)	RS(255, 223)	8.1	5.0 meters	>5.0 meters	1.9 dB	-72.7 dBm

Table is representative - there are about 28 logical rate combinations offering unique QoS in terms of Rate, BER and latency

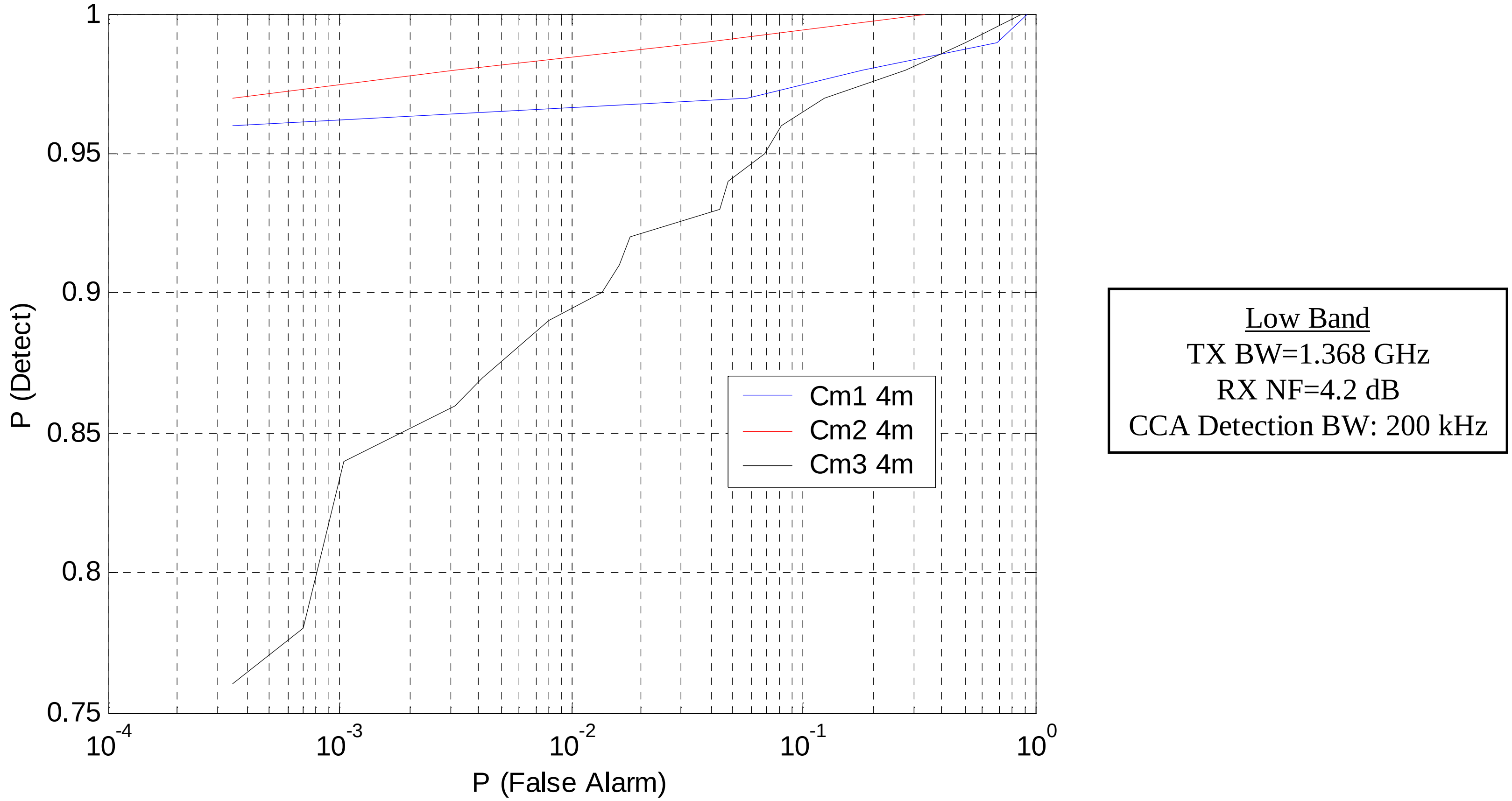
DFE and RAKE

- Both DFE and RAKE can improve performance
- Decision Feedback Equalizer (DFE) combats ISI, RAKE combats ICI
  - DFE or RAKE implementation is a receiver issue (beyond standard)
    - Our proposal supports either / both
    - Each is appropriate depending on the operational mode and market
  - DFE is currently used in the XSI 100 Mbps TRINITY chip set[1]
  - DFE with M-BOK is efficient and proven technology (ref. 802.11b CCK devices)
  - DFE Die Size Estimate: <0.1 mm^2
  - DFE Error Propagation: Not a problem on 98.75% of the TG3a channels

Note 1: http://www.xtremespectrum.com/PDF/xsi_trinity_brief.pdf

CCA Performance

The following figure represents the CCA ROC curves for CM1, CM2 and CM3 at 4.1 GHz. This curve shows good performance on CM1 and CM2 with high probability of detection and low probability of false alarm (e.g. usage of a CAP CSMA based algorithm is feasible); however, on CM3 use of the management slots (slotted aloha) is probably more appropriate.



Our CCA scheme allows monitoring channel activity during preamble acquisition to minimize probability of false alarm acquisition attempts.

Multiple User Separation Distance – CM1 to CM4

Initial Conditions:
- *ACQ Symbol Duration=140.35 nS*
- *5 Finger RAKE*

114 Mbps, 8-BOK, 2/3 Rate FEC

Averaged Outage Range

	CM1	CM2	CM3	CM4
Meters Distance	15.0	13.5	11.5	10.0

Coexistence Ratios – 1 MUI

Ref \ Int	CM1	CM2	CM3	CM4
CM1	0.60	0.58	0.53	0.50
CM2	0.67	0.65	0.59	0.55
CM3	0.71	0.69	0.62	0.59
CM4	0.83	0.80	0.73	0.69

200 Mbps, 16-BOK, R-S FEC

Averaged Outage Range

	CM1	CM2	CM3	CM4
Meters Distance	11.1	10.0	8.8	7.5

Coexistence Ratios – 1 MUI

Ref \ Int	CM1	CM2	CM3	CM4
CM1	0.55	0.53	0.48	0.46
CM2	0.61	0.59	0.54	0.51
CM3	0.67	0.65	0.59	0.56
CM4	0.77	0.74	0.67	0.64

Multiple User Separation Distance – CM1 to CM4

Continuing

Coexistence Ratios – 2 MUI

Ref \ Int	CM1	CM2	CM3	CM4
CM1	0.85	0.82	0.74	0.70
CM2	0.94	0.91	0.83	0.78
CM3	1.01	0.97	0.88	0.84
CM4	1.17	1.13	1.03	0.97

Coexistence Ratios – 3 MUI

Ref \ Int	CM1	CM2	CM3	CM4
CM1	1.04	1.00	0.91	0.86
CM2	1.16	1.12	1.02	0.96
CM3	1.24	1.19	1.08	1.03
CM4	1.43	1.38	1.26	1.19

Coexistence Ratios – 2 MUI

Ref \ Int	CM1	CM2	CM3	CM4
CM1	0.78	0.75	0.68	0.65
CM2	0.87	0.84	0.77	0.72
CM3	0.95	0.91	0.83	0.79
CM4	1.09	1.05	0.96	0.90

Coexistence Ratios – 3 MUI

Ref \ Int	CM1	CM2	CM3	CM4
CM1	0.96	0.92	0.84	0.79
CM2	1.06	1.03	0.94	0.88
CM3	1.16	1.12	1.02	0.96
CM4	1.33	1.28	1.17	1.11

PHY Preamble and Header

PHY Synchronization	SFD	PHY Header	MAC Header	payload

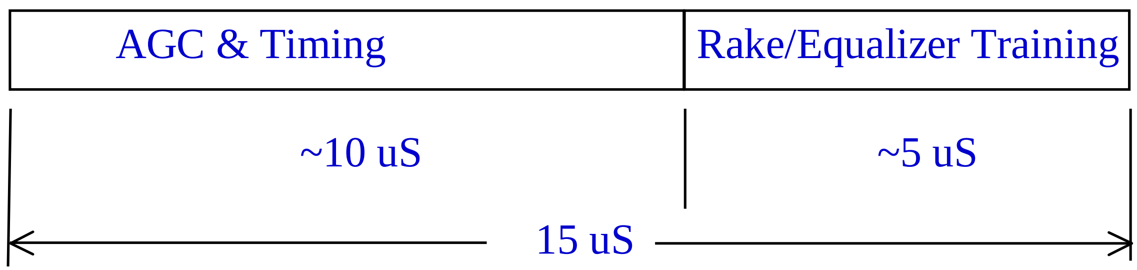
- Three Preamble Lengths (Link Quality Dependent)
  - Short Preamble (10 μs, short range <4 meters, high bit rate)
  - Medium Preamble (default) (15 μs, medium range ~10 meters)
  - Long Preamble (30 μs, long range ~20 meters, low bit rate)
  - Preamble selection done via blocks in the CTA and CTR
- PHY Header Indicates FEC type, M-BOK type and PSK type
  - Data rate is a function of FEC, M-BOK and PSK setup
  - Headers are sent with 3 dB repetition gain for reliable link establishment

PHY Synchronization Preamble Sequence

(low band medium length sequence[1])

JNJNB5ANB6APAPCPANASASCNJNASK9B5K6B5K5D5D5B9ANASJPJNK5MNCP
ATB5CSJPMTK9MSJTCTASD9ASCTATASCSANCSASJSJSB5ANB6JPN5DAASB9K
5MSCNDE6AT3469RKWAVXM9JFEZ8CDS0D6BAV8CCS05E9ASRWR914A1BR

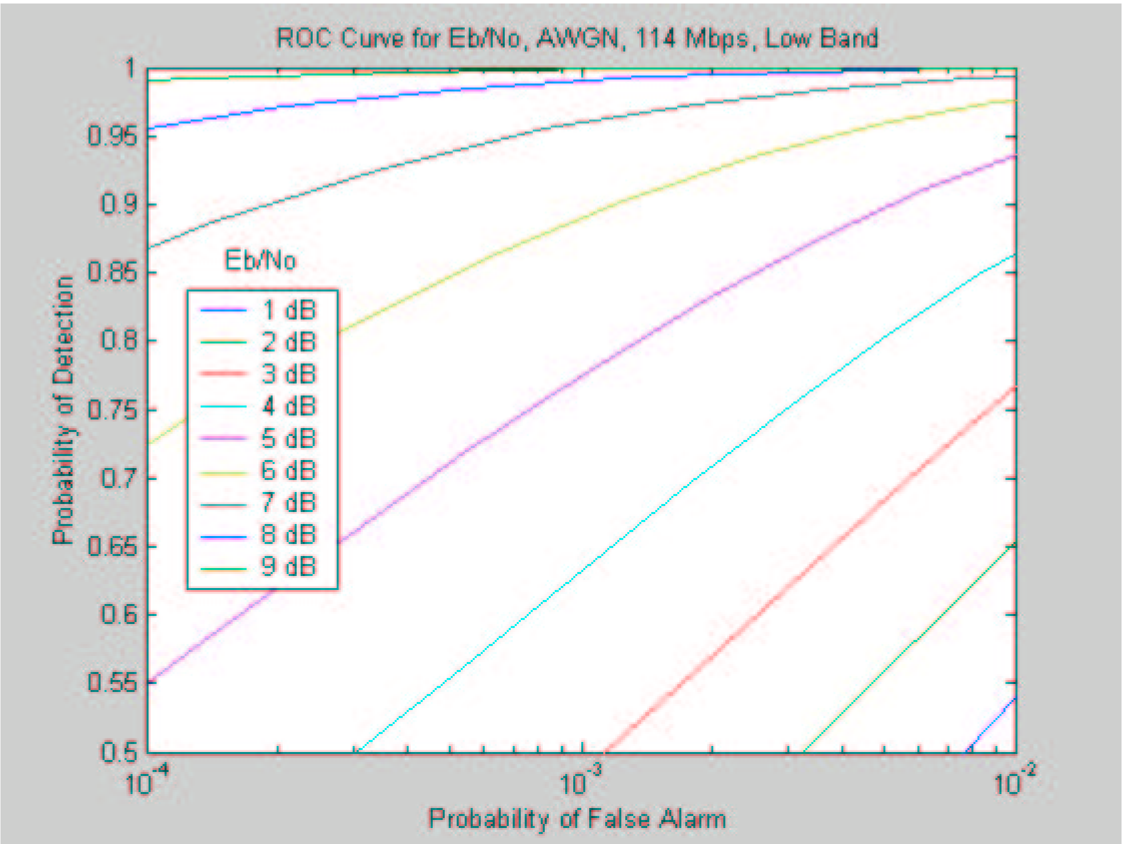
Notation is Base 32



[1] see document 03/154r2 for sequences for the long, short and high band preambles

Acquisition ROC Curves

Acquisition ROC curve vs. Eb/No at 114 Mbps



ROC Probability of detection vs. Eb/No at 114 Mbps for Pf=0.01

114 Mbps Eb/No	Pd
9 dB	1.0
8 dB	0.999
7 dB	0.994
6 dB	0.976
5 dB	0.935
4 dB	0.865
3 dB	0.770
2 dB	0.655
1 dB	0.540

Pf: Probability of False Alarm
Pd: Probability of Detection

Acquisition Assumptions and Comments

Timing acquisition uses a sliding correlator that searches through the multi-path components looking for the best propagating ray

Two degrees of freedom that influence the acquisition lock time (both are SNR dependent):

1. The time step of the search process
2. The number of sliding correlators

Acquisition time is a compromise between:

- acquisition hardware complexity (i.e. number of correlators)
- acquisition search step size
- acquisition SNR (i.e. range)
- acquisition reliability (i.e. Pd and Pf)

Acquisition Assumptions and Comments (cont.)

We’ve limited the number of correlators during acquisition to three and we’ve presented results against a 15 uS preamble length.

Naturally we could have shortened the acquisition time by increasing the acquisition hardware complexity. Our acquisition performance numbers are not absolutes but arise due to our initial assumptions.

NBI Rejection

1. XSI - CDMA

- The XSI CDMA codes offer some processing gain against narrowband interference (<14 dB)
- Better NBI protection is offered via tunable notch filters
  - Specification outside of the standard
- Each notch has an implementation loss <3 dB (actual loss is implementation specific)
- Each notch provides 20 to 40 dB of protection
- Uniform sampling rate facilitates the use of DSP baseband NBI rejection techniques

2. Comparison to Multi-band OFDM NBI Approach

- Multi-band OFDM proposes turning off a sub-band of carriers that have interference
  - RF notch filtering is still required to prevent RF front end overloading
- Turning off a sub-band impacts the TX power and causes degraded performance
- Dropping a sub-band requires either one of the following:
  - FEC across the sub-bands
    - Can significantly degrade FEC performance
  - Handshaking between TX and RX to re-order the sub-band bit loading
    - Less degradation but more complicated at the MAC sublayer

Overhead and Throughput Summary

Low Band Results,
See 03154r3 for High Band Results

We've limited the number of correlators during acquisition to three. These results are for a 15 uS preamble length.

All rates in Mbps, times in µs							
PHY Header bits	24						
MAC Header Bits	80						
HCS bits	16						
Header Bits	120						
Payload Bytes	1024						
Payload Bits	8192						
FCS Bits	32						
FEC Overhead symbols (conv)	730						
FEC Overhead symbols (RS)	3112						
Symbol Rate	57						
Header equivalent "FEC" rate	0.333333						
Header BOK bits per symbol	1						
Initial PHY Header rate	19						
FEC		conv	conv	concat.	conv	R/S	R/S
Bit Rate		28.5	57	75	114	200	400
FEC symbol rate		57	114	171.5247	228	228.6996	457.3991
BOK		2	3	8	16	16	16
BPSK/QPSK		BPSK	BPSK	BPSK	BPSK	BPSK	QPSK
Bits per symbol		1	2	3	4	4	8
Payload FEC rate		0.5	0.5	0.437255	0.5	0.87451	0.87451
T_PA_INITIAL	15						
T_PA_CONT	0						
T_PHYHDR_INITIAL	1.263158						
T_MACHDR_INITIAL	4.210526						
T_HCS_INITIAL	0.842105						
T_PHYHDR_CONT		0.842105	0.421053	0.32	0.210526	0.12	0.06
T_MACHDR_CONT		2.807018	1.403509	1.066667	0.701754	0.4	0.2
T_HCS_CONT		0.561404	0.280702	0.213333	0.140351	0.08	0.04
T_MPDU		287.4386	143.7193	109.2267	71.85965	40.96	20.48
T_FCS		1.122807	0.561404	0.426667	0.280702	0.16	0.08
T_SIFS	5	5	5	5	5	5	5
T_FEC_OH		12.80702	6.403509	22.39911	3.201754	13.60737	6.803686
T_MIFS	0	0	0	0	0	0	0
T_ONE_FRAME		327.6842	177	158.3682	101.6579	81.04316	53.67948
Throughput_1		24.99968	46.28249	51.72755	80.584	101.0819	152.6095
T_FIVE_FRAMES		1498.772	762.5439	603.3816	394.4298	247.9232	137.1195
Throughput_5		27.32904	53.71494	67.88408	103.8461	165.2125	298.7176

PHY PIB, Layer Management and MAC Frame Formats

No significant MAC or superframe modifications required!

- From MAC point of view, 8 available logical channels
- Band switching done via DME writes to MLME

Proposal Offers MAC Enhancement Details (complete solution)

- PHY PIB
  - RSSI, LQI, TPC and CCA
- Clause 6 Layer Management Enhancements
  - Ranging MLME Enhancements
  - Multi-band UWB Enhancements
- Clause 7 MAC Frame Formats
  - Ranging Command Enhancements
  - Multi-band UWB Enhancements
- Clause 8 MAC Functional Description
  - Ranging Token Exchange MSC

Additional Information can be found in doc -03/154r3 including XSI draft text for the standard (in the appendix of -03/154r3).

802.15.3a Early Merge Work

XtremeSpectrum will be cooperating with Motorola

Self-Evaluation

6.1 General Solution Criteria

CRITERIA	*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	+

Self-Evaluation (cont.)

6.2 PHY Protocol Criteria

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	+

Self-Evaluation (cont.)

6.3 MAC Protocol Enhancement Criteria

CRITERIA	***REF.***	**IMPORTANCE LEVEL**	***PROPOSER RESPONSE***
MAC Enhancements And Modifications	4.1.	*C*	+

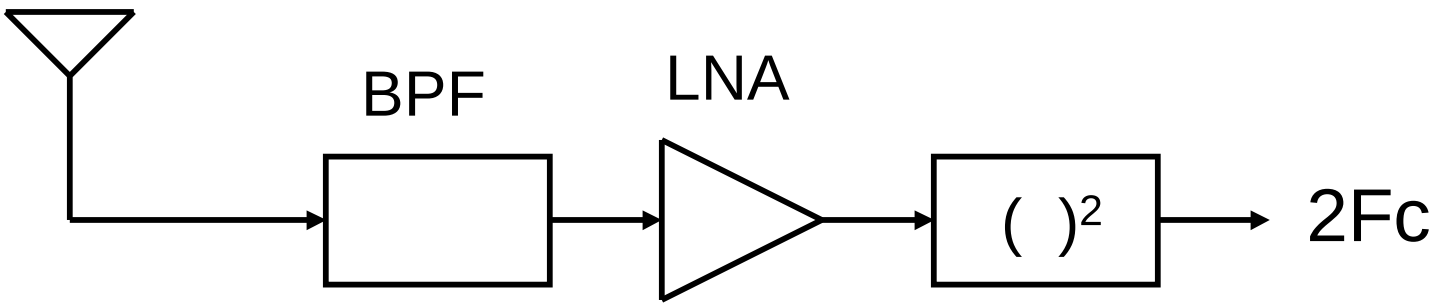
Additional Technical Slides

Strong Support for CSMA/CCA

- Important as alternative SOP approach
- Allows use of 802.11 MAC
- Allows use of CAP in 802.15.3 MAC
- Could implement CSMA-only version of 802.15.3 MAC
- Completely Asynchronous
  - Independent of Data-Stream
  - Does not depend on Preamble
  - ID's and Gives real-time signal strength on all neighboring piconets
- Very simple hardware

How it Works

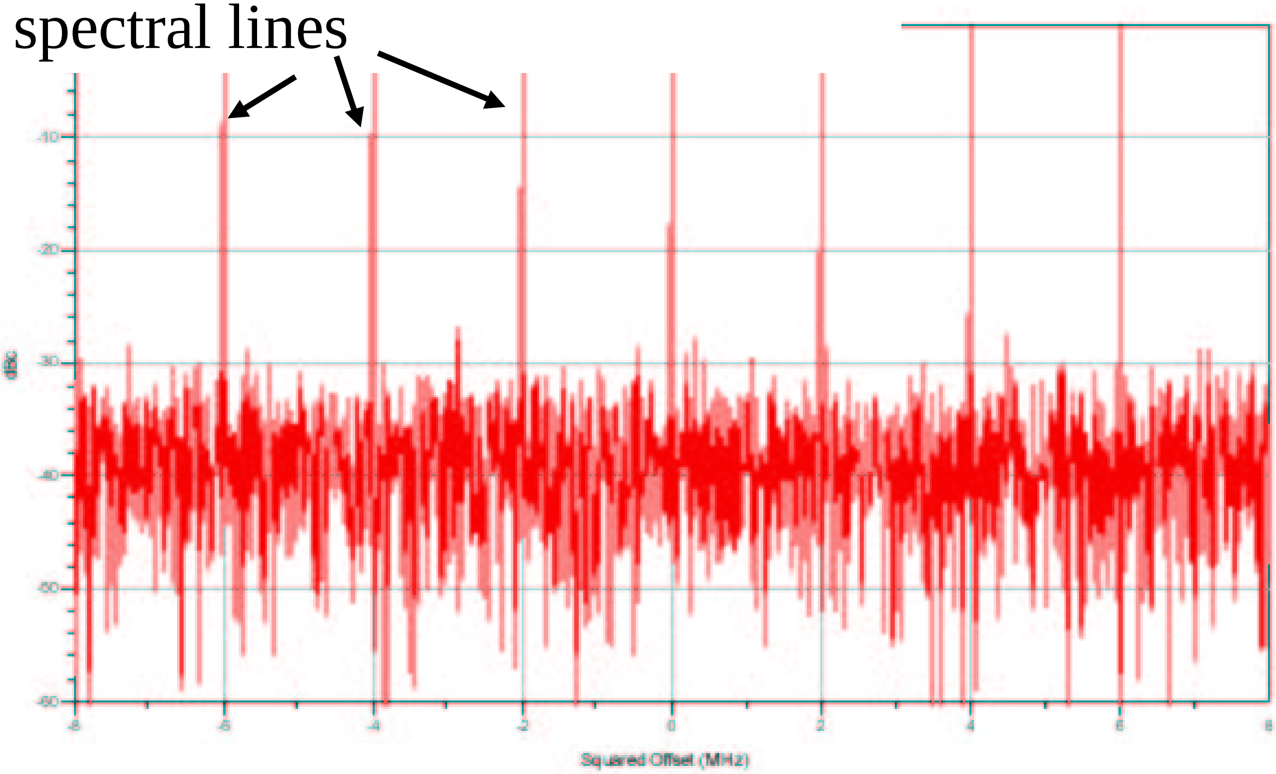
- Fc = wavelet center frequency = 3x chip rate
- Piconet ID is chip rate offset of ±1 or ±3 MHz



- Standard technique for BPSK clock recovery
  - Output is filtered and divided by 2 to generate clock

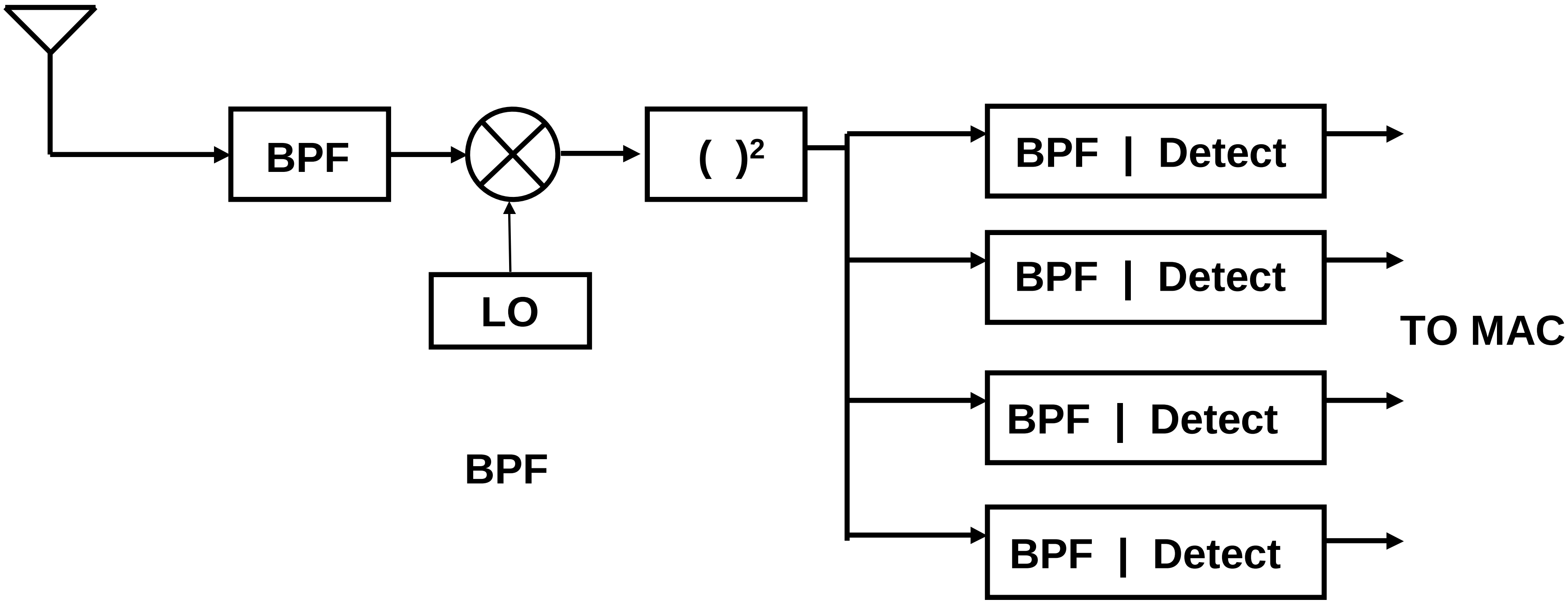
Output of the Squaring Circuit

Piconets clearly identified by spectral lines



How it Works

- Can also be done at baseband:



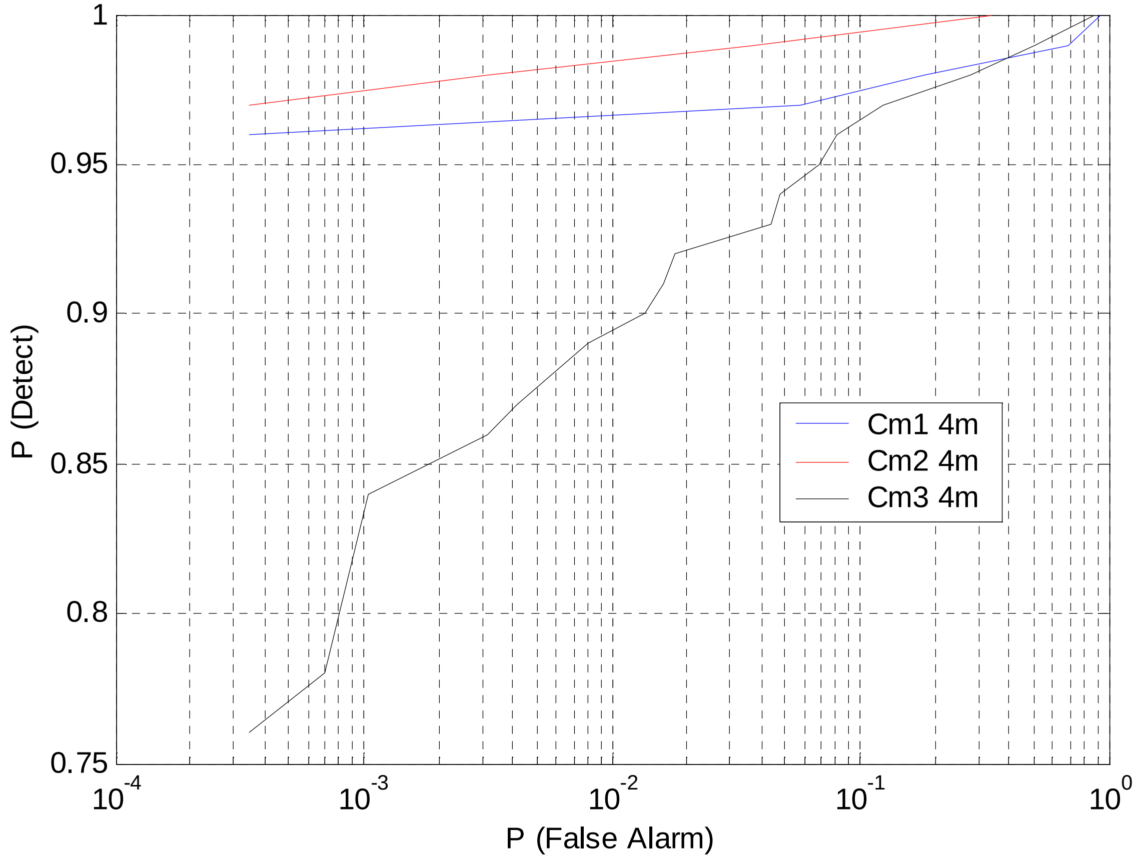
- ID's all operating piconets
- Completely Independent of Data Stream
- DOES NOT REQUIRE PREAMBLE/HEADER
- **5us** to ID or react to signal level changes

Gives MAC Sophisticated Capabilities

- Handoff
  - What piconets are around
  - How big they are (refresh every 5 us)
- PHY provides all required info to efficiently support CCA/CSMA MAC functionality

CCA Performance

The following figure represents the CCA ROC curves for CM1, CM2 and CM3 at 4.1 GHz. This curve shows good performance on CM1 and CM2 with high probability of detection and low probability of false alarm (e.g. usage of a CAP CSMA based algorithm is feasible); however, on CM3 use of the management slots (slotted aloha) is probably more appropriate.



Low Band
TX BW=1.368 GHz
RX NF=4.2 dB
CCA Detection BW: 200 kHz

Our CCA scheme allows monitoring channel activity during preamble acquisition to minimize probability of false alarm acquisition attempts.

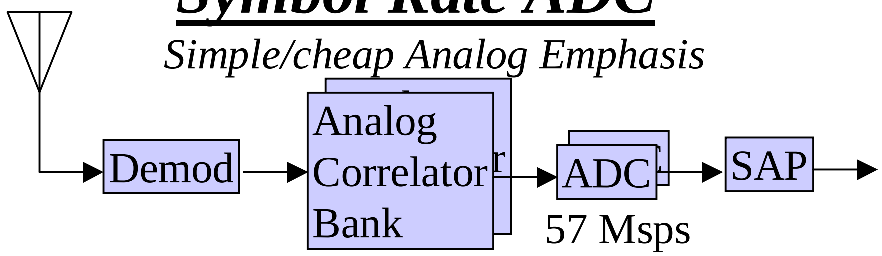
Scalability Across Applications

watts/ performance/ dollars	***Implementation Scaling***
Transmit-only applications	No IFFT DAC – super low power Ultra simple yet capable of highest speeds
Big Appetite	RF sampling Growth with DSP MUD, digital RFI nulling, higher MBOK Gets easier as IC processes shrink
Medium Appetite	Analog with few RAKE 1X, 2X, or 4X chip rate sampling Digital RAKE & MBOK
Smallest Appetite	Symbol-rate sampling with 1 RAKE

Scaleable power/cost/performance Adaptable to broad application classes

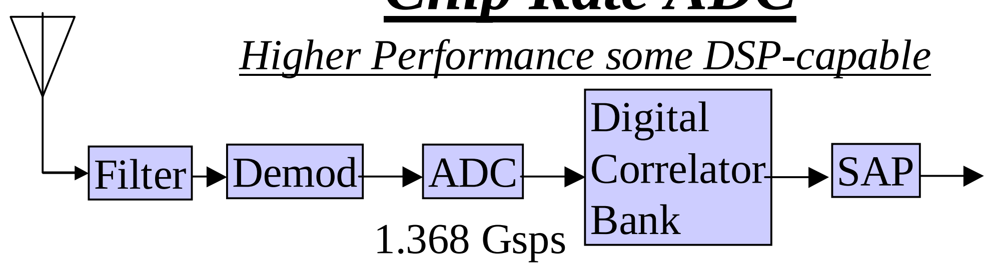
Symbol Rate ADC

Simple/cheap Analog Emphasis



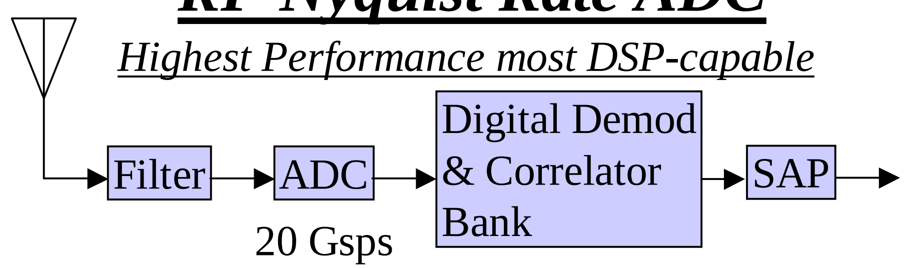
Chip Rate ADC

Higher Performance some DSP-capable



RF Nyquist Rate ADC

Highest Performance most DSP-capable



Location Awareness and the 802.15.3a ALT PHY

- The FCC recognized that UWB offers a unique high-precision location potential
- This ranging capability is recognized by the wireless industry
- Ranging/Location Awareness were identified as requirements for TG3a ALT PHY
- The choice of the waveform for the 15.3a ALT PHY will impact the ranging and location capability of a 15.3a WPAN systems

Location Awareness and the 802.15.3a ALT PHY

- There is significant interest
- Safety of life etc.
- On Monday of this week numerous presentations were made before 802.15 interest group on ranging/location applications for WPAN technology

Companies List Ranging As Important

Source	Affiliation(s)	Pages
Patrick Houghton	Aetherwire & Location	4-12
Jason Ellis	General Atomics	13-17
Lajuane Brooks	LB&A Consulting	18-21
John Lampe	Nanotron Technologies	22-24
Uri Kareev	Pulsicom	25-28
In Hwan Kim	Samsung Electronics	29-34
Ted Kwon	Samsung / CUNY	35-39
Mark Bowles	Staccato Communications	40-43
Philippe Rouzet	ST Microelectronics	42-56
Oren Eliezer	InfoRange	57-61
Kai Siwiak	TimeDerivative / Q-Track	62-65
Peter Batty	Ubisense Limited	66-71
Serdar Yurdakul	Wisair	72-80
Richard Nowakowski	City of Chicago- OEMC R&D	81-88
15.4IGa Leadership	**(Summary & Recommendation)**	**89**

Source: Document 04/266r0

Typical Range/Location Accuracy Requirements for WPAN in TG4 IG

Contributor Affiliation	Applications	Ranging Resolution
Aetherwire & Location	Military	10 cm
General Atomics	Inventory Control, Sensors, Security	3 inches to 3 feet accuracy
ST Microelectronics	Tracking and safety purposes, medical applications	10s of cm or 1 m
TimeDerivative / Q-Track	Numerous	10 – 300 cm
Ubisense Limited	Healthcare, workplace, security	15 cm

CE Ranging/Location Requirements

- The CE SIG (Panasonic, Philips, Samsung, Sharp, Sony) presented a set of CE requirements for the TG3a Alt PHY (Document 03/276r0)
- The purpose of the CE SIG is to provide TG3a with a consensus view of requirements and criteria priorities on Alt PHY for consumer electronics applications
- Purpose is to assist TG3a in selection of an Alt PHY which can be successful in consumer markets

Criteria	**Home Theatre**	**Portable**
Ranging/Location Awareness	Location awareness is desirable: range 10m, resolution <30cm	Location awareness is highly desirable: range 10m, resolution <30cm

Ranging Resolution Depends on Signal Bandwidth

- Accurate and precise ranging depends
  - Coherently processed signal bandwidth
  - Latency in the measurement of the round-trip time
    - which drives the required clock accuracy
- DS-CDMA uses direct time-domain detection and
  - Offers higher coherent bandwidth
  - Offers the lowest latency in measuring round-trip time
- OFDM
  - Far more complex - operates in frequency domain
  - Round trip measurement appears to require lots of processing within this loop (FFT – Complex Multiply – IFFT etc.)
    - Requires higher clock accuracy to provide less range accuracy
  - Coherently processed bandwidth is smaller
- Selection of PHY affects the
  - Ability to support ranging
  - Accuracy
  - Cost

Multiband OFDM Location Awareness Support

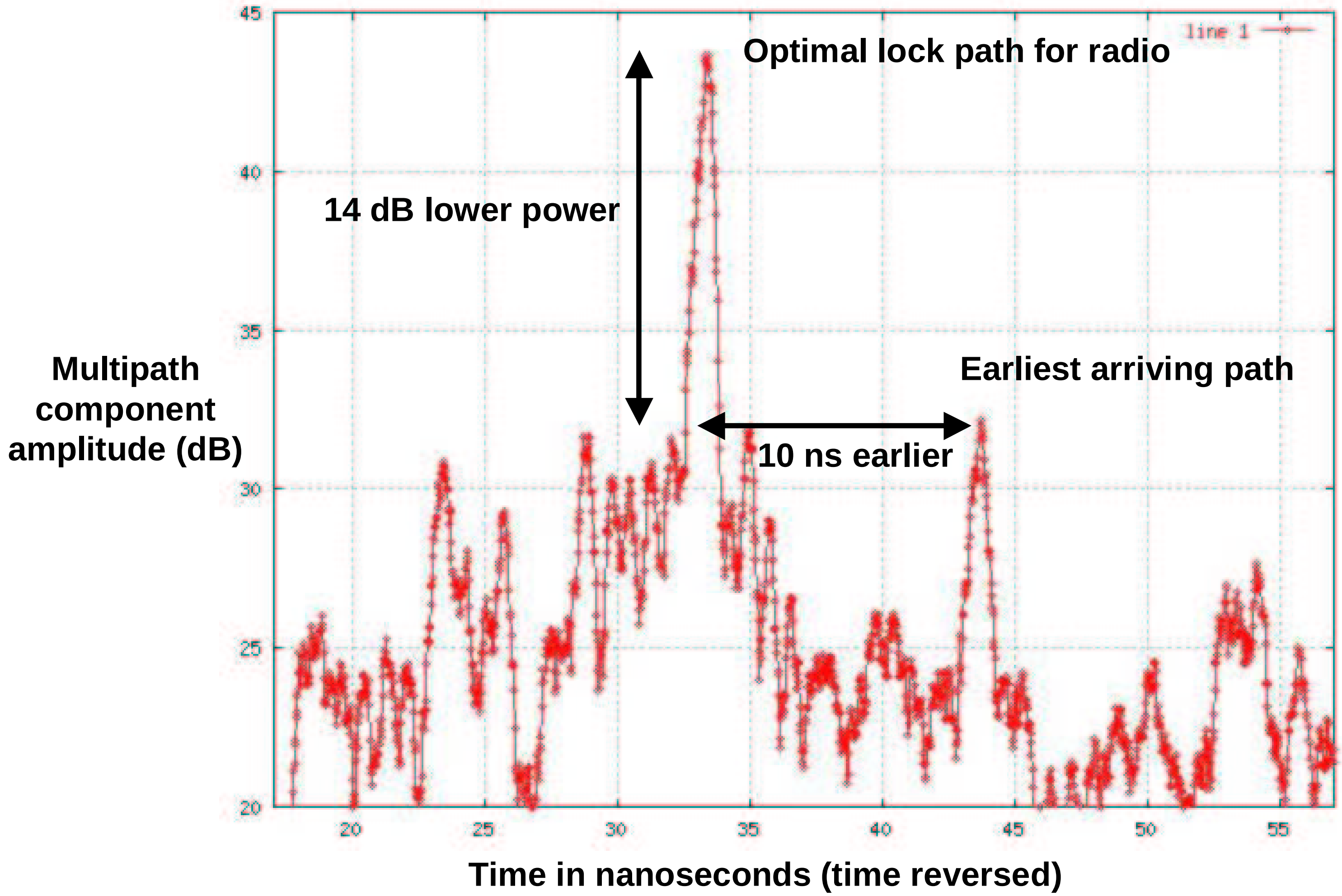
- OFDM self-reported support for Location Awareness:
  - "The TFI-OFDM system has the capability to determine the relative location of one device with respect to another. The relative location information can be obtained by estimating the round trip delay between the devices. As the bandwidth of each sub-band in the TFI-OFDM system is 528 MHz, the minimum resolvability between the multi-path fingers is 1.9 ns. Hence, the minimum level of accuracy that can be obtained for the location awareness is 57 cm. " (TFI-OFDM Proposal, 03/142r2 page 56)
- Mechanism to do this was not disclosed

Location Awareness Support for DS-CDMA PHY Proposals

- Other TG3a PHY proposals have between 2 and 7+ GHz of bandwidth
- Corresponding range resolution is roughly 4 to 13 cm

XtremeSpectrum has demonstrated high resolution ranging capability to better than 10 cm resolution at 20 m range

Measured Multipath Resolution with an Operating XtremeSpectrum Radio



Conclusions on Location Awareness

- Location Awareness is a unique opportunity that the TG3a ALT PHY can provide for a wide range of critical WPAN applications
- Precision location capability is fundamentally determined by the choice of ALT PHY waveform
- Multiband OFDM fails to provide low-cost, high-precision location awareness capability identified for many WPAN applications
- The XtremeSpectrum/Motorola DS-CDMA proposal provides ranging and location capability that exceeds all location awareness requirements for WPAN applications

Partial Comparison Table

FEATURE	XSI	MBOA-OFDM
All CMOS	RF & Digital Proven in .18u Scales to better performance in 90 nm	Projected in 90nm – no advantage
Simple Antenna	Simple etch on PCB – multiple choices	Same – no advantage
Early time to market	Production ICs here today	Chips no earlier than 2005
Early market adoption	Production ICs here today	Chips no earlier than 2005
Robust to multipath & Complexity	2-RAKE equal to OFDM performance 5-RAKE superior to OFDM perf	More complex for same perf Same complexity for less perf
CSMA Support	No Preamble – Data independent 5us ID, mag of all neighboring nets	Requires Preamble
Could work with 802.11 MAC	YES – CSMA support allows this	NO – SNR much lower Requires Preamble
PSD Backoff	1.3 to 2.2 dB	1.3 dB
Xmit Only	Very Simple, Very Low Power	Full DAC and IFFT required
US Reg's Compliance	Assured	Questionable at best. FH hopping rules may drop range by almost 1/2

Key Features Meet Application Requirements

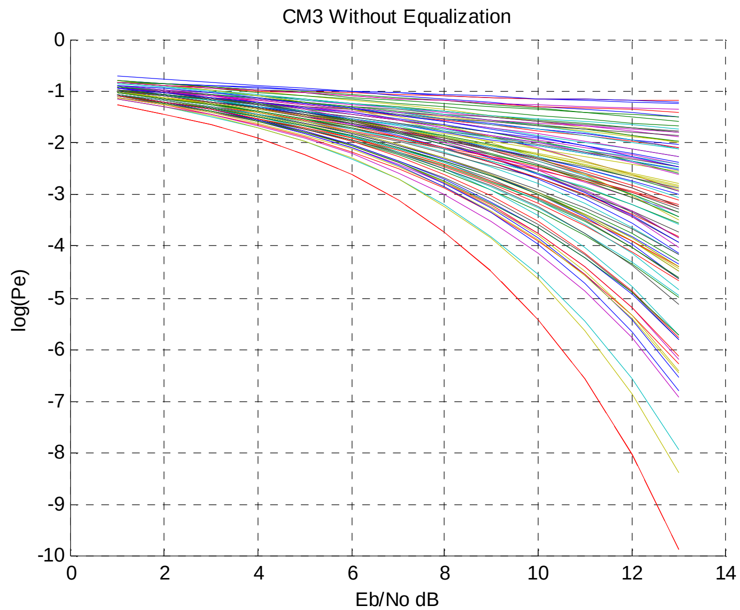
- Multi-User (Multi-Piconet) Capable
  - Piconets are independent – my TV or PC doesn't coordinate/sync with my neighbor's
  - Every network supports full data-rate
    - Even at extended data rates
  - Allows very close adjacent piconets
    - Two apartments with antennas on opposite sides of the same wall
- Streaming Video Capable
  - High QOS, High Speed, Low Latency
  - Works In Home/Office/Warehouse RF environments -- Dense & High Multipath
- Low Complexity
  - Small Die Size, Low Parts Count – Low Cost
  - Low Power – Light-Weight Long-Life Batteries

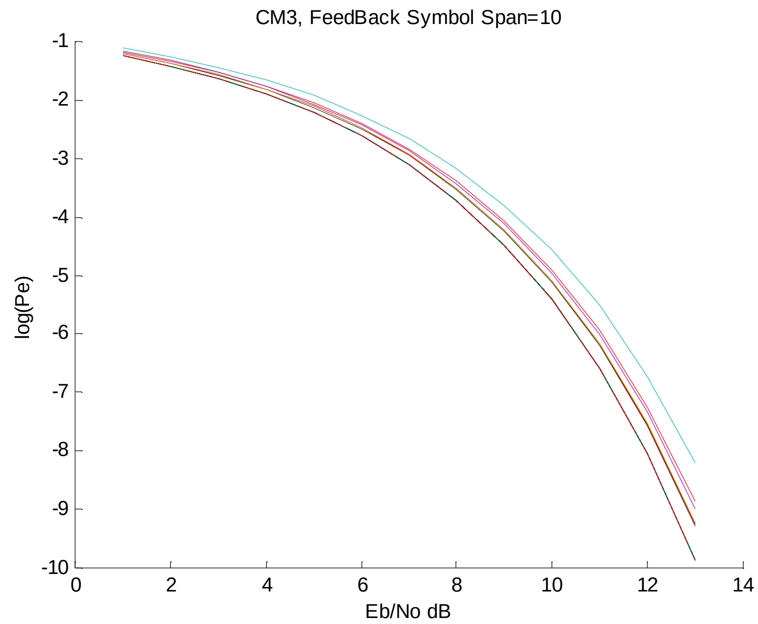
Key Features Meet Application Requirements

- Spectrally Efficient[1]
  - Meet Regulations and Coexists with others
    - Proven — 802.11a,b – Cordless & Cell Phones (.9, 2.4, 5.8 GHz) – Microwave ovens – GPS
  - Modulation results low Eb/No – Highest data-rate & range versus TX emission level.
  - Coded modulation method allows future growth
- Growth Path To Higher Data Rates With Backward Compatibility
  - Architecture allows component (FEC, each receiver channel, etc) usage to be adjusted such that incremental hardware additions result in the highest incremental SNR improvement.

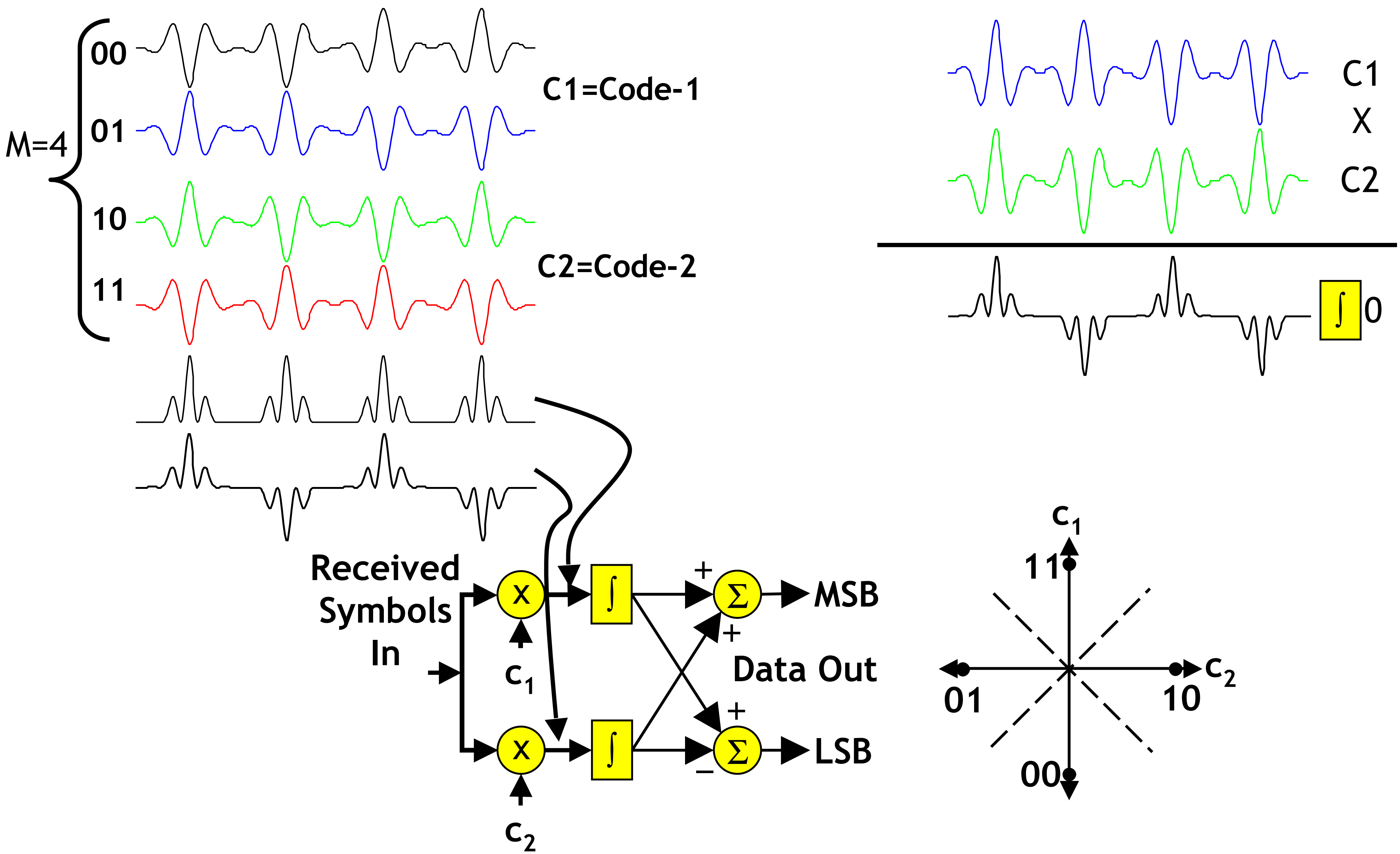
Note 1: Reference doc IEEE802.15-03/211

DFE (Decision Feedback Equalization) used for LOS channels and NLOS channels (dotted red line represents theoretical performance). Results shown for High Band, Symbol Duration=1/114e6 seconds.



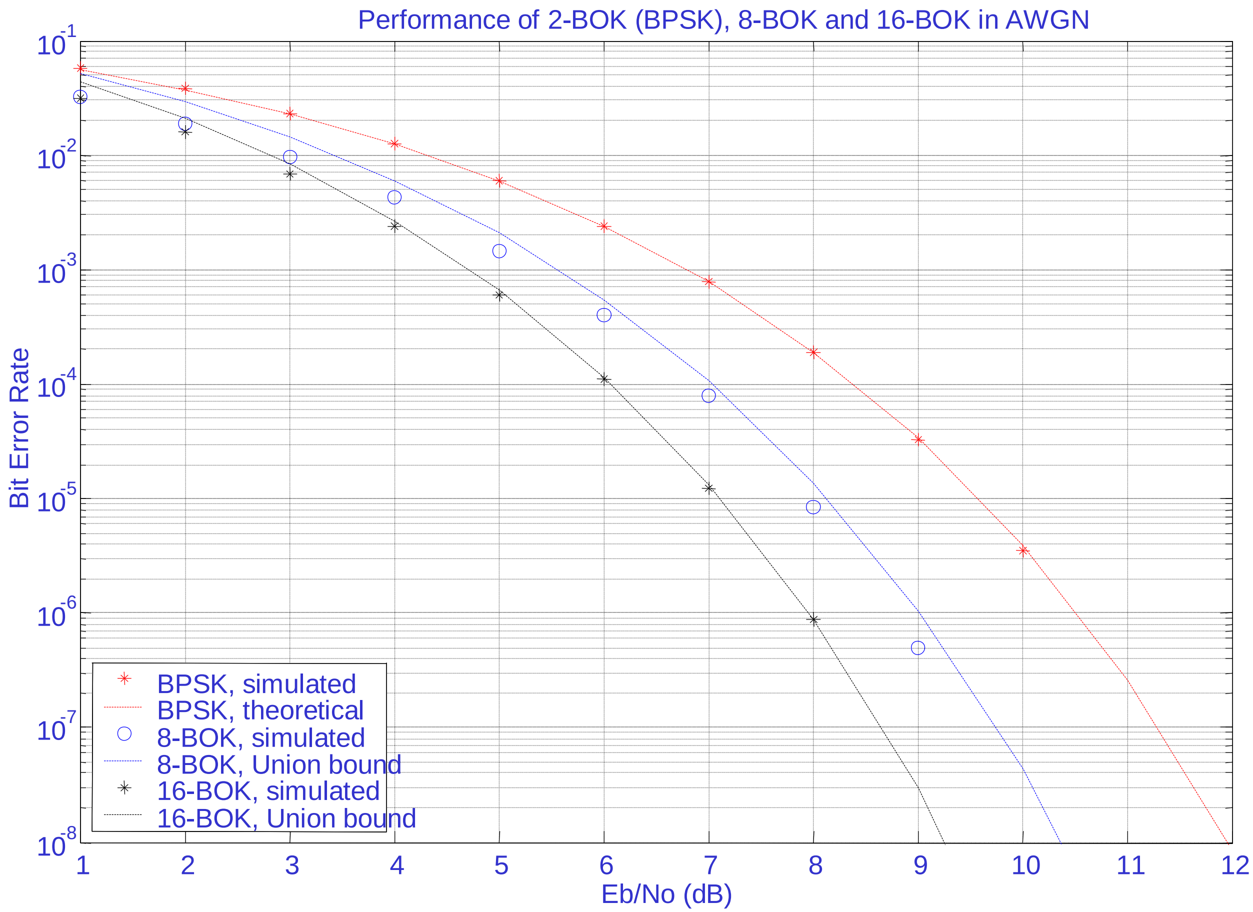


M-BOK (M=4) Illustration

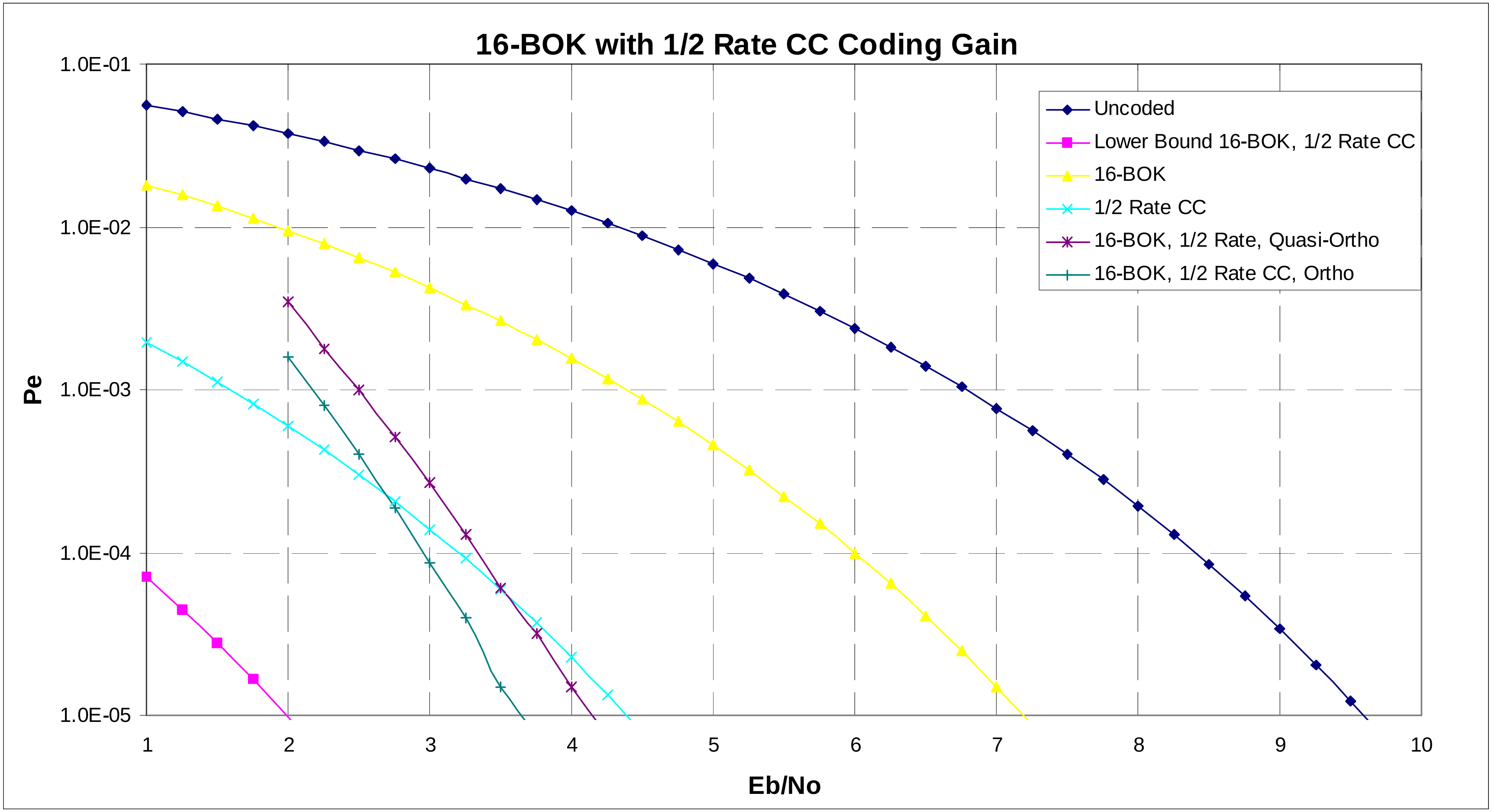


MBOK Coding Gain

- MBOK used to carry multiple bits/symbol
- MBOK exhibits coding gain compared to QAM

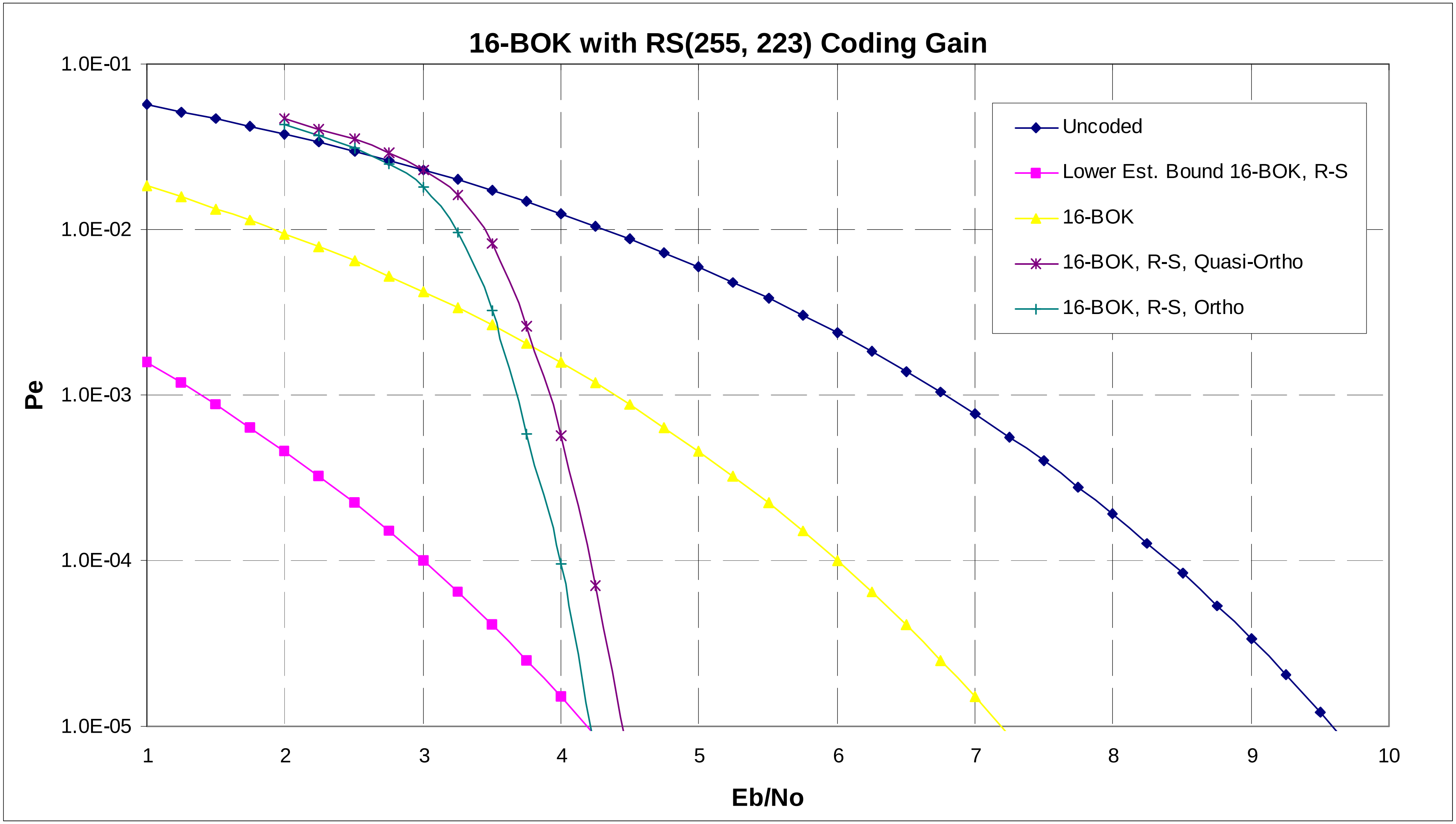


16-BOK with ½ Rate CC Coding Gain



We are falling above the lower bound … this is due to sub-optimal soft decision mapping of the BOK symbols to bits. This is on-going work and we expect to have this resolved in the near future.

16-BOK with RS(255,223) Coding Gain



The lower bound estimate was actually done only at 10e-5; so while the lower bound is exact at 10e-5, it is only an estimate above 10e-5. Notice that with orthogonal codes we exactly fall on the lower bound.

Technical Feasibility

- BPSK operation with controlled center frequency has been demonstrated in the current XSI chipset with commensurate chipping rates at 10 meters
- Current chipset uses convolutional code with Viterbi at 100 Mchip rate. We've traded-off Reed-Solomon vs. Viterbi implementation complexity and feel Reed-Solomon is suitable at higher data rates.
- Long preamble currently implemented in chipset … have successfully simulated short & medium preambles on test channels.
- DFE implemented in the current XSI chipset at 100 Mbps. Existence proof is that IEEE802.11b uses DFE with CCK codes, which is a form of MBOK … so it can be done economically.
- NBI filtering is currently implemented in the XSI chipset and has repeatedly been shown to work.

http://www.xtremespectrum.com/PDF/xsi_trinity_brief.pdf

Glossary

DS: direct sequence
CDMA: code division multiple access
PSK: phase shift keying
M-BOK: multiple bi-orthogonal keying
RX: receive
TX: transmit
DFE: decision feedback equalizer
PHY: physical layer
MAC: multiple access controller
LB: low band
HB: high band
RRC: root raised cosine filtering
LPF: low pass filter
FDM: frequency division multiplexing
CDM: code division multiplexing
TDM: time division multiplexing
PNC: piconet controller
FEC: forward error correction
BPSK: bi-phase shift keying
QPSK: quadri-phase shift keying
CCA: clear channel assessment
RS: Reed-Solomon forward error correction
QoS: quality of service
BER: bit error rate
PER: packet error rate
AWGN: additive white gaussian noise
ISI: inter-symbol interference
ICI: inter-chip interference

DME: device management entity
MLME: management layer entity
PIB: Personal Information Base
RSSI: received signal strength indicator
LQI: link quality indicator
TPC: transmit power control
MSC: message sequence chart
LOS: line of sight
NLOS: non-line of sight
CCK: complementary code keying
ROC: receiver operating characteristics
Pf: Probability of False Alarm
Pd: Probability of Detection
RMS: Root-mean-square
PNC: Piconet Controller
MUI: Multiple User Interference