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

**Submission Title:** [Merger#2 Proposal DS-CDMA ]
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**Re:** [Response to Call for Proposals, document 02/372r8, replaces doc 03/123]

**Abstract:** []

**Purpose:** [Summary Presentation of the Merger #2 proposal.]

# This Contribution is the Initial Proposal for a Technical Merger Between:

- Communication Research Lab (CRL)
- ParthusCeva
- XtremeSpectrum, Inc

# Major Contributors For This Proposal Update

| | |
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## Supported by:

Motorola

Members of CRL-UWB Consortium

# CRL-UWB Consortium

- *Organization à*

  UWB Technology Institute of CRL and associated over 30 Manufacturers and Academia.

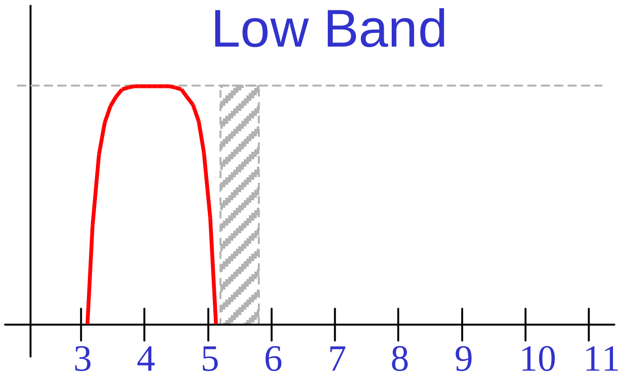
- *Aim à*
  - R&D and regulation of UWB wireless systems.
  - Channel measurement and modeling with experimental analysis of UWB system test-bed in band (*960MHz*, *3.1- 10.6GHz*, *22-29GHz*, and *over 60GHz*).
  - R&D of low cost module with higher data rate over 100Mbps.
  - Contribution in standardization with *ARIB*, *MMAC*, and *MPHPT* in Japan.

# Presentation Roadmap

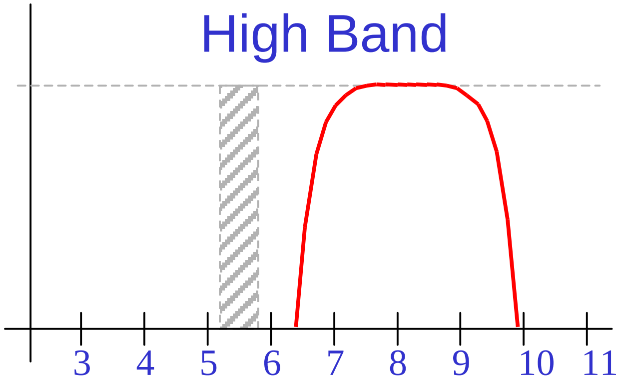
- Proposal Summary
  - Overview
  - Spectral flexibility
  - Improvements
- Scalability
- Coexistence & regulatory compliance
- Multi-piconet operation
- Performance
- Implementation complexity
- Additional technical material

# Proposal Summary

# Two Band DS-CDMA

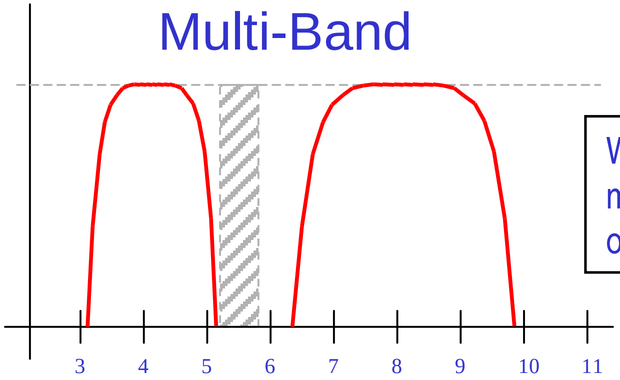


- Low Band (3.1 to 5.15 GHz)
  - 29 Mbps to 450 Mbps



- High Band (5.825 to 10.6 GHz)
  - 29 Mbps to 900 Mbps

3 Spectral Modes of Operation



- Multi-Band (3.1 to 5.15 GHz plus 5.825 GHz to 10.6 GHz)
  - Up to 1.35 Gbps

With an appropriate diplexer, the multi-band mode will support full-duplex operation (RX in one band while TX in the other)

# Example Low Band Modes

| Info. Data Rate | Constellation | Symbol Rate | Quadrature | FEC Rate |
|---|---|---|---|---|
| 29 Mbps | 2-BOK | 57 | No | R = 0.50 |
| 57 Mbps | 4-BOK | 57 | No | R = 0.50 |
| 86 Mbps | 4-BOK | 57 | No | R = 0.75 |
| 114 Mbps | 4-BOK | 57 | Yes | R = 0.50 |
| 112 Mbps | 64-BOK | 42.75 | No | R = 0.44 |
| 200 Mbps | 4-BOK | 57 | Yes | R = 0.875 |
| 224 Mbps | 64-BOK | 42.75 | Yes | R = 0.44 |
| 448 Mbps | 64-BOK | 42.75 | Yes | R = 0.87 |

*Table is representative - there are multiple other rate combinations offering unique QoS in terms of Rate, BER and latency*

*R=0.44 is concatenated ½ convolutional code with RS(55,63)*
*R=0.50, 0.75 & 0.875: [punctured] k=7 convolutional code*
*R=0.87 is RS(55,63)*

# Example High Band Modes

| Info. Data Rate | Constellation | Symbol Rate | Quadrature | FEC Rate |
|---|---|---|---|---|
| 29 Mbps | 2-BOK | 57 | No | R = 0.50 |
| 57 Mbps | 2-BOK | 114 | No | R = 0.50 |
| 114 Mbps | 4-BOK | 114 | No | R = 0.50 |
| 112 Mbps | 64-BOK | 42.75 | No | R = 0.44 |
| 200 Mbps | 4-BOK | 114 | No | R = 0.875 |
| 224 Mbps | 64-BOK | 85.5 | No | R = 0.44 |
| 450 Mbps | 64-BOK | 85.5 | Yes | R = 0.44 |
| 900 Mbps | 64-BOK | 85.5 | Yes | R = 0.87 |

*Table is representative - there are multiple other rate combinations offering unique QoS in terms of Rate, BER and latency*

*R=0.44 is concatenated ½ convolutional code with RS(55,63)*
*R=0.50 convolutional code*
*R=0.87 is RS(55,63)*

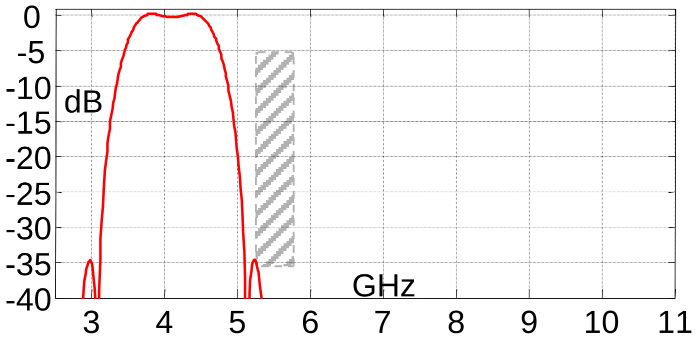
# Codes for MBOK & SOP

- M-ary Bi-orthogonal Keying (MBOK) provides improved power efficiency relative to BSPK/QPSK
  - Ideal for power-constrained UWB operations
  - Length-24 & length-32 ternary (-1/0/+1) codes
  - 1,2,3,or 6 bits of data sent with each code symbol
  - Supports high data rates without increasing symbol rate
- Multiple code sets to support multiple piconets
  - Chosen for low cross-correlation (isolation) and flat spectrum
  - Chip rates are slightly offset for each code set to minimize cross-correlation

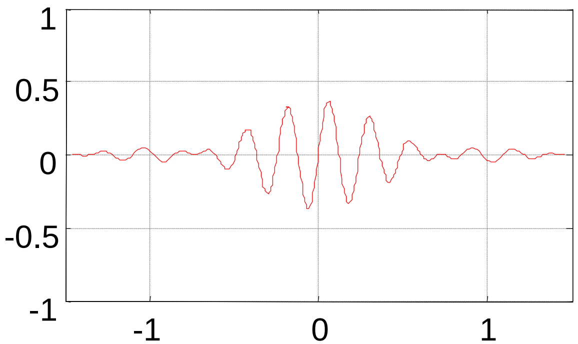
# Proposal Improvements

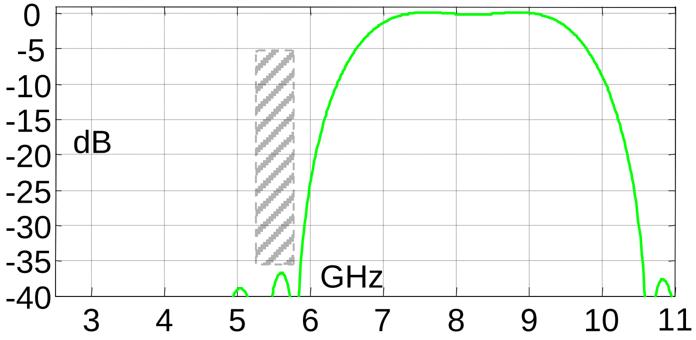
- Soft-Spectrum Adaptation (SSA): Spectral flexibility for coexistence and performance
  - Flexible pulse shaping
  - Protection for sensitive bands with no coordination or handshaking requirements
  - Potential for improved link performance
- Advanced error protection mode: Combined Iterative De-mapping/Decoding (CIDD)
  - Simple and scalable FEC modes to simultaneously reduce complexity and improve performance and scalability

# Joint Time Frequency Reference Wavelet Family

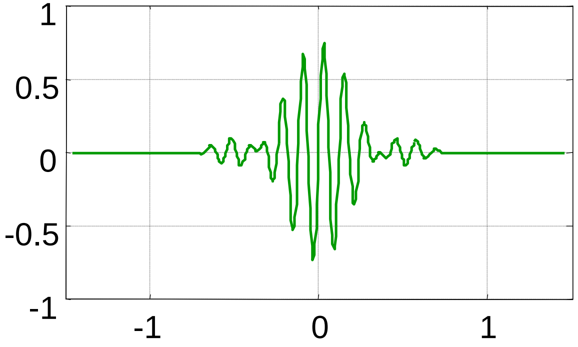


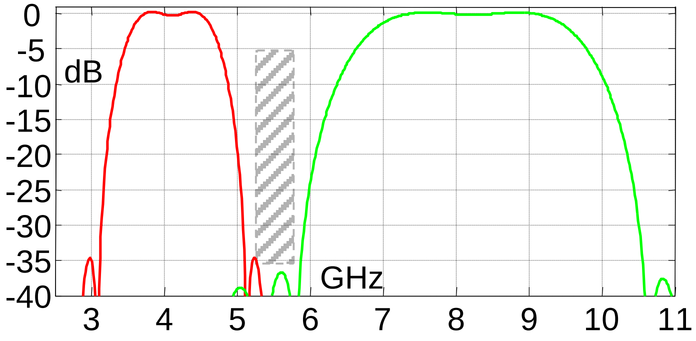
Long
Wavelet



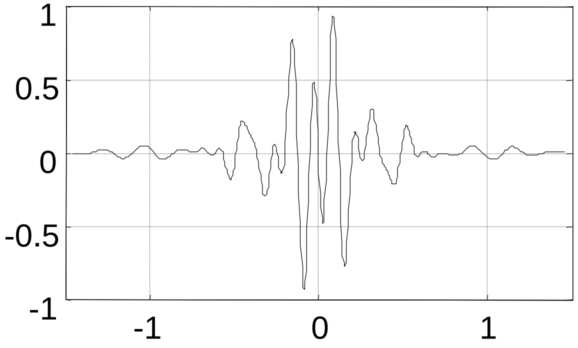


Mid
Wavelet

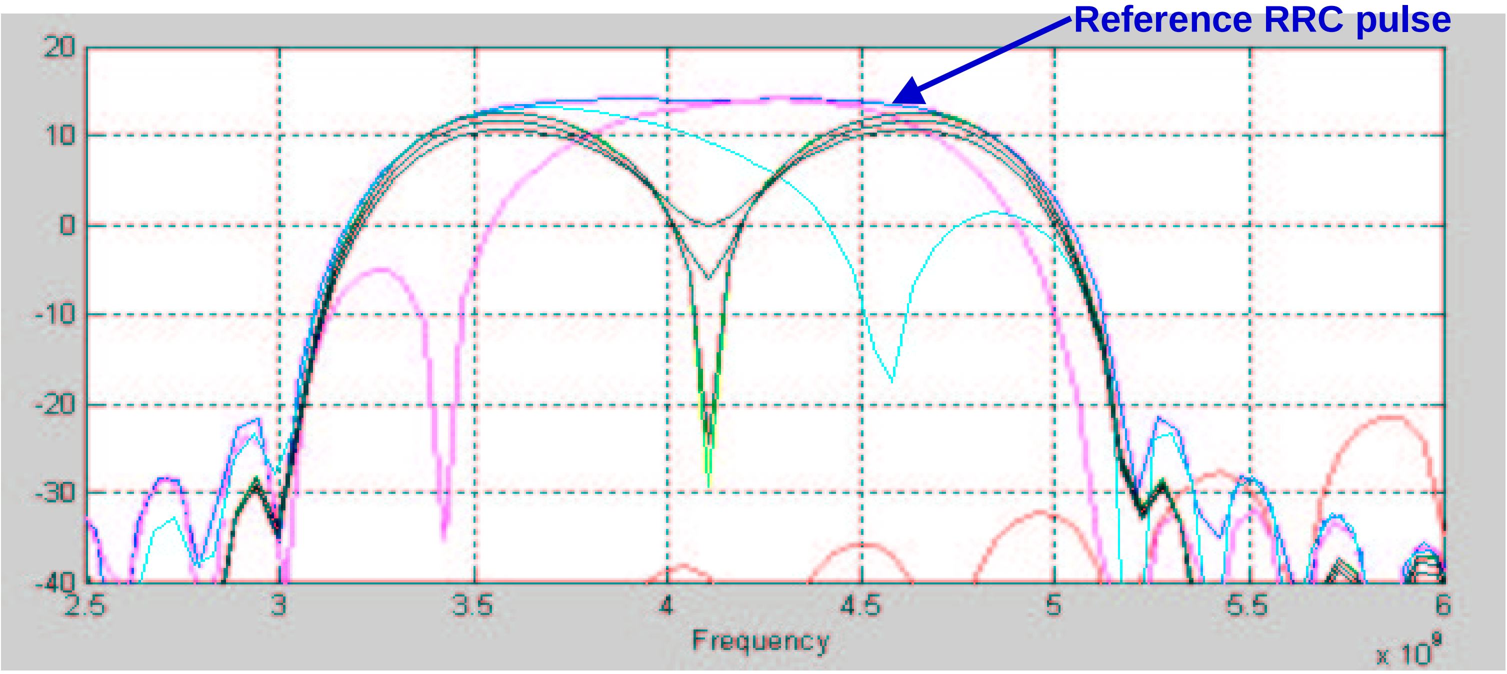




Example
Duplex
Wavelet

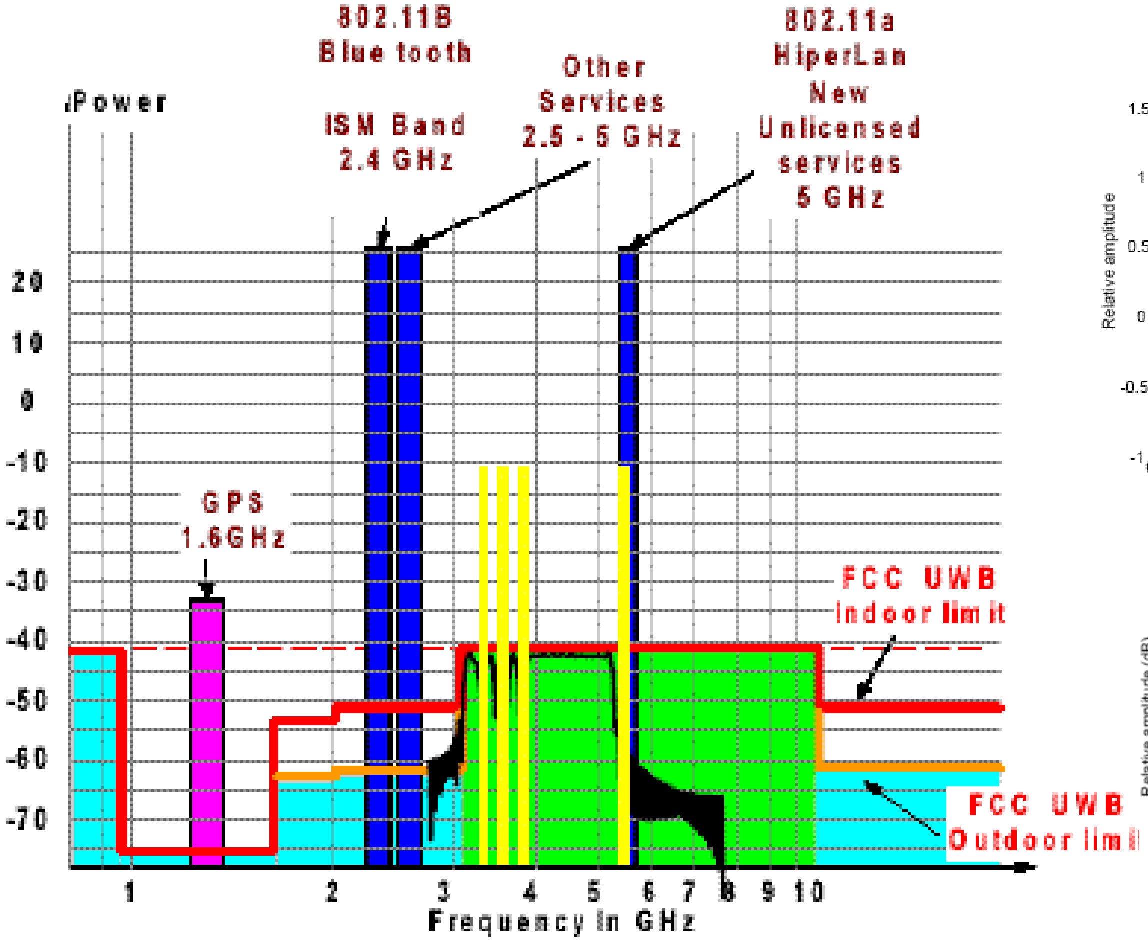


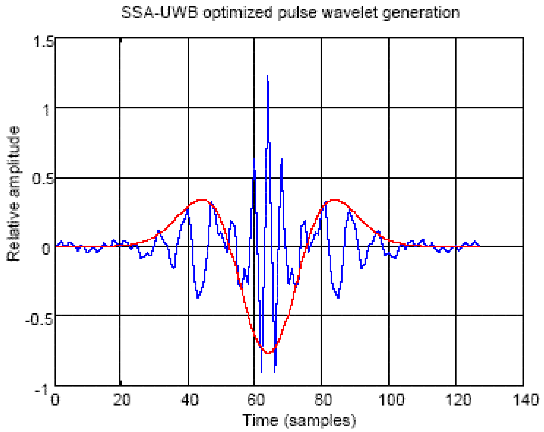
# Proposed Soft-Spectrum Wavelets

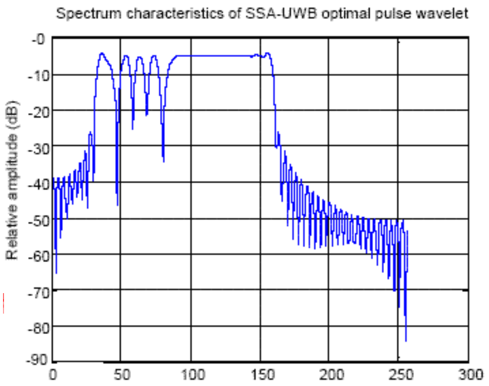


- Standard defines “reference” pulse for each band
- Soft-spectrum used to define modified pulse shapes
  - Allows controlled “notches” to protect sensitive frequencies
  - Can also make “flatter” pulses to increase Tx power
  - Requires no Tx-Rx coordination

# Optimized SSA-UWB Pulse for Coexistence with Radio Astronomy Bands







Frequency Samples

# DS-CDMA with SSA Provides Simpler Spectral Flexibility

- SSA flexible transmit pulse shape
  - Flexibility to protect sensitive frequency bands or improve link performance
  - Different implementations optimize pulse for different requirements
  - Standard provides limit on correlation loss due to different pulse shapes (3 dB limit proposed)
  - Many receive architectures affected only by difference in Tx power
- Requires no handshake or message protocol to establish or coordinate
  - No changes in data rate, interleaver, etc.
- Provides a path to global harmonization and compliance using optimized SSA-UWB pulse wavelets

# MB-OFDM Dynamic Bands and Tones Requires Dynamic Coordination

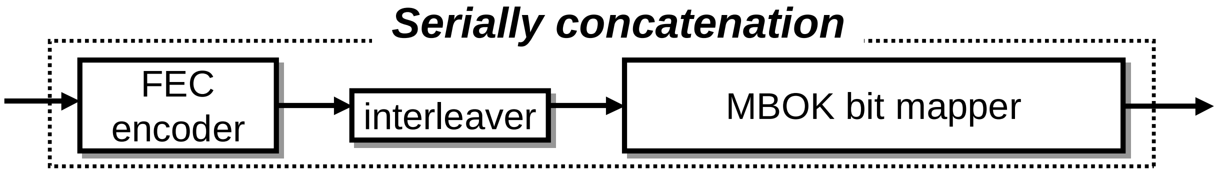
- MB-OFDM proposes that “bands and tones can be dynamically turned on/off” for enhanced coexistence or to meet changing regulations
  - Dynamically dropping/adding tones or bands would require a message protocol to dynamically coordinate link parameter changes between transmitter and receiver:
    - Dynamic changes in bit-to-carrier tone mapping?
    - Changes to interleaver? Changes to hopping patterns/codes?
    - All would require dynamic coordination between transmitters and receivers – No details have been provided on this mechanism
  - Unknown impact on link and piconet performance
    - Loss of diversity protection against Rayleigh fading for affected bits?
    - Impact on link performance, data throughput, SOPs, or acquisition?

# Powerful and Scalable Error Correction Coding

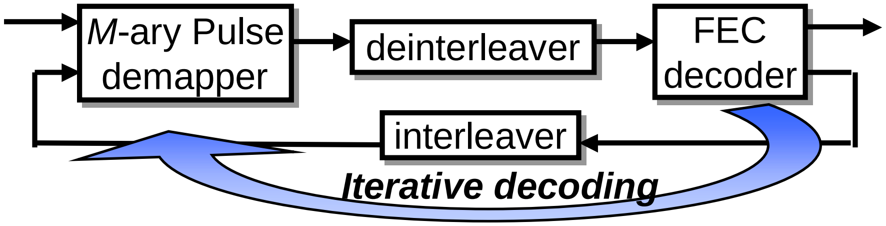
- Original forward error uses k=7 convolutional code for robust link performance
- Concatenation with Reed-Solomon (63,55) code
  - Can be used as optional outer code in conjunction with convolutional code for improved coding gain
- Additional k=4 convolutional code support to enable use of flexible CIDD iterated decoding technology
  - Proposed transmitter will be required to contain k=4 and k=7 convolutional encoder – minimal complexity impact
  - Up to 2 dB additional coding gain available
  - Interleaver length will be chosen to ensure that decoding latency is acceptable
  - Further analysis of iterated k=4 code in multipath conditions is still underway

# Channel Coding and Decoding

- *Combined Iterative demapping/decoding (CIDD)*
  - The structure of coded UWB systems can be viewed as *serially concatenation code*



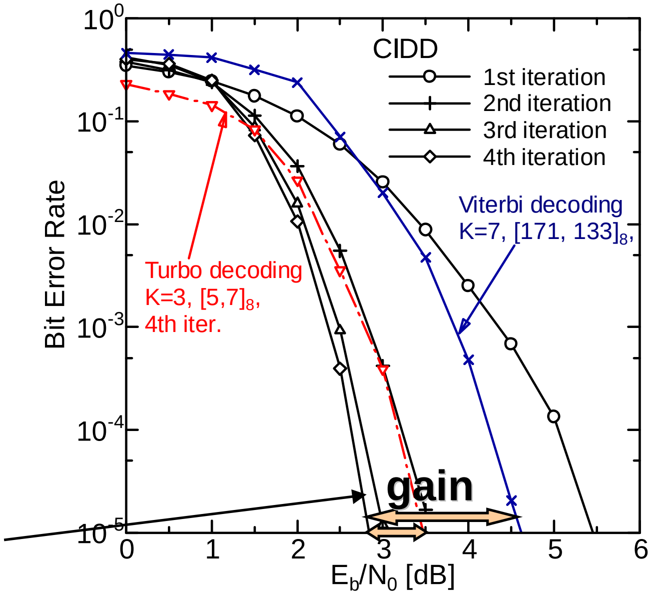
  - Based on this viewpoint, iterative decoding strategy is available



## *Performance of CIDD*

- *4-ary BOK and 4-ary PSM (125Mbps)*
- *K*=3 convolutional coding [*2]
- Random bit-wise interleaver
- Interleaver length is 512 bits
- Single user and AWGN channel

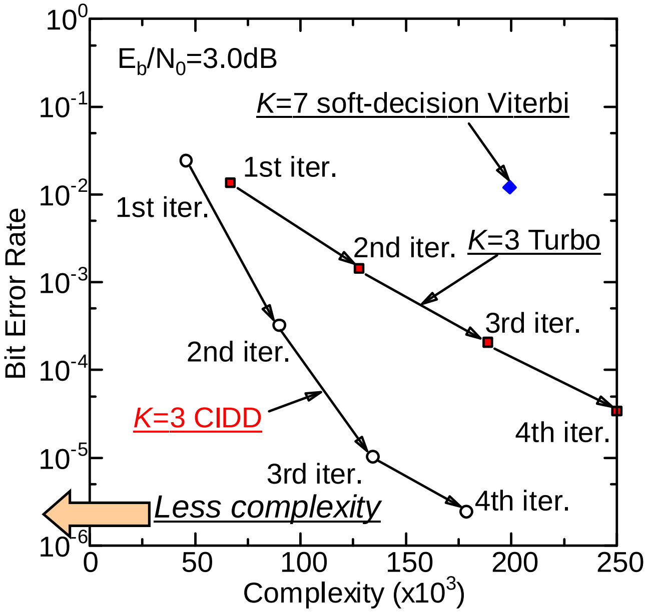
*CIDD provides the best BER performance !*



## *Complexity of CIDD*[*1]

- *K*=3 complexity is 1/8 less than *K*=7[*2]
- *M*-ary pulse shape demapper complexity is 1/10 less than *K*=7

*CIDD is less complexity than turbo and K=7 convolutional decoder.*

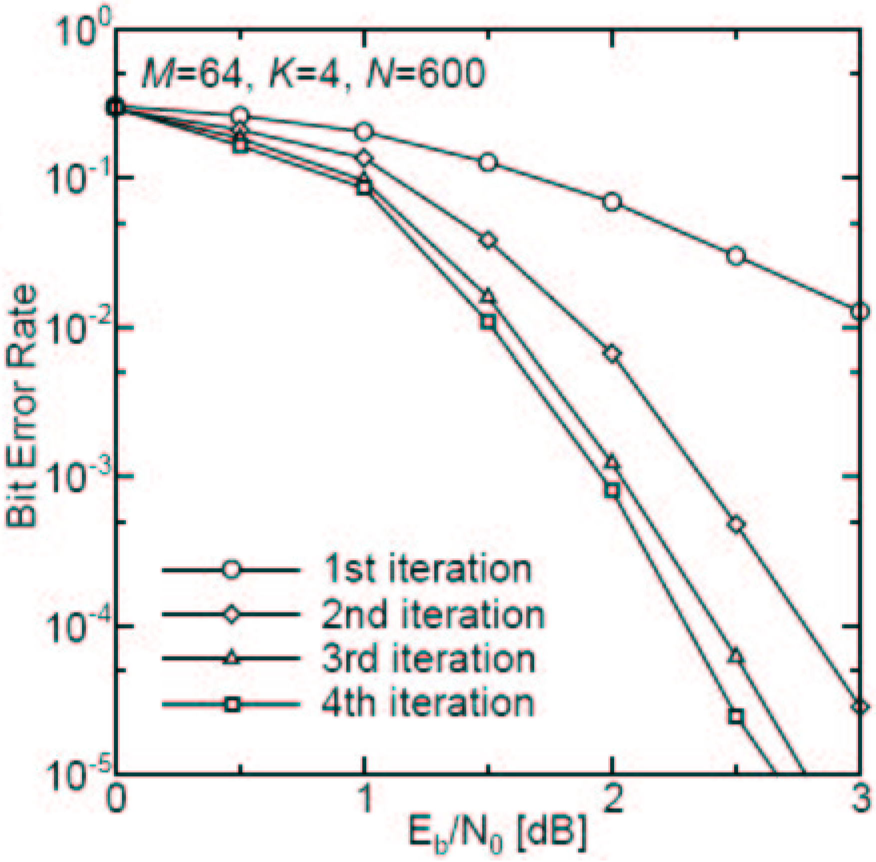


*1: P.H.Y. Wu, "On the complexity of turbo decoding algorithm, " Proc. of IEEE VTC'01-Spring, vol.2, pp.1439-1443, May 2001.

*2: Proposed CIDD code uses k=4 convolutional code, results show are for k=3 code, Results for k=4 are under development.

# Iterated Decoding Performance for 64-BOK

- 64BOK
- Half-rate and K=4 convolutional code
- N=600bits
- Ternary code
- Uniform random interleaver



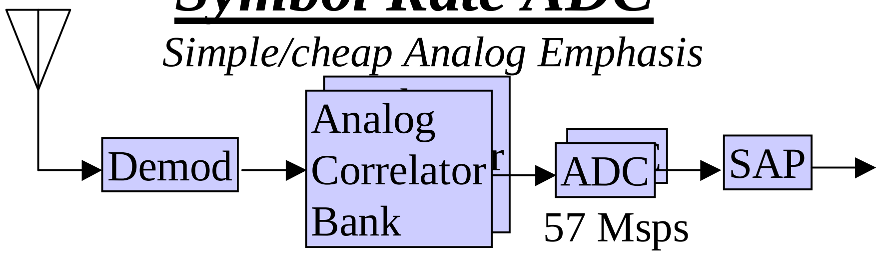
# Fixed Transmitter Spec
# Scalable Receivers Across Applications

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



Demod

Analog Correlator Bank

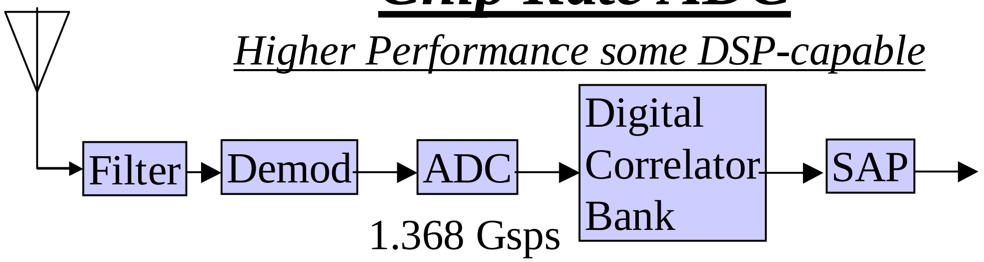
ADC

57 Msps

SAP

## Chip Rate ADC

*Higher Performance some DSP-capable*



Filter

Demod

ADC

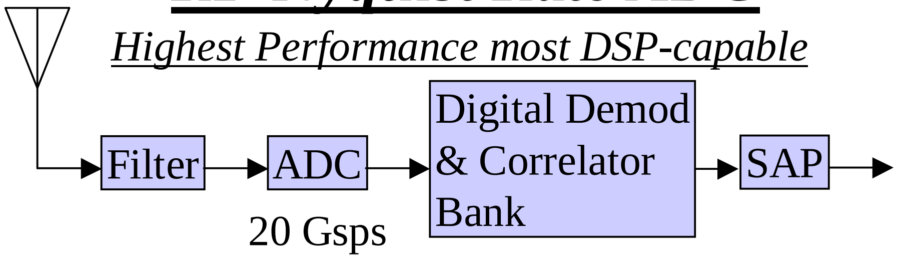
1.368 Gsps

Digital Correlator Bank

SAP

## RF Nyquist Rate ADC

*Highest Performance most DSP-capable*



Filter

ADC

20 Gsps

Digital Demod & Correlator Bank

SAP

# Coexistence with Existing Services and Regulatory Compliance

# UWB Interference and Regulatory Compliance

- The DS-CDMA is clearly compliant with the FCC rules for UWB
- After the initial proposal of MB-OFDM, some TG members expressed concern about its compliance with FCC rules
  - Frequency hoppers were not analyzed or tested in the FCC rulemaking process
  - Rules state that FCC compliance testing will require stopping any FH – thus a potential 5-10 dB reduction in transmitted power
- No clarification has been provided by the FCC either directly or through the MBOA

# Analysis Requested by FCC

- Primary concern is that the FCC would determine that FH-UWB results in higher interference levels than those anticipated by R&O
- If so, it would be difficult for the FCC to change rules to accommodate MB-OFDM – even if it wanted to
  - Significant opposition to initial UWB by other users
  - Any move to loosen rules would be strenuously opposed
- Therefore, the FCC encouraged the IEEE to evaluate interference potential of any proposed standard
- Initial analysis indicated that MB-OFDM interference is worse than AWGN or DS-CDMA at same power

# MB-OFDM Interference is Identical to that of Prohibited *Gated UWB* Signals

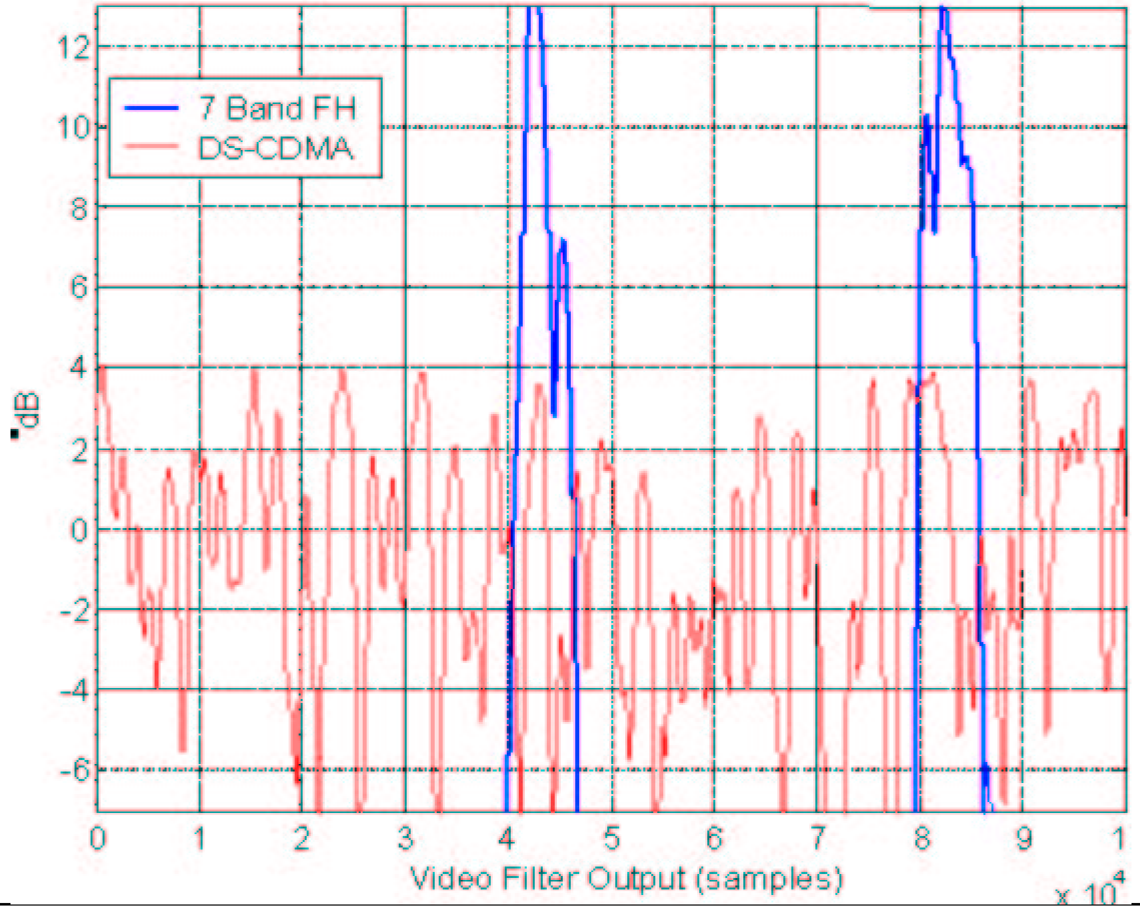
- Further analysis now indicates that FH-UWB also leads to interference levels that exceed those anticipated by FCC in R&O
    - Followed analysis approach used by NTIA
    - MB-OFDM has interference characteristics identical to *gated UWB signals* – specifically prohibited by the rules unless their transmit power is reduced
    - Provides a clear indication that these interference levels exceed those considered acceptable in the R&O
- Gated UWB signals with the same interference characteristics as MB-OFDM would require 5-10+ dB *power reduction* to comply with existing rules

# Gated UWB Interference Restricted by UWB Rules

- NTIA and FCC wrote the UWB rules to differentiate between *gated* and *non-gated* UWB signals
  - Gated signals are required to reduce transmit power to protect potential victims from excessive pulsed interference
  - 41 CFR Part 15.521 (d): "If pulse gating is employed where the transmitter is quiescent for intervals that are long compared to the nominal pulse repetition interval, measurements shall be made with the pulse train ***gated on***."
- MB-OFDM is a hybrid waveform that appears as a *non-gated* signal in its full FH-spread bandwidth, but appears as a *gated* signal to any victim receivers
  - Escapes classification as a *gated* UWB signal under rules
  - Still results in the same interference potential as a *gated* signal that has not applied the required power reduction

# MB-OFDM Signal Appears as a *Gated* Signal to Potential Victim Receivers

**DS and 1/7 duty-cycle OFDM Real-time Power in a 10 MHz Bandwidth**

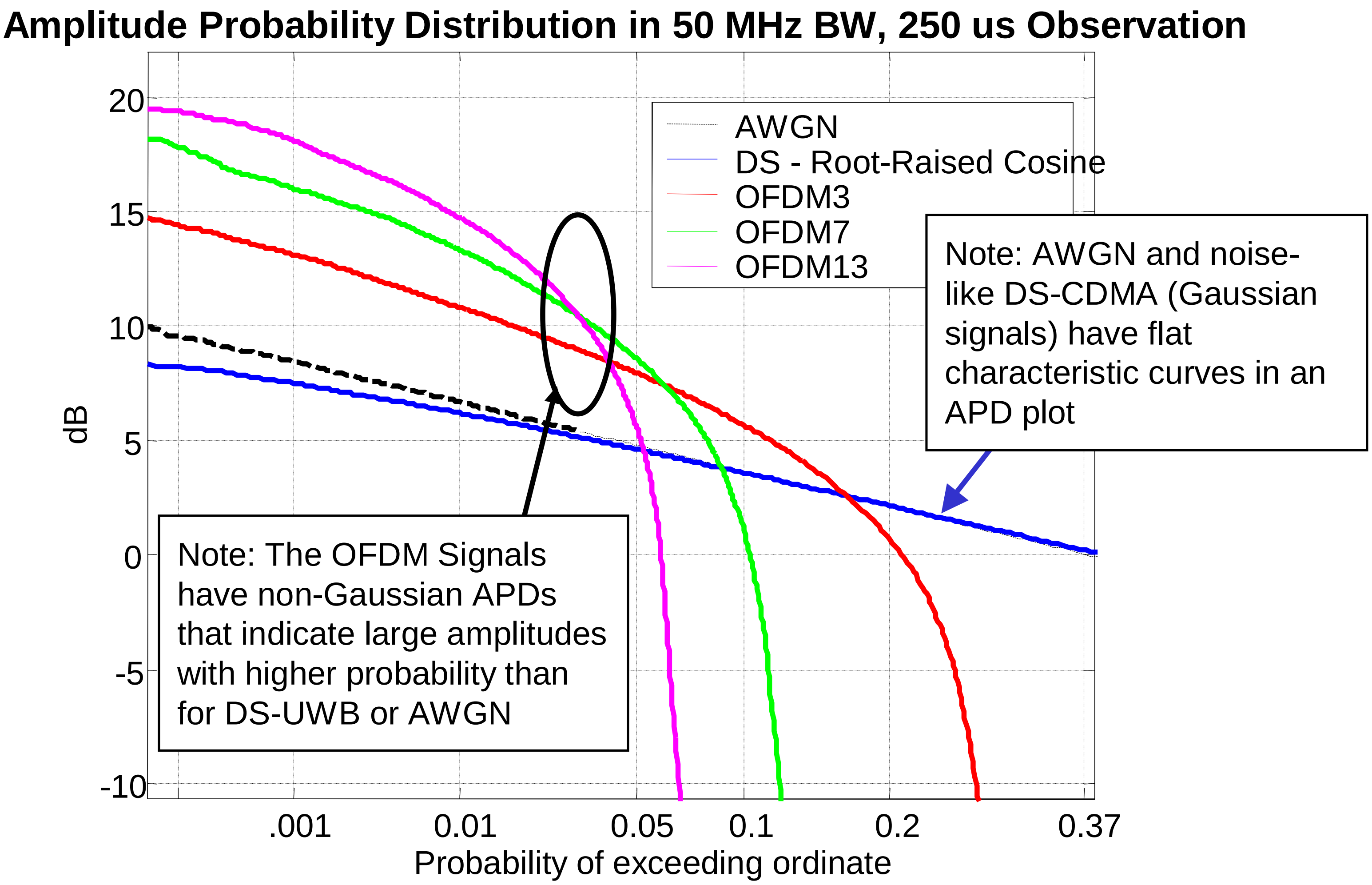


# NTIA Interference Analysis

- Extensive analysis performed by the NTIA & FCC
  - Actual testing of UWB transmitters with specific receivers
  - Analytical analysis for general & specific waveforms/systems
  - Interference characterization through simulated and measured *Amplitude Probability Distribution* (APD) analysis
- APDs form a critical part of the NTIA analysis for victim receivers, particularly when the interference has non-Gaussian characteristics (like MB-OFDM):

> "The APD gives insight to the potential interference from UWB signals in a wide variety of receiver bandwidths and UWB characteristics, especially when the combination of interferer and victim produces non-Gaussian interference in the victim receiver. If the interference is Gaussian, victim receiver performance degradation is correlated to the interfering signal average power alone and there is no need for further analysis using the APD. *If the interference is non-Gaussian or sinusoidal, information in the APD may be critical to quantifying its effect on victim receiver performance degradation.”*
>
> -- NTIA Special Publication 01-383, January 2001, [emphasis added]

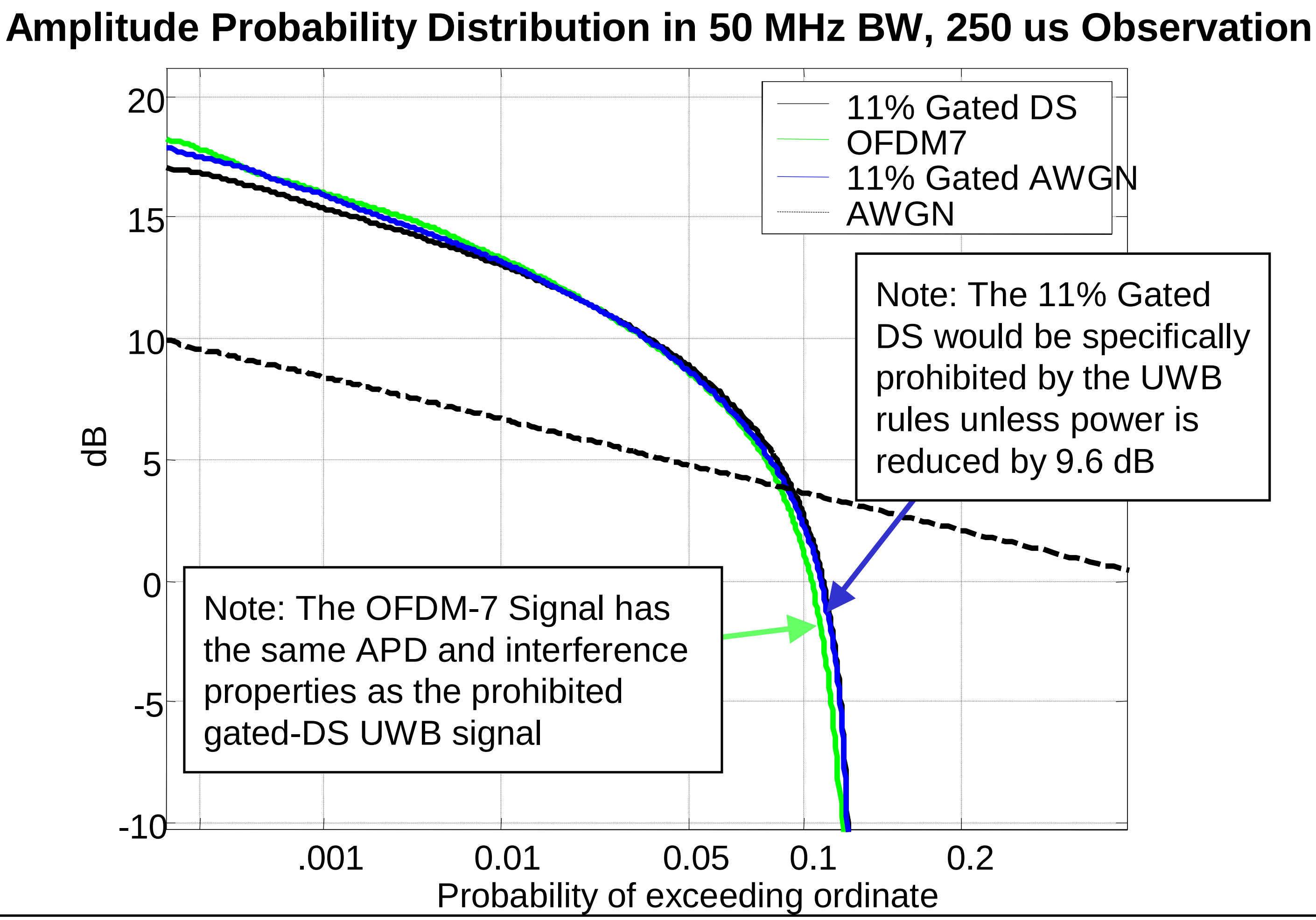
# APD Analysis for DS-CDMA and MB-OFDM



Note: AWGN and noise-like DS-CDMA (Gaussian signals) have flat characteristic curves in an APD plot

Note: The OFDM Signals have non-Gaussian APDs that indicate large amplitudes with higher probability than for DS-UWB or AWGN

# APD Analysis for MB-OFDM & *Gated DS-CDMA*



Note: The 11% Gated DS would be specifically prohibited by the UWB rules unless power is reduced by 9.6 dB

Note: The OFDM-7 Signal has the same APD and interference properties as the prohibited gated-DS UWB signal

# APD Analysis Conclusions

- In the initial rulemaking, the FCC only studied signals that continuously occupied a single frequency band
  - –Restrictions on *gated signals* only effective for such signals
  - –MB-OFDM does not meet this criterion
- APD analysis shows that MB-OFMD has identical interference properties as *gated* UWB signals that are *specifically prohibited* by the existing rules
- An FCC rule change or interpretation to accommodate MB-OFDM or other FH-UWB waveforms would potentially undermine the effectiveness of the rules in preventing harmful interference
  - –Would require an FNPRM & public proceedings to effect any rule change which might permit MB-OFDM in even a limited form
  - –Changes would certainly be opposed by UWB opponents
    - ETSI submission already noting increased interference from FH (Draft TR 101 994-1 (2003-10), Comments by Vodaphone)

# Support for Simultaneous Operating Piconets

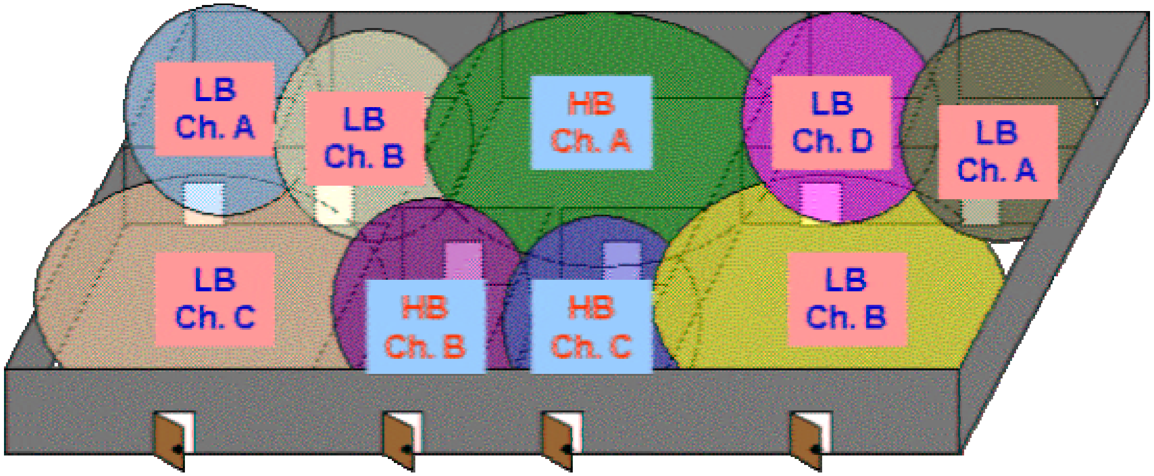
# Multiple Access: A Critical Choice

**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<br>Ch. X | Low Band (FDM)<br>Channel X (CDM)<br>802.15.3a piconet<br>(TDM/TDMA) |
| HB<br>Ch. X | High Band (FDM)<br>Channel X (CDM)<br>802.15.3a piconet<br>(TDM/TDMA) |



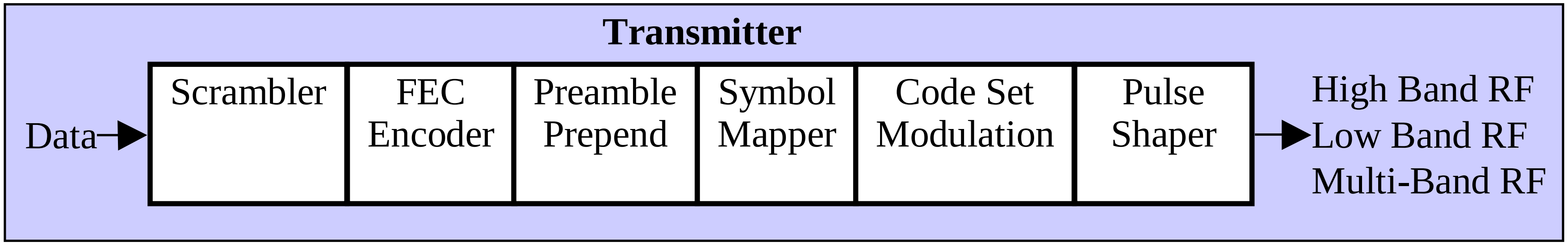
An environment depicting multiple collocated piconets

# DS-CDMA Scales to More Piconets

- DS-CDMA:
  - Low band: 4 full-rate piconets
  - High band: 4 full-rate piconets (optional)
  - Both bands: 8 total full-rate piconets (optional)
    - Can provide total overlapped SOPs or full duplex operation
- MB-OFDM:
  - Mode 1: 4 full-rate piconets
  - Mode 2: 4 full-rate piconets (optional)
    - Require use of 3 lowest hop bands, so overlaps Mode I
  - Mode 1 + Mode 2: 4 full-rate piconets (optional)
    - Acquisition occurs in lower 3 bands
    - Mode 1 and Mode 2 devices operating together provide no additional SOP benefit (acquisition limited)

# Proposal Details

# This PHY proposal is based upon proven and common communication techniques


**Transmitter**

Data → Scrambler → FEC Encoder → Preamble Prepend → Symbol Mapper → Code Set Modulation → Pulse Shaper →

High Band RF
Low Band RF
Multi-Band RF

- Multiple bits/symbol via MBOK coding
- Data rates from 29 Mbps to 1.35 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

# PHY Preamble and Header

| | | | | |
|---|---|---|---|---|
| **PHY Synchronization** | **SFD** | **PHY Header** | **MAC Header** | **payload** |

- Three Preamble Lengths (Link Quality Dependent)
    - Short Preamble (5 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 repeat-3 code for increased reliability

# 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)
- 2,4,8-BOK with length 24 ternary codes
- 64-BOK with length-32 ternary codes
- Up to 6 bits/symbol bi-phase, 12 bits/symbol quad-phase
    - 1 sign bit and up to 5 bit code selection per modulation dimension
- Total number of 24-chip codewords (each band): 4x4=16
    - 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

# Pulse Shaping and Modulation

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

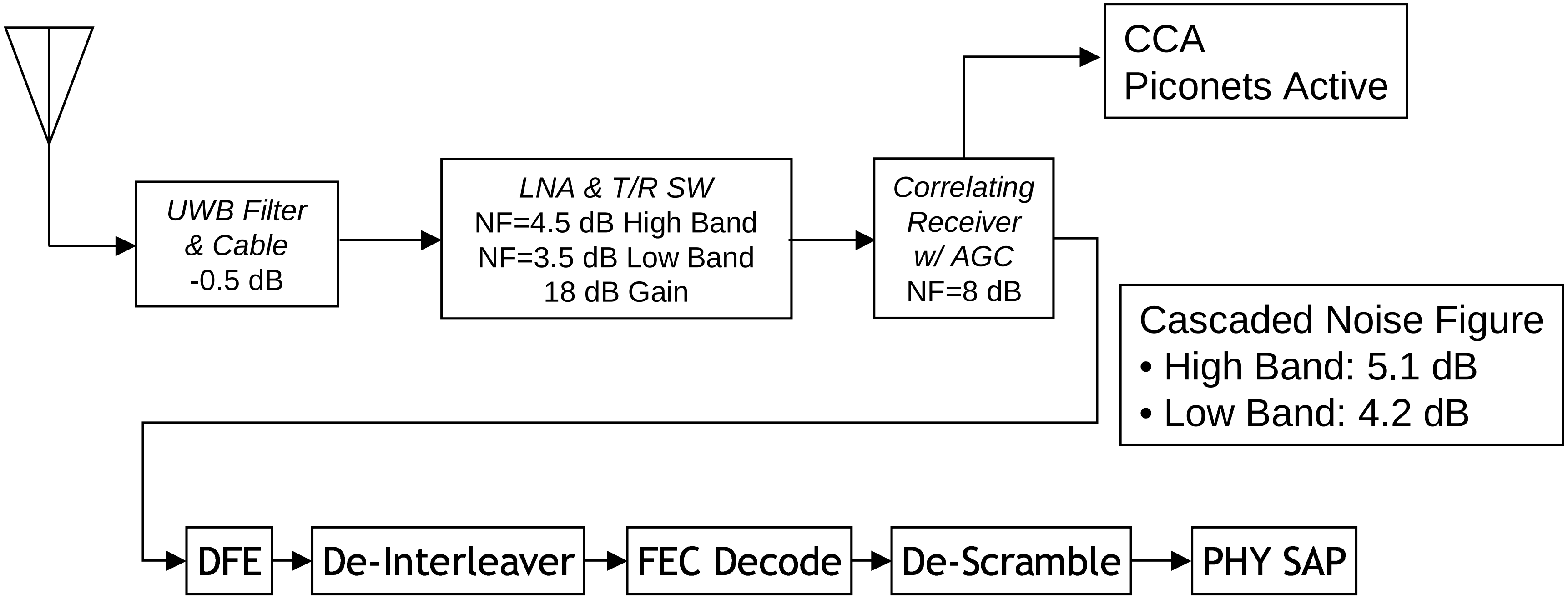
| | **RRC BW** | **Chip Rate** | **Code Length** | **Symbol Rate** |
|---|---|---|---|---|
| **Low Band** | 1.368 GHz | 1.368 GHz<br>(±1 MHz, ± 3 MHz) | 24 or 32 chips/symbol | 57 or 42.75 MS/s |
| **High Band** | 2.736 GHz | 2.736 GHz<br>(±1 MHz, ± 3 MHz) | 24 or 32 chips/symbol | 114 or 85.5 MS/s |

# Code Set Spectral Back-off and Cross-correlation

| | 2-BOK | 4-BOK | 8-BOK | 64-BOK |
|---|---|---|---|---|
| Spectral Pk-to-Avg Backoff | 2.2 dB | 2.1 dB | 1.7 dB | <1 dB |

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

# Noise Figure Budget & Receiver Structure



*UWB Filter & Cable*
-0.5 dB

*LNA & T/R SW*
NF=4.5 dB High Band
NF=3.5 dB Low Band
18 dB Gain

*Correlating Receiver w/ AGC*
NF=8 dB

CCA
Piconets Active

Cascaded Noise Figure
- High Band: 5.1 dB
- Low Band: 4.2 dB

DFE
De-Interleaver
FEC Decode
De-Scramble
PHY SAP

- We will use 6.6 db NF (low band) and 8.6 db NF (high band) for link budgets to allow comparison with other proposals

# Performance

# Link Budgets for 110+ Mbps

| Parameter | 4-BOK | 4-BOK w/ CIDD (3 iter.) | 64-BOK | MB-OFDM |
|---|---|---|---|---|
| Information Data Rate | 114 Mb/s | 114 Mb/s | 112 Mb/s | 110 Mb/s |
| Average TX Power | -9.9 dBm | -9.9 dBm | -9.9 dBm | -10.3 dBm |
| Total Path Loss | 64.4 dB<br>(@ 10 meters) | 64.4 dB<br>(@ 10 meters) | 64.4 dB<br>(@ 10 meters) | 64.2 dB<br>(@ 10 meters) |
| Average RX Power | -74.4 dBm | -74.4 dBm | -74.4 dBm | -74.5 dBm |
| Noise Power Per Bit | -93.4 dBm | -93.4 dBm | -93.5 dBm | -93.6 dBm |
| CMOS RX Noise Figure | 6.6 dB | 6.6 dB | 6.6 dB | 6.6 dB |
| Total Noise Power | -86.8 dBm | -86.8 dBm | -86.9 dBm | -87.0 dBm |
| Required Eb/N0 | 4.4 dB | 3.0 dB | 2.4 dB | 4.0 dB |
| Implementation Loss | 2.5 dB | 2.5 dB | 4.0 dB | 2.5 dB |
| Link Margin | 5.6 dB | 7.0 dB | 6.0 dB | 6.0 dB |
| RX Sensitivity Level | -79.7 dBm | -81.3 dBm | -80.4 dBm | -80.5 dB |

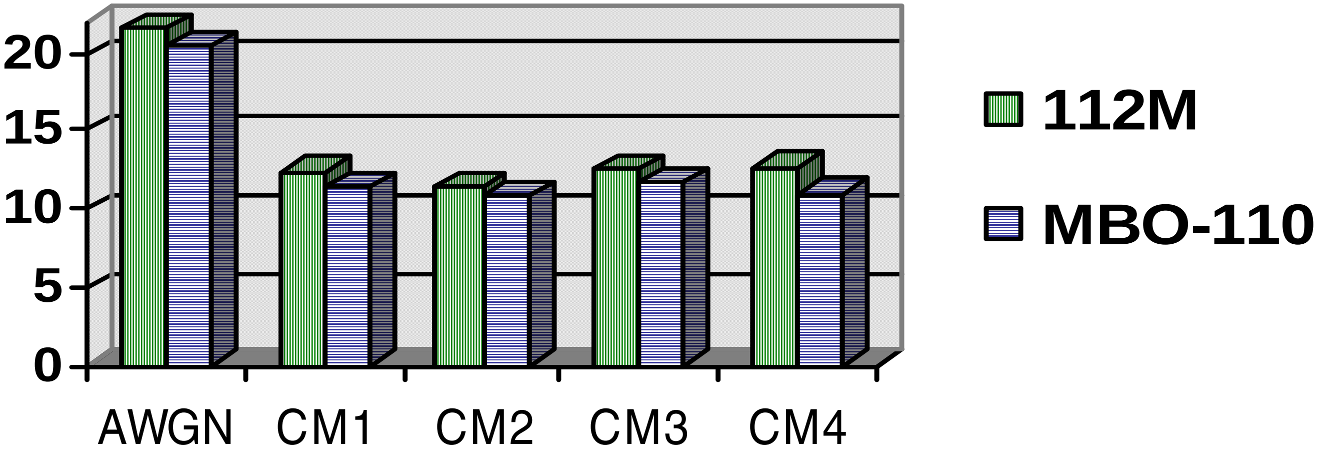
# Link Budgets for 200+ Mbps

| Parameter | 4-BOK | 64-BOK | MB-OFDM |
|---|---|---|---|
| Information Data Rate | 200 Mb/s | 224 Mb/s | 200 Mb/s |
| Average TX Power | -9.9 dBm | -9.9 dBm | -10.3 dBm |
| Total Path Loss | 56.5 dB<br>(@ 4 meters) | 56.5 dB<br>(@ 4 meters) | 56.2 dB<br>(@ 4 meters) |
| Average RX Power | -66.4 dBm | -66.4 dBm | -66.5 dBm |
| Noise Power Per Bit | -91.0 dBm | -91.0 dBm | -91.0 dBm |
| CMOS RX Noise Figure | 6.6 dB | 6.6 dB | 6.6 dB |
| Total Noise Power | -84.4 dBm | -83.9 dBm | -84.4 dBm |
| Required Eb/N0 | 6.8 dB | 2.4 dB | 4.7 dB |
| Implementation Loss | 2.5 dB | 4.0 dB | 2.5 dB |
| Link Margin | 8.7 dB | 11.1 dB | 10.7 dB |
| RX Sensitivity Level | -75.1 dBm | -77.5 dBm | -77.2 dBm |

# AWGN Link Budgets for Higher Rates

| Parameter | Value | Value |
|---|---|---|
| Information Data Rate | 448 Mb/s | 480 Mb/s |
| Average TX Power | -9.9 dBm | -10.3 dBm |
| Total Path Loss | 50.5 dB<br>(@ 2 meters) | 50.2 dB<br>(@ 2 meters) |
| Average RX Power | -60.4 dBm | -60.5 dBm |
| Noise Power Per Bit | -87.5 dBm | -87.2 dBm |
| CMOS RX Noise Figure | 6.6 dB | 6.6 dB |
| Total Noise Power | -80.9 dBm | -80.6 dBm |
| Required Eb/N0 | 4.4 dB | 4.9 dB |
| Implementation Loss | 4.0 dB | 3.0 dB |
| Link Margin | 12.1 dB | 12.2 dB |
| RX Sensitivity Level | -72.5 dBm | -72.7 dB |

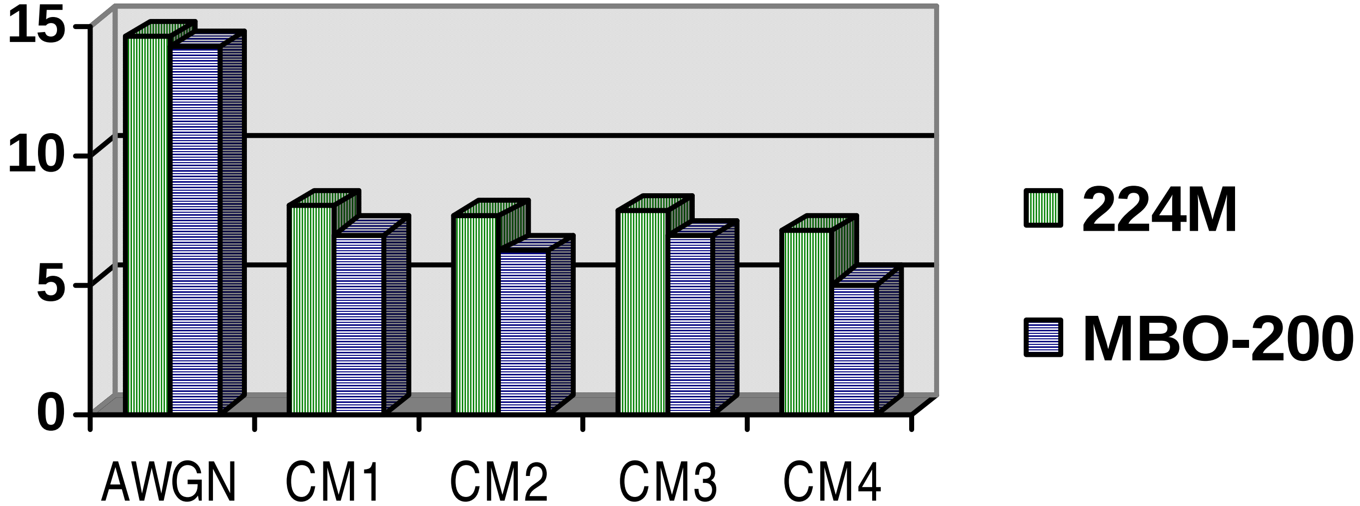
# Distance achieved for worst packet error rate of best 90% = 8% (Digital implementation, no equaliser)



| Worst PER = 8% | AWGN | CM1 | CM2 | CM3 | CM4 |
|---|---|---|---|---|---|
| 112Mbps | 21.6 m<br>(20.5 m) | 12.8 m<br>(11.5 m) | 11.8 m<br>(10.9 m) | 13.0 m<br>(11.6 m) | 12.3 m<br>(11.0 m) |
| 224Mbps | 14.5 m<br>(14.1m) | 8.0 m<br>(6.9 m) | 7.6 m<br>(6.3 m) | 7.8 m<br>(6.8 m) | 7.0 m<br>(5.0 m) |
| 448Mbps | 8.7m<br>(7.8m) | 3.3 m<br>(2.9m) | 3.3 m<br>(2.6m) | 2.9 m | - |

Fully impaired simulation including channel estimation, ADC and multipath (ICI/ISI, Finite energy capture etc.)
MB-OFDM figures in blue for comparison
AWGN figures are over a single ideal channel instead of CM1-4.

# Distance achieved for worst packet error rate of best 90% = 8% (Digital implementation, no equaliser)



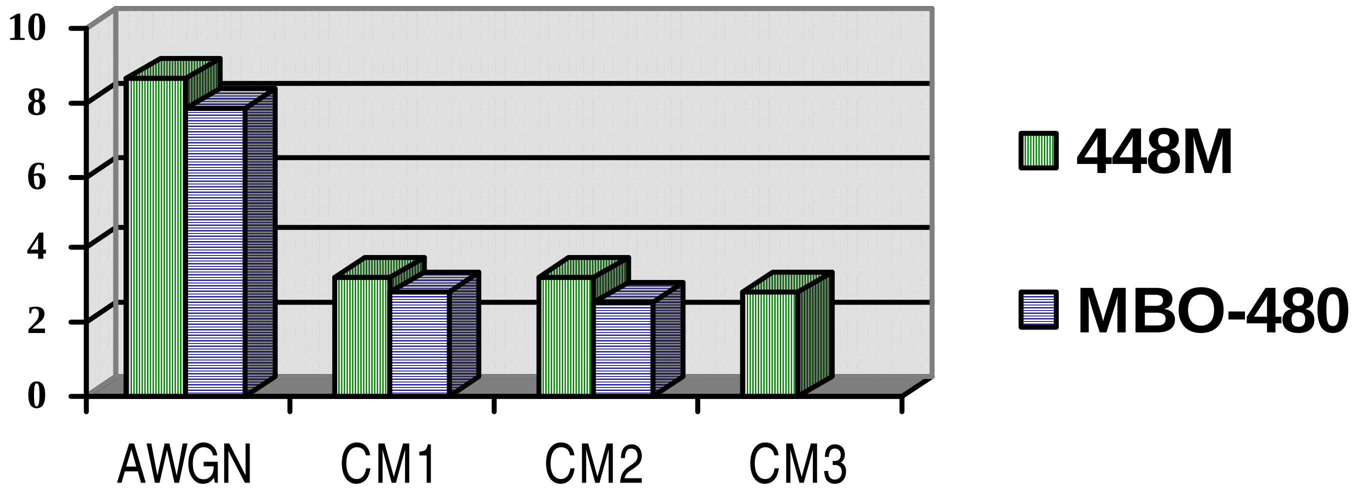
| Worst PER = 8% | AWGN | CM1 | CM2 | CM3 | CM4 |
|---|---|---|---|---|---|
| 112Mbps | 21.6 m<br>(20.5 m) | 12.8 m<br>(11.5 m) | 11.8 m<br>(10.9 m) | 13.0 m<br>(11.6 m) | 12.3 m<br>(11.0 m) |
| 224Mbps | 14.5 m<br>(14.1m) | 8.0 m<br>(6.9 m) | 7.6 m<br>(6.3 m) | 7.8 m<br>(6.8 m) | 7.0 m<br>(5.0 m) |
| 448Mbps | 8.7m<br>(7.8m) | 3.3 m<br>(2.9m) | 3.3 m<br>(2.6m) | 2.8 m | - |

Fully impaired simulation including channel estimation, ADC and multipath (ICI/ISI, Finite energy capture etc.)

MB-OFDM figures in blue for comparison

AWGN figures are over a single ideal channel instead of CM1-4.

# Distance achieved for worst packet error rate of best 90% = 8% (Digital implementation, no equaliser)



| Worst PER = 8% | AWGN | CM1 | CM2 | CM3 | CM4 |
|---|---|---|---|---|---|
| 112Mbps | 21.6 m<br>(20.5 m) | 12.8 m<br>(11.5 m) | 11.8 m<br>(10.9 m) | 13.0 m<br>(11.6 m) | 12.3 m<br>(11.0 m) |
| 224Mbps | 14.5 m<br>(14.1m) | 8.0 m<br>(6.9 m) | 7.6 m<br>(6.3 m) | 7.8 m<br>(6.8 m) | 7.0 m<br>(5.0 m) |
| 448Mbps | 8.7m<br>(7.8m) | 3.3 m<br>(2.9m) | 3.3 m<br>(2.6m) | 2.8 m | - |

Fully impaired simulation including channel estimation, ADC and multipath (ICI/ISI, Finite energy capture etc.)
MB-OFDM figures in blue for comparison
AWGN figures are over a single ideal channel instead of CM1-4.

# Single adjacent piconet

| $d_{int}/d_{ref}$ 1 interferer | CM1 | CM2 | CM3 | CM4 |
|---|---|---|---|---|
| 112Mbps | 0.47 | 0.49 | 0.48 | 0.55 |
| 224Mbps | 0.72 | 0.79 | 0.72 | 0.93 |
| 448Mbps | 1.5 | 2.9 | 1.6 | - |

Relative distance to a single adjacent piconet interferer

# Two adjacent piconets

| $d_{int}/d_{ref}$ 2 interferers | CM1 | CM2 | CM3 | CM4 |
|---|---|---|---|---|
| 112Mbps | 0.66 | 0.69 | 0.69 | 0.95 |
| 224Mbps | 1.06 | 1.10 | 1.01 | 1.31 |
| 448Mbps | 2.3 | 4.1 | 2.3 | - |

Relative distance to two adjacent piconet interferers

# Three adjacent piconets

| $d_{int}/d_{ref}$ 3 interferers | CM1 | CM2 | CM3 | CM4 |
|---|---|---|---|---|
| 110Mbps | 0.80 | 0.81 | 0.80 | 1.16 |
| 220Mbps | 1.19 | 1.30 | 1.22 | 1.59 |
| 490Mbps | 2.7 | 5.0 | 2.8 | - |

Relative distance to three adjacent piconet interferers

# Complexity
# Area/Gate count, Power consumption

| | Gate equiv (kgate) | Area ($mm^2$) | Power mW Rx Data @ 120Mbps | Power mW Rx Data @ 450Mbps | Power mW Preamble Rx |
|---|---|---|---|---|---|
| RF section (Up to and incl. A/D - D/A) | - | 2.8 | 60 | 60 | 60 |
| RAM - 24kbits | 22k | 0.132 | 10 | 10 | 10 |
| Matched filter | 65k | 0.390 | 53 | 97 | - |
| Channel estimation (extra) | 24k | 0.144 | - | - | 80 |
| Viterbi Decoder (k=7) RS decoders (55/63) | 90k | 0.54 | 45 | 25 | |
| Rest of Baseband Section (including Tx) | 65k | 0.39 | 25 | 60 | 25 |
| Total | 266k | 1.6 $mm^2$ D<br>2.8 $mm^2$ A | 193mW | 252mW | 175mW |

- Standard cell library implementation in 0.13µm CMOS

# Lower performance (up to 224Mbps) Area/Gate count, Power consumption

| | Gate equiv | Area ($mm^2$) | Power mW Rx Data @ 120Mbps | Power mW Rx Data @ 224Mbps | Power mW Preamble Rx |
|---|---|---|---|---|---|
| RF section (Up to and incl. A/D - D/A) | - | 2.8 | 60 | 60 | 60 |
| RAM - 24kbits | 15k | 0.09 | 10 | 10 | 10 |
| Matched filter | 38k | 0.22 | 26 | 61 | - |
| Channel estimation | 24k extra | 0.14 | - | - | 80 |
| RS decoders (55/63) | 40k | 0.24 | 15 | 15 | - |
| Rest of Baseband Section | 65k | 0.39 | 15 | 25 | 25 |
| **Total** | 182k | 2.8$mm^2$ A<br>1.1$mm^2$ D | 136mW | 208mW | 175mW |

- Standard cell library implementation in 0.13µm CMOS

# Additional Technical Slides

# 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

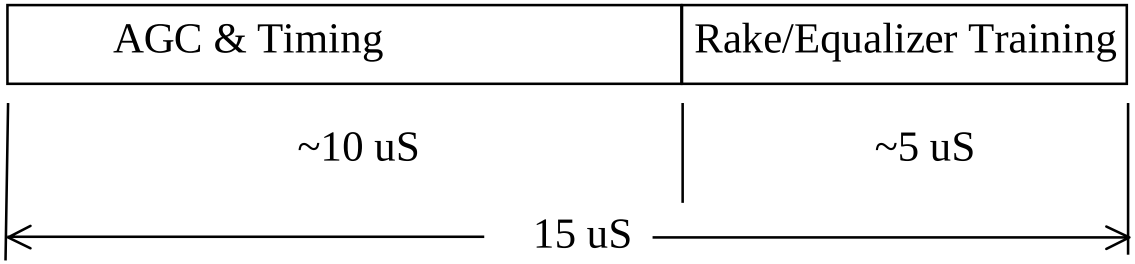
Note 1: http://www.xtremespectrum.com/PDF/xsi_trinity_brief.pdf

# PHY Synchronization Preamble Sequence

## (low band <u>medium</u> length sequence)

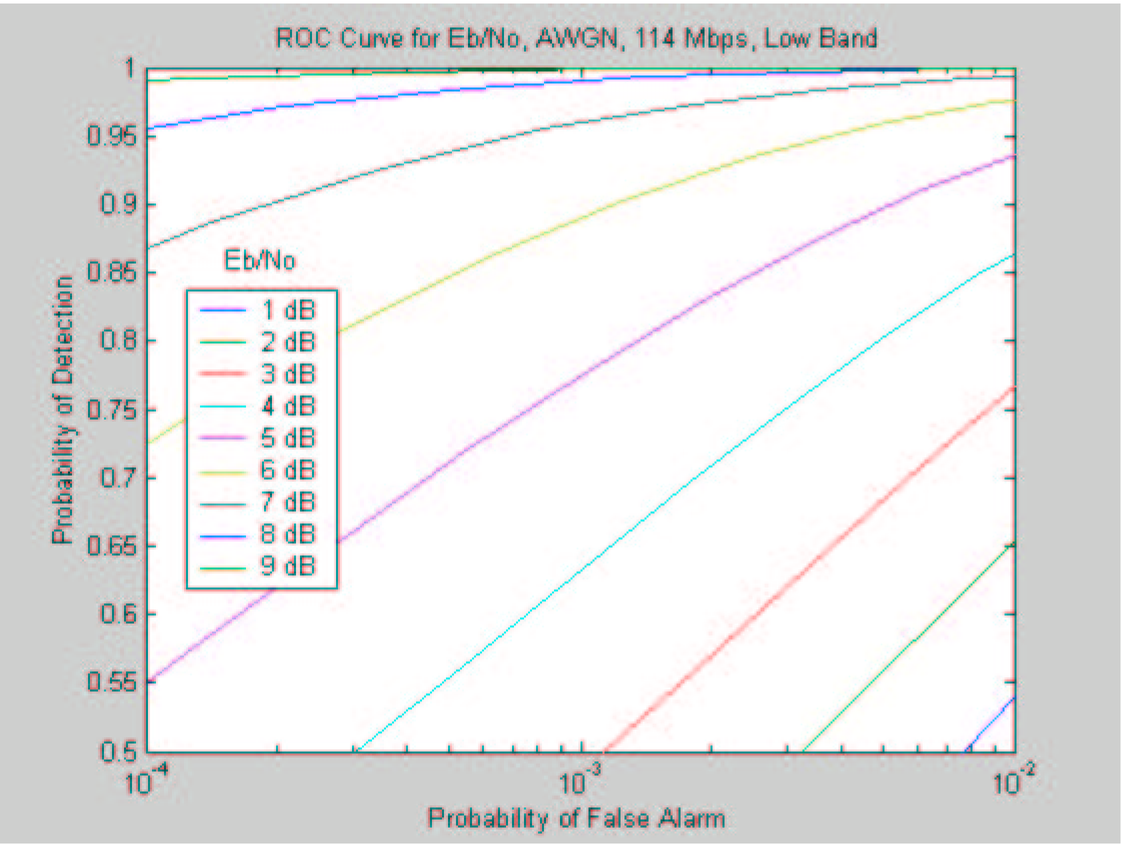
```
JNJNB5ANB6APAPCPANASASCNJNASK9B5K6B5K5D5D5B9ANASJPJNK5MNCP
ATB5CSJPMTK9MSJTCTASD9ASCTATASCSANCSASJSJSB5ANB6JPN5DAASB9K
5MSCNDE6AT3469RKWAVXM9JFEZ8CDS0D6BAV8CCS05E9ASRWR914A1BR
```

Notation is Base 32



# 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 – here we assumed 3

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)

# 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* | + |

# NBI Rejection

## 1. DS - CDMA

- The DS CDMA codes offer 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

# 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

# Ternary Length 24 Code Set

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 |

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

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 |
| -1 | 1 | -1 | 1 | 1 | -1 | 1 | 0 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 0 | -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 |

# 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 |
| -1 | -1 | -1 | 1 | 1 | 1 | -1 | -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 | 0 | 1 | 1 | -1 | 1 | -1 | 1 | 0 | 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 |

# Ternary Orthogonal Length 32 Code Set

- `+ 0 - 0 - 0 - 0 + 0 + 0 - 0 + 0 + 0 - 0 - 0 - 0 - 0 - 0 + 0 - 0`
- `- 0 + - 0 - 0 - + + + 0 0 0 0 0 0 0 0 0 - 0 + 0 0 - 0 - - + - -`
- `0 0 0 0 - - 0 0 0 0 0 0 + + 0 0 - + 0 0 - - - + - + 0 0 - - + -`
- `0 0 0 + + - - 0 0 - 0 0 + 0 + - 0 0 0 0 + - - 0 0 - 0 - - 0 - +`
- `- + + 0 0 0 0 - - 0 - + 0 + 0 0 + - - + 0 0 0 - - 0 - 0 0 - 0 0`
- `0 0 0 + - 0 0 0 0 0 0 - + 0 0 0 - 0 0 - + + + - - 0 0 - + - - -`
- `0 + - 0 0 0 + + - - 0 0 - 0 0 + 0 - + 0 0 0 0 + - - 0 0 - 0 - -`
- `0 0 0 0 + + - 0 + - - - 0 0 0 + 0 0 0 0 - 0 0 0 + - - - 0 - + -`
- `0 0 0 0 0 0 + - 0 0 0 0 0 0 - + - - - - 0 0 - + + + - - 0 0 - +`
- `0 0 0 + 0 0 0 0 - + + 0 - - + - 0 - - - 0 0 0 0 + 0 0 0 - - + -`
- `0 0 0 0 + + 0 0 0 0 0 0 - - 0 0 - + 0 0 - - + - - + 0 0 - - - +`
- `+ - 0 0 0 + 0 0 0 0 - + + 0 - - + - 0 - - - 0 0 0 0 + 0 0 0 - -`
- `0 0 0 0 0 0 + + 0 0 0 0 0 0 - - - + - + 0 0 - - + - - + 0 0 - -`
- `- - + - 0 0 0 + 0 0 0 0 - + + 0 - - + - 0 - - - 0 0 0 0 + 0 0 0`
- `0 0 0 0 - + 0 0 0 0 0 0 + - 0 0 - - 0 0 - + - - - - 0 0 - + + +`
- `+ 0 - - + - 0 0 0 + 0 0 0 0 - + 0 0 - - + - 0 - - - 0 0 0 0 + 0`
- `0 + 0 - 0 + 0 + 0 + 0 + 0 + 0 - 0 + 0 - 0 + 0 + 0 - 0 - 0 - 0 +`
- `0 + 0 0 - 0 + 0 0 0 0 + + - + + + + + - 0 - 0 - + 0 - 0 0 0 0 0`
- `+ - + + 0 0 - + - + + + 0 0 - + 0 0 + + 0 0 0 0 0 0 - - 0 0 0 0`
- `+ + - 0 0 0 0 - + 0 + + 0 + 0 0 - - + + 0 0 0 - + 0 + 0 0 - 0 0`
- `0 0 0 - + + - 0 0 + 0 0 + 0 + + 0 0 0 0 + + - 0 0 + 0 + - 0 - -`
- `+ - + 0 0 + + - - - + 0 0 + + + 0 + - 0 0 0 0 0 0 - + 0 0 0 0 0`
- `+ 0 0 + + - 0 0 0 0 - + 0 + + 0 - 0 0 - - + + 0 0 0 - + 0 + 0 0`
- `+ + + - 0 0 0 + 0 0 0 0 + - + 0 - - - + 0 - + + 0 0 0 0 + 0 0 0`
- `+ + + + - + 0 0 + + - - - + 0 0 0 0 0 0 + - 0 0 0 0 0 0 - + 0 0`
- `+ + + 0 + - + + 0 0 0 - 0 0 0 0 + 0 0 0 - + - - 0 + + - 0 0 0 0`
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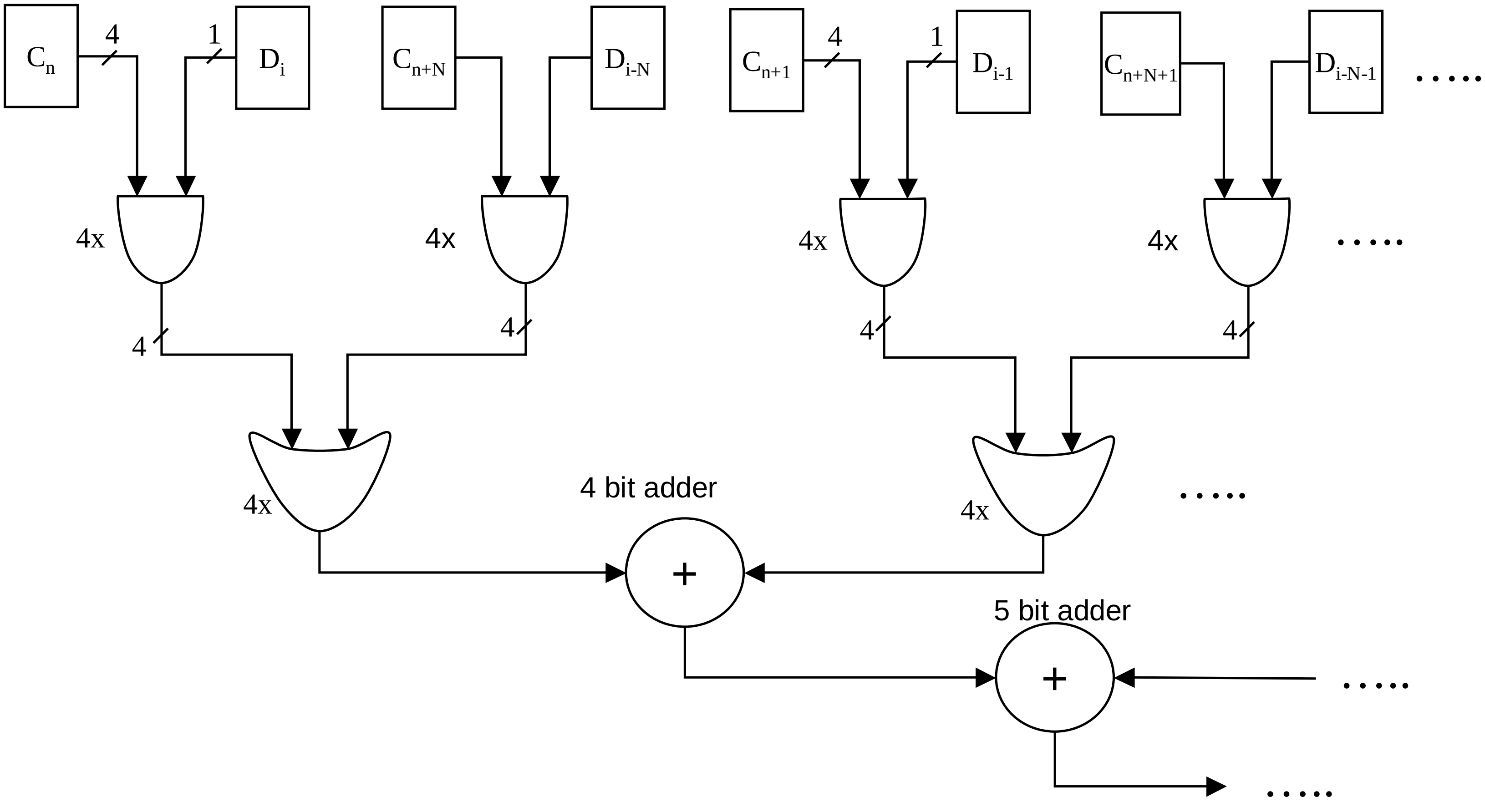
- `0 0 + + + 0 + - + + 0 0 0 - 0 0 0 0 + 0 0 0 - + - - 0 + + - 0 0`
- `- + - + + + 0 0 - + + - + + 0 0 0 0 0 0 - - 0 0 0 0 0 0 + + 0 0`
- `0 0 0 0 + + + 0 + - + + 0 0 0 - 0 0 0 0 + 0 0 0 - + - - 0 + + -`
- `- - - + 0 0 + + + + - + 0 0 + + 0 0 - + 0 0 0 0 0 0 + - 0 0 0 0`
- `0 - 0 0 0 0 + + + 0 + - + + 0 0 + - 0 0 0 0 + 0 0 0 - + - - 0 +`

# Example Matched Filter Configuration

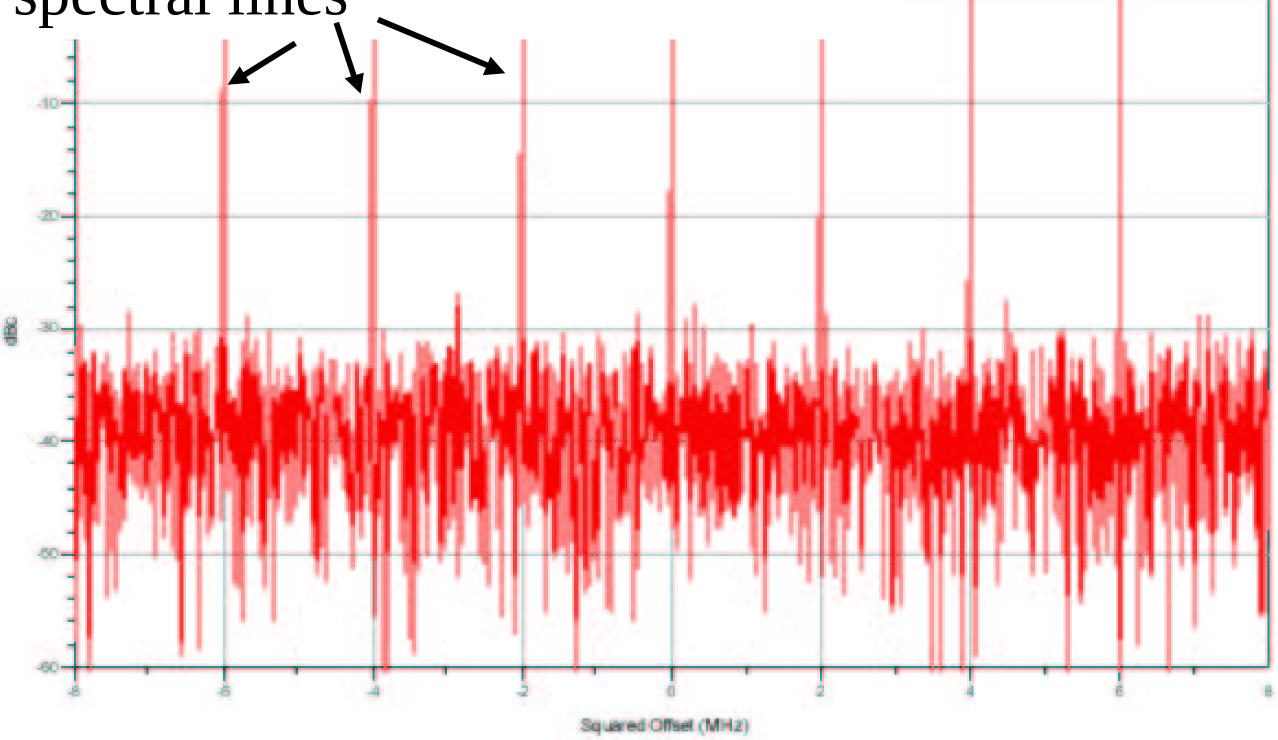


# Strong Support for CSMA/CCA

- 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 all neighboring piconets
- Very simple hardware

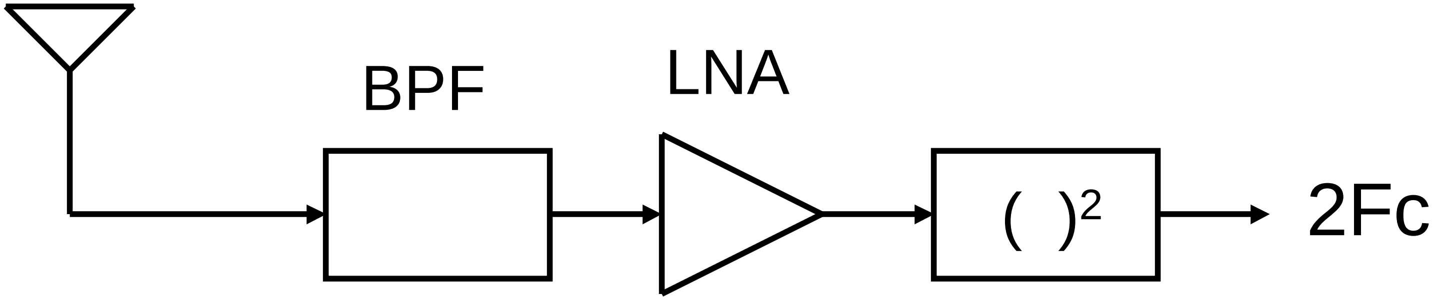
# Output of the Squaring Circuit

Piconets clearly identified by spectral lines



# How it Works

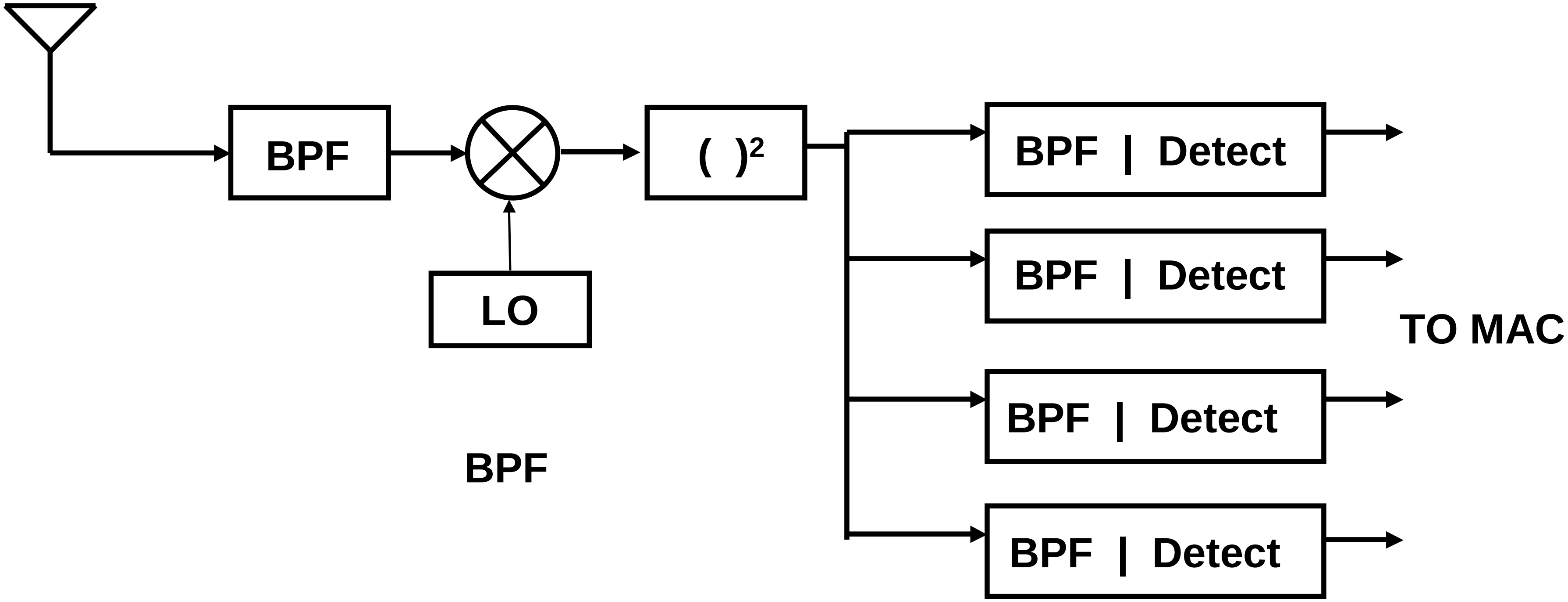
- Fc = wavelet center frequency = 3x chip rate
- Piconet ID is chip rate offset of ±1 or ±3 MHz



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

# How it Works

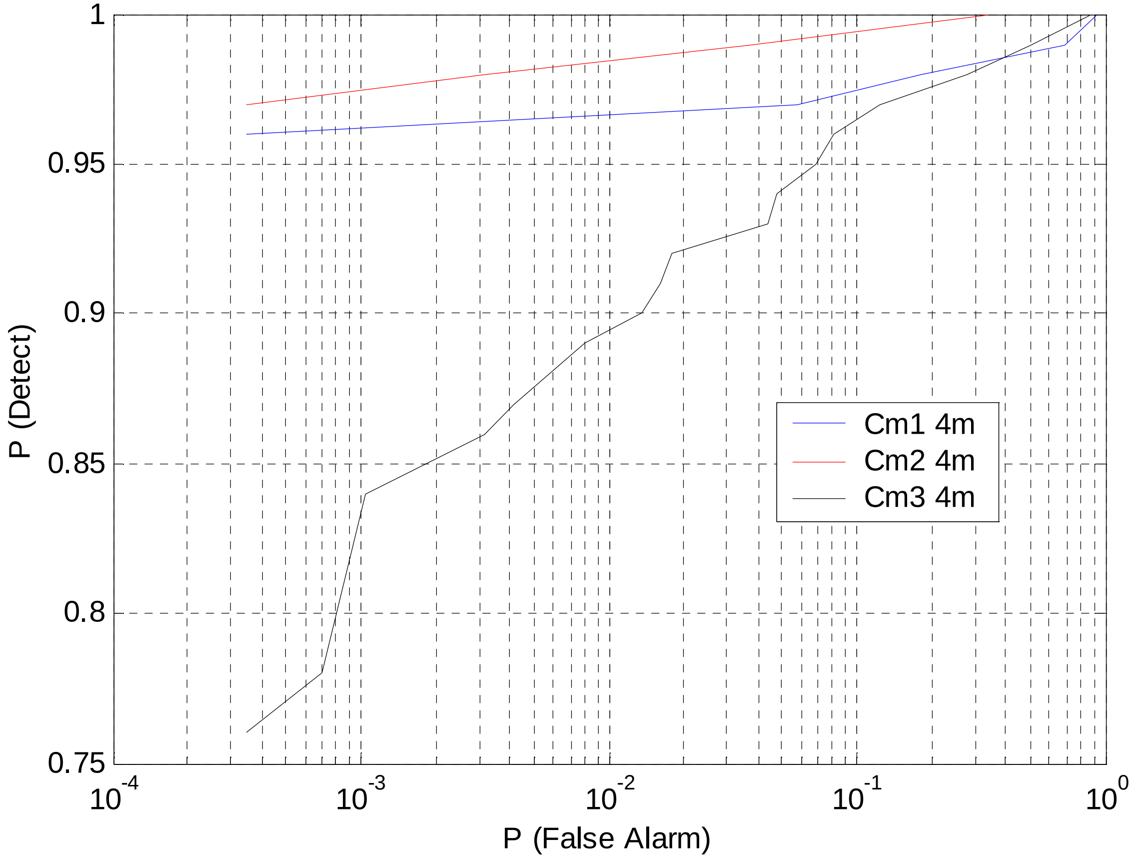
- Can also be done at baseband:



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

# CCA Performance

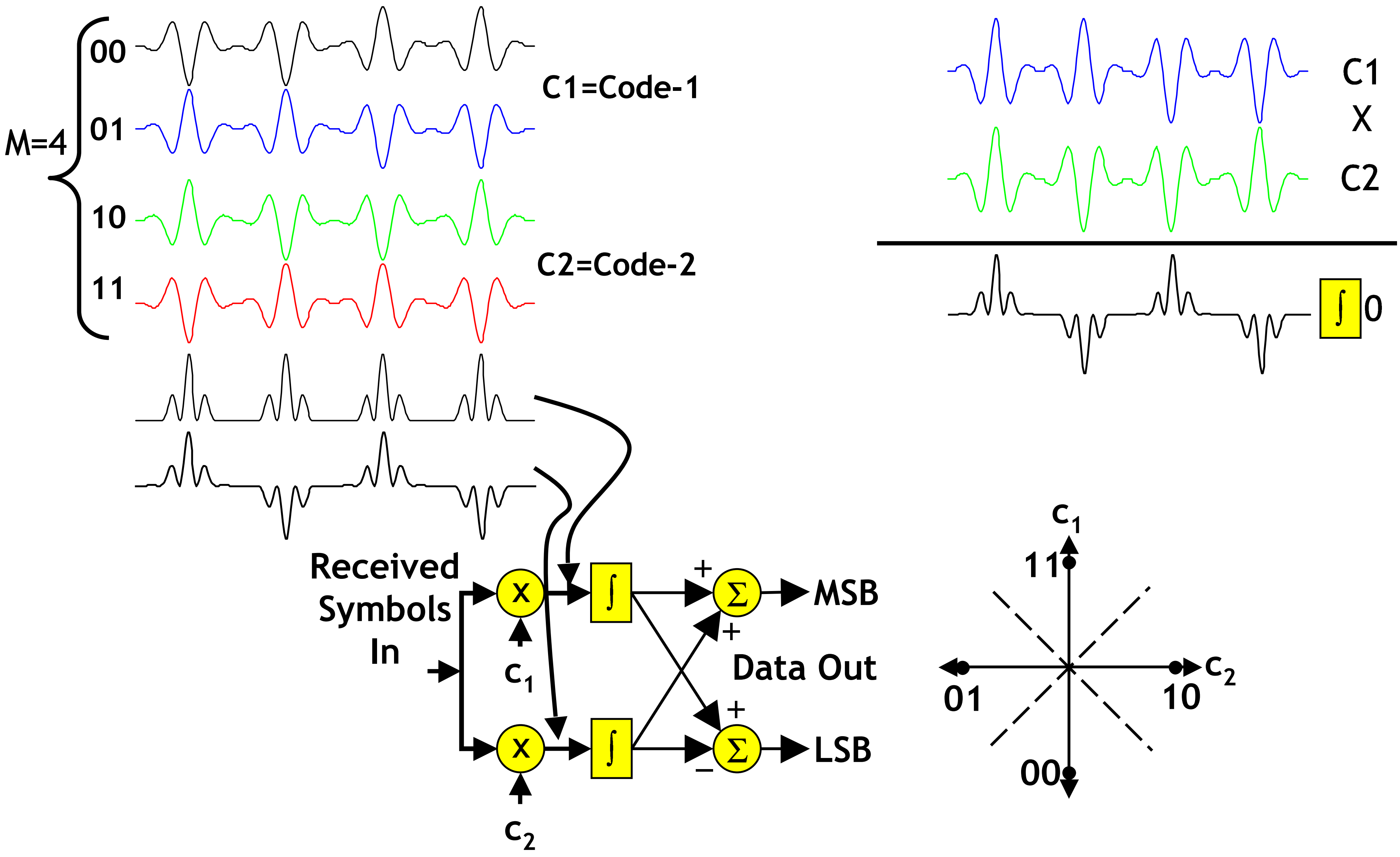
The following figure represents the CCA ROC curves for CM1, CM2 and CM3 at 4.1 GHz. This curve shows good performance on CM1 and CM2 with high probability of detection and low probability of false alarm (e.g. usage of a CAP CSMA based algorithm is feasible); however, on CM3 use of the management slots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



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

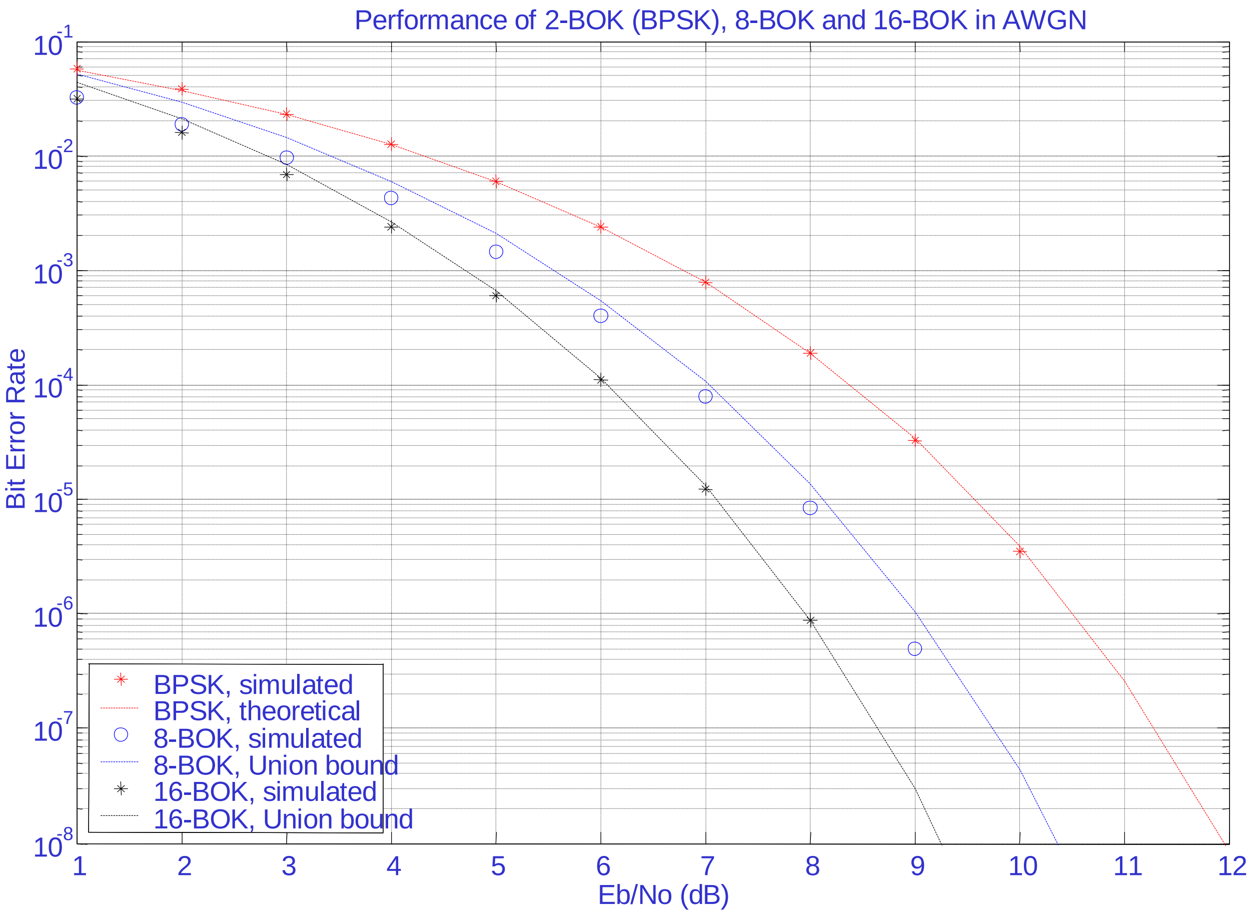
***Our CCA scheme allows monitoring channel activity during preamble acquisition to minimize probability of false alarm acquisition attempts.***

# M-BOK (M=4) Illustration



# MBOK Coding Gain

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



# Example of CIDD Decoder Latency

- Estimation of the throughput
  - The throughput of SISO channel decoder has been achieved 500Mbps. (SOVA or max log-MAP + sliding window technique)
  - We believe that soft output MBOK demapper achieve more than 500Mbps throughput.
  - Then, the total throughput of CIDD (including interleaver /de-interleaver) achieve more than 400Mbps.

# Example of CIDD Decoder Latency

- Assuming that we have a 450Mbps-CIDD processor,
  - After 4 iterations, the throughput becomes 125Mbps.
  - If the codeword length (=interleaver size) is 250 bits, the *decoder latency is 2.5usec*.
  - *If a 248-bit cyclic shift interleaver is employed, the BER at $E_b/N_0$=2.75dB is less than 1e-5 ! (16-BOK+K=4 code)*
- Assuming that we have a 330Mbps-CIDD processor,
  - After 3 iterations, the throughput becomes 110Mbps.
  - If the codeword length (=interleaver size) is 250 bits, the *decoder latency is 2.3usec*.
  - *If a 248-bit cyclic shift interleaver is employed, the BER at $E_b/N_0$=2.75dB is less than 5e-5 ! (16-BOK+K=4 code)*

# 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