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

Submission Title: [Merger#2 Proposal DS-CDMA]
Date Submitted: [17 September 2003]
Source: [Matt Welborn, Michael Mc Laughlin & Ryuji Kohno] Company [XSI, ParthusCeva & CRL]
Address [8133 Leesburg Pike, Suite 700, Vienna, Va. 22182, USA]
Voice:[+1 703.269.3000], FAX: [+1 703.749.0248], E-Mail:[mwelborn@xtremespectrum.com]

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.]

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

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

Major Contributors For This Proposal Update

Matt Welborn	*XtremeSpectrum Inc.*
Michael Mc Laughlin	*ParthusCeva Inc.*
John McCorkle	*XtremeSpectrum Inc.*
Ryuji KOHNO	*Yokohama National University*
Shinsuke HARA	*Osaka University*
Shigenobu SASAKI	*Niigata University*
Tetsuya YASUI	*CRL-UWB Consortium*
Honggang ZHANG	*CRL-UWB Consortium*
Kamya Y. YAZDANDOOST	*CRL-UWB Consortium*
Kenichi TAKIZAWA	*CRL-UWB Consortium*
Yuko RIKUTA	*CRL-UWB Consortium*

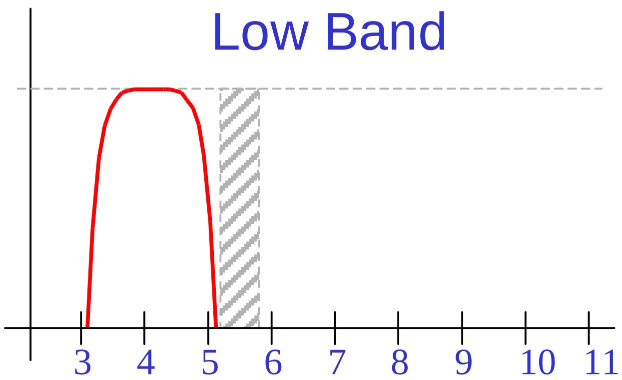
Supported by:
Motorola
Members of CRL-UWB Consortium

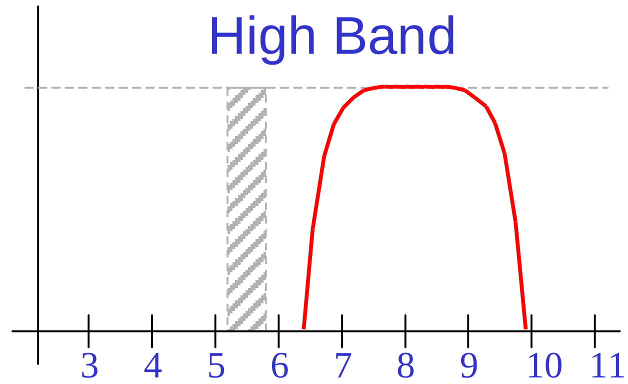
Takahiro YAMAGUCHI	*Advantest Corporation*
Tasuku TESHIROGI	*Anritsu Corporation*
Hideaki ISHIDA	*CASIO Computer Co., Ltd.*
Hiroyo OGAWA	*Communications Research Laboratory*
Toshiaki MATSUI	*Communications Research Laboratory*
Akifumi KASAMATSU	*Communications Research Laboratory*
Tomohiro INAYAMA	*Fuji Electric Co., Ltd.*
Toshiaki SAKANE	*Fujitsu Limited*
Yoichi ISO	*Furukawa Electric Co., Ltd.*
Yoshinori OHKAWA	*Hitachi Cable, Ltd.*
Yoshinori ISHIKAWA	*Hitachi Communication Technologies, Ltd.*
Masatoshi TAKADA	*Hitachi Kokusai Electric Inc.*
Satoshi SUGINO	*Matsushita Electric Works, Ltd.*
Makoto SANYA	*Matsushita Electric Industrial Co., Ltd.*
Tetsushi IKEGAMI	*Meiji University*

Members of CRL-UWB Consortium (cont.)

Yoshiaki KURAISHI	*NEC Engineering, Ltd.*
Makoto YOSHIKAWA	*NTT Advanced Technology Corporation*
Yoshihito SHIMAZAKI	*Oki Electric Industry Co., Ltd.*
Masami HAGIO	*Oki Network LSI Co., Ltd.*
Toru YOKOYAMA	*OMRON Corporation*
Hiroyuki NAGASAKA	*Samsung Yokohama Research Institute*
Sumio HANAFUSA	*SANYO Electric Co., Ltd.*
Makoto ITAMI	*Science University of Tokyo*
Hideyo IIDA	*Taiyo Yuden Co., Ltd.*
Eishin NAKAGAWA	*Telecom Engineering Center*
Takehiko KOBAYASHI	*Tokyo Denki University*
Kiyomichi ARAKI	*Tokyo Institute of Technology*
Jun-ichi TAKADA	*Tokyo Institute of Technology*

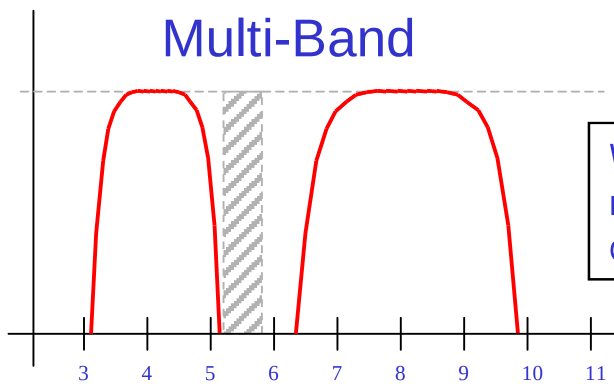
Two Band DS-CDMA





- **Low Band (3.1 to 5.15 GHz)**
  - **25 Mbps to 450 Mbps**
- **High Band (5.825 to 10.6 GHz)**
  - **25 Mbps to 900 Mbps**

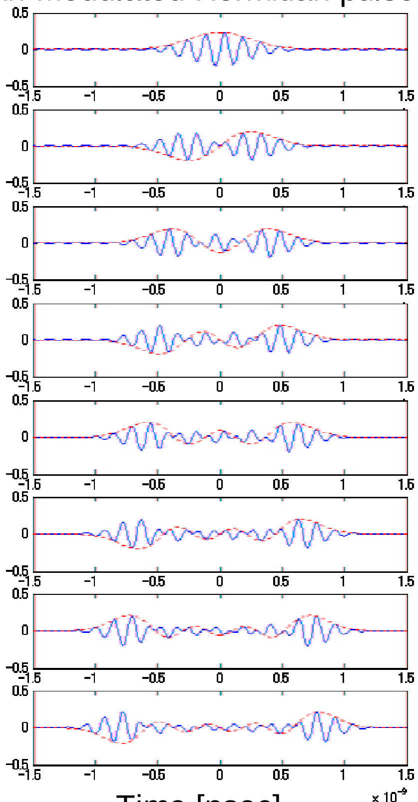
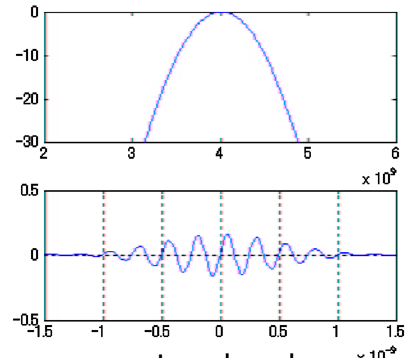
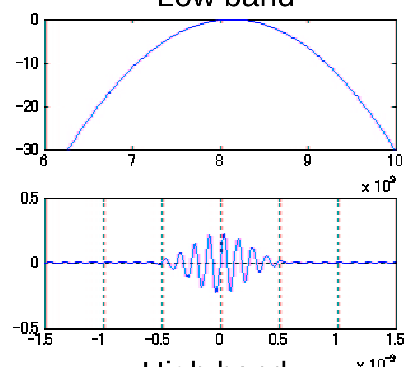
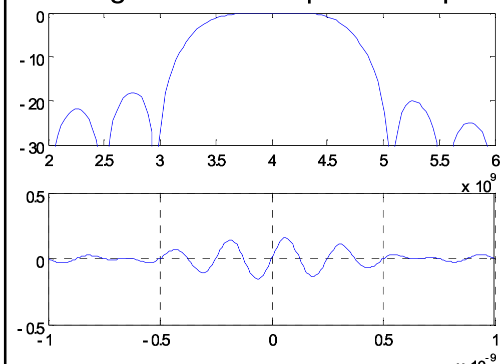
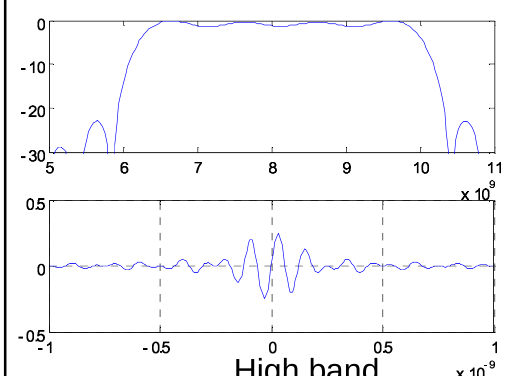
3 Spectral Modes of Operation



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

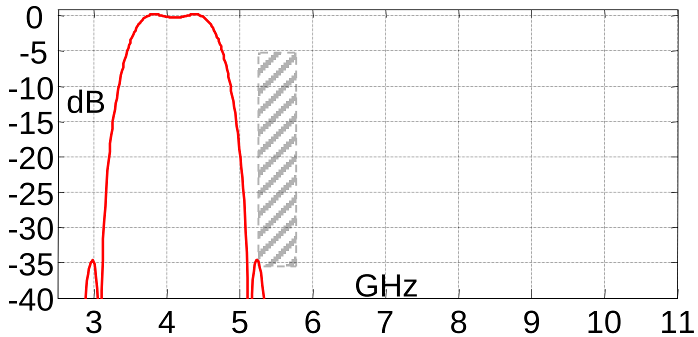
- **Multi-Band (3.1 to 5.15 GHz plus 5.825 GHz to 10.6 GHz)**
  - **Up to 1.35 Gbps**

New Merged Wavelet Options for DS-CDMA Proposal

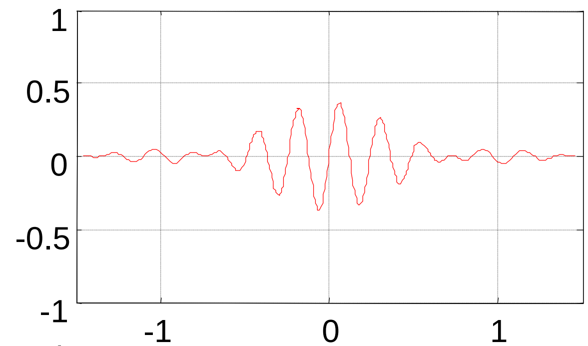
	Optimized SSA	***Additional Mode for new merger with CRL***	***Previous merger proposal***
Pulse shape	• Single band *Ex.*: Modulated Hermitian pulses  Time [nsec]	• Dual-band *Ex.*: Modulated order-0 modified Hermitian pulse  Low band  High band	• Dual-band • Designed wavelet pulse shape  Low band  High band

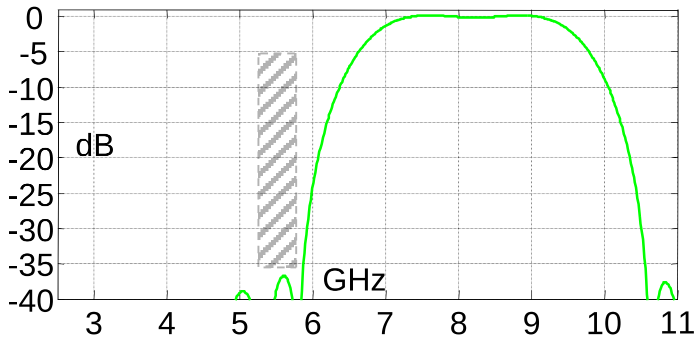
	Optimized SSA	Merger #2 proposal	Initial Merger proposal with CRL
Modulation	• 4-ary biorthogonal keying by 8-chip 2 WH codes	• *M*-ary biorthogonal keying • 24-chip & 32-chip Ternary codes • Four 24-chip codes per piconet	• *M*-ary biorthogonal keying • 24-chip & 32-chip Ternary codes • Four 24-chip codes per piconet
FEC Encoding	• Half rate *K*=3 convolutional code •600 bit interleaver	• *K*=7 convolutional code • (63, 55)-Reed Solomon code • Concatenated code	• *K*=7 convolutional code •Half rate *K*=3 convolutional code •600 bit interleaver • (63, 55)-Reed Solomon code • Concatenated code
FEC Decoding	• Half rate *K*=3 convolutional code • 4-iteration of combined iterative demapping and decoding	• *K*=7 convolutional code • (63, 55)-Reed Solomon code • Concatenated code	•*K*=7 convolutional code • Half rate *K*=3 convolutional code •600 bit interleaver • Up to 4-iteration of combined iterative demapping and decoding • (63, 55)-Reed Solomon code • Concatenated code
Improvement			•1.5 dB improvement with over previous merger with CIDD

Joint Time Frequency Wavelet Family

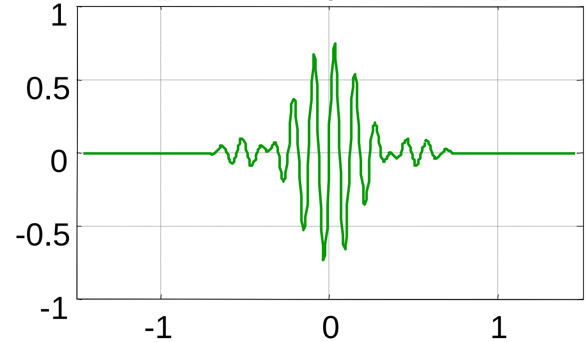


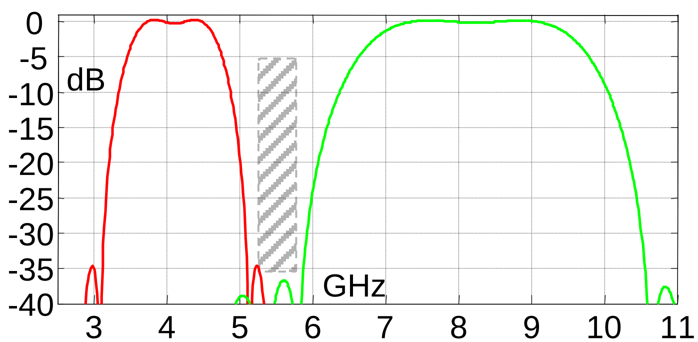
Long Wavelet



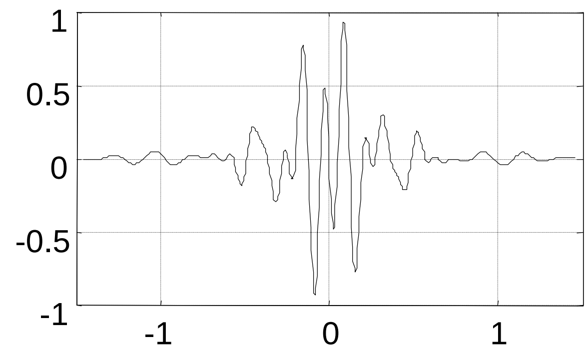


Mid Wavelet



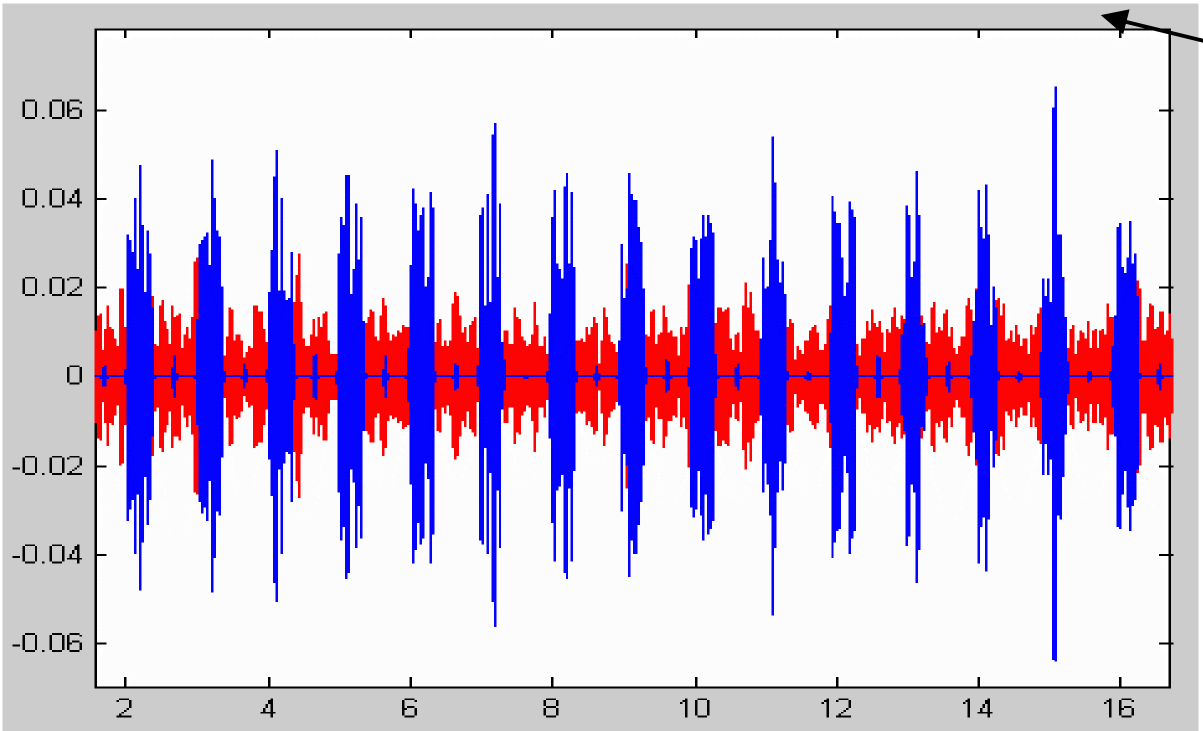


Example Duplex Wavelet



FH/Gated versus DS-CDMA in a 40 MHz BW Victim Receiver – Pre Detection

Volts



FH-OFDM
DS-CDMA

DS-CDMA is more benign

μs

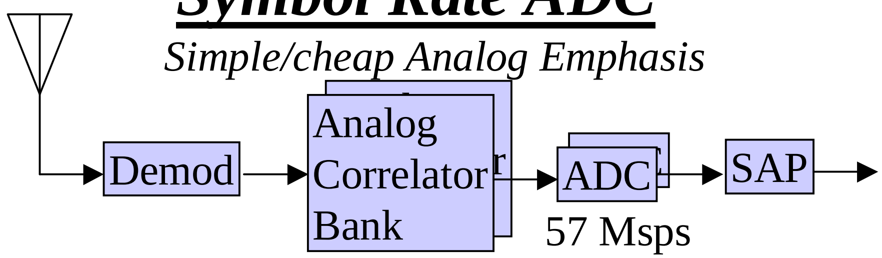
Fixed Transmitter Spec
Scalable Receivers Across Applications

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

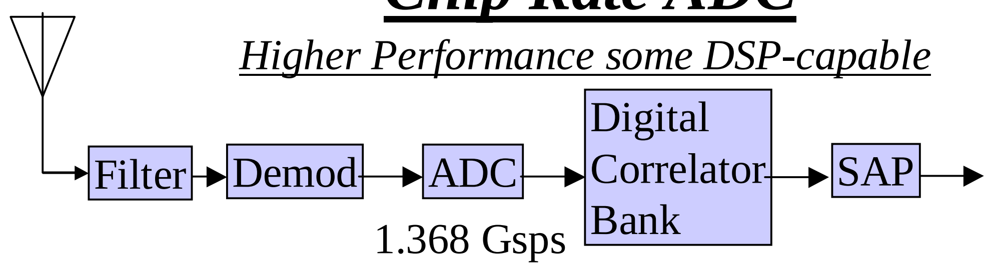
Symbol Rate ADC

Simple/cheap Analog Emphasis



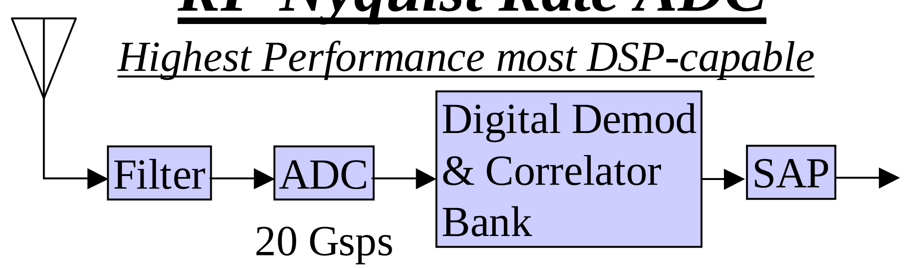
Chip Rate ADC

Higher Performance some DSP-capable



RF Nyquist Rate ADC

Highest Performance most DSP-capable

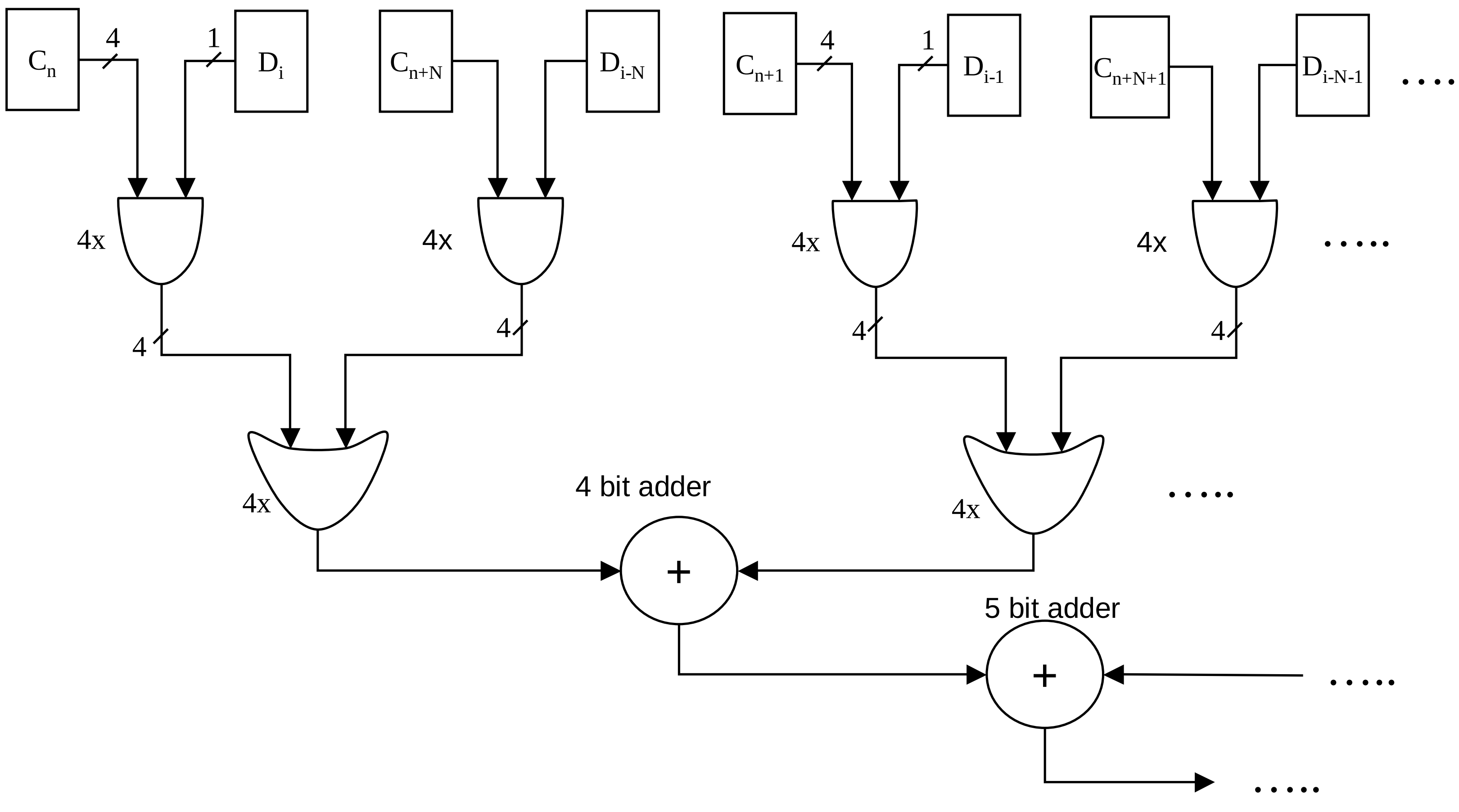


Link Budgets for 110+ Mbps

Parameter	4-BOK	MERGER	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 (@ 10 meters)	64.4 dB (@ 10 meters)	64.4 dB (@ 10 meters)	64.2 dB (@ 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	2.9 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	7.1 dB	6.1 dB	6.0 dB
RX Sensitivity Level	-78.9 dBm	-78.9 dBm	-80.5 dBm	-80.5 dB

FIR Gate count for example FIR implementation

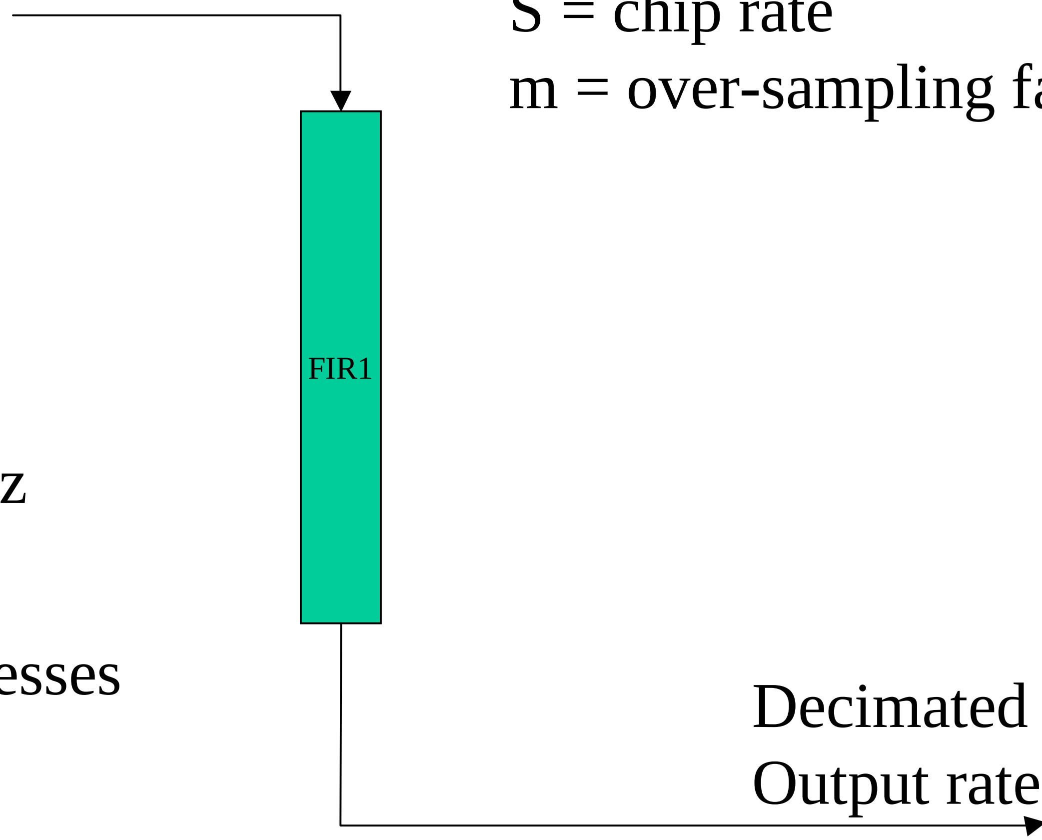
Example Matched Filter Configuration



Serial FIR implementation

Input rate S*m

S = chip rate
m = over-sampling factor



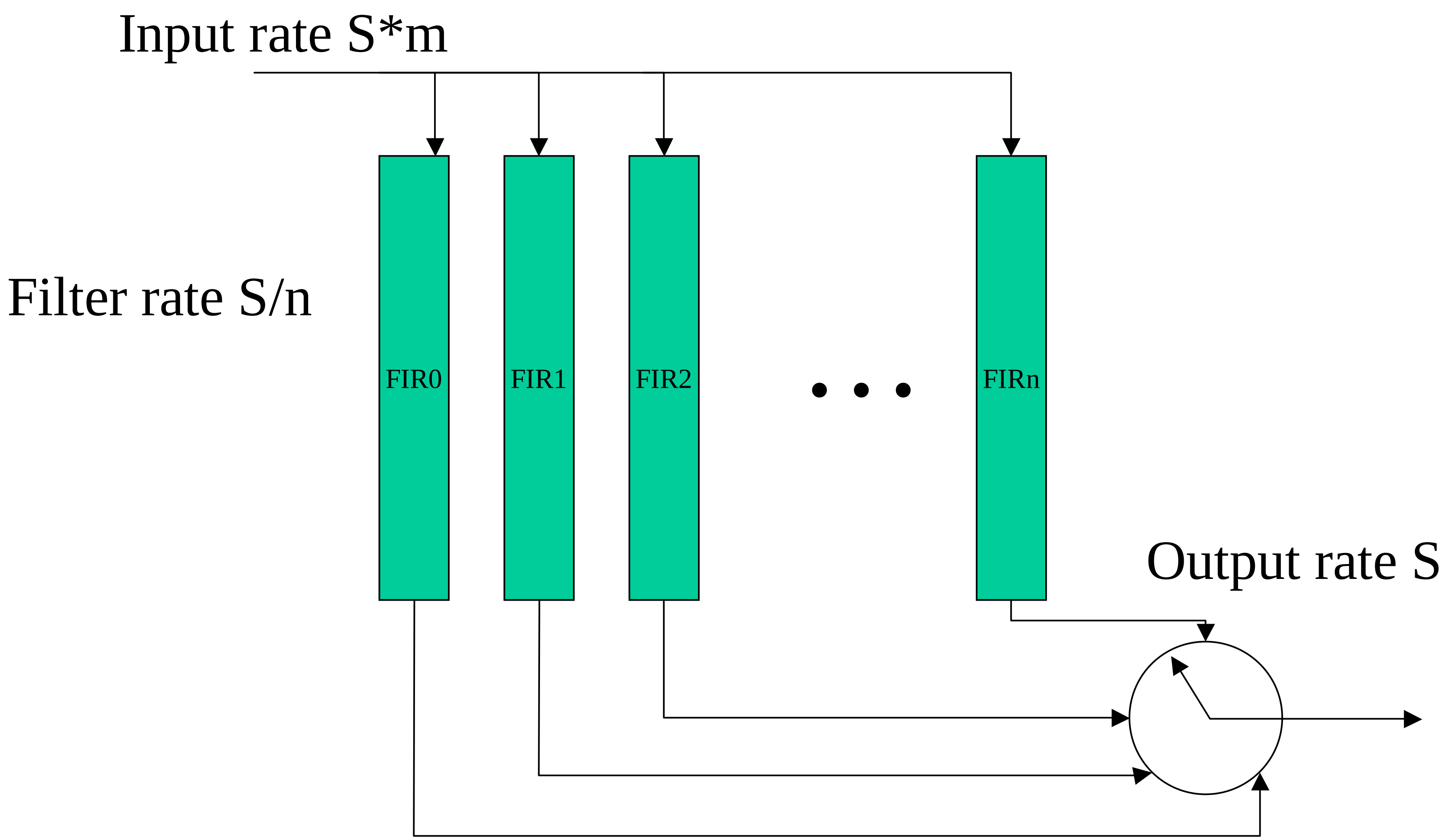
Filter rate S

S= 1368MHz

Too fast for
current processes

Decimated
Output rate S

Parallel FIR implementation



Filter rate

- S=1368, m=4
- n = 16 => Filter rate = 86MHz
- Filter spread 60ns = 300/(4*1368MHz)
- Taps per filter = 300
- Number of taps = n x 300 = 4800
- No. 1st stage adders (or gates) = 2400
- No second stage adders (4 bit) = 1200
- No of rest of adders (second to nth stage) = 1200

Gate count

- Total no. adders = 2400
- Average gates/adder = 27
  - 20 for 4 bit adder
  - Bits per adder grows down the tree
- Total Adder Gates = 65,000
- Other gates 10,000
- **Total gates = 75,000**

Simultaneous Operating Piconets

SOP Performance Depends on Several Factors

- **Signal bandwidth**
  - Other things being equal, more bandwidth gives better SOP performance
  - DS-CDMA proposal has greater overall signal bandwidth
- **Required SNR for acceptable performance**
  - Coded MBOK provides very good coding gain in AWGN
  - MB-OFDM AWGN SNR requirements get worse in multipath channels, particularly at higher data rates
- **Probability distribution of MAI**
  - Unstructured interference: non-noise-like PDF can have worse impact
  - Taking advantage of MAI structure can improve SOP performance: for DS-CDMA, MUD has potential to significantly improve SOP
- **Energy capture**
  - Implementation trade-off; efficient capture demonstrated for DS-CDMA

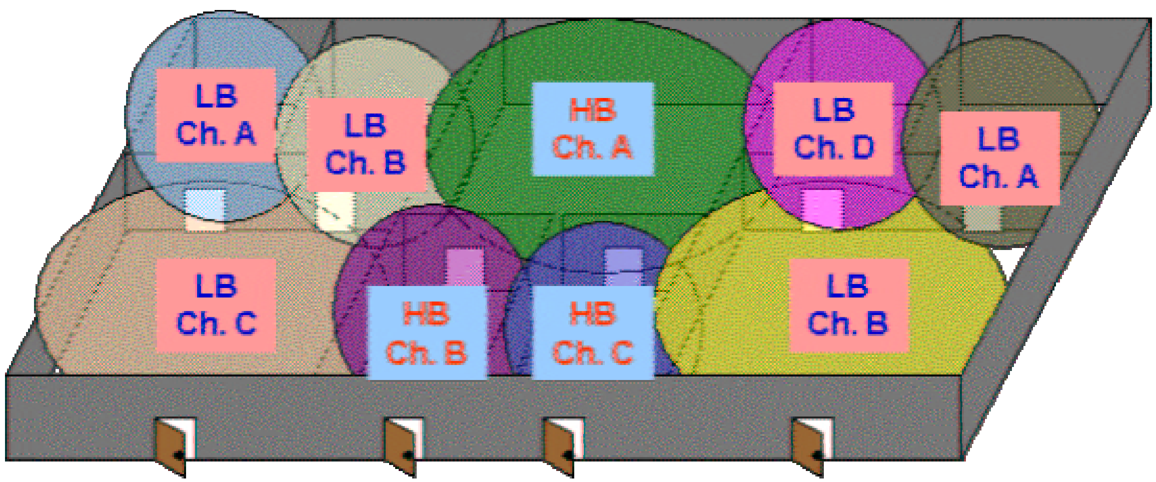
Multiple Access: A Critical Choice

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

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)
  - Mode 1 + Mode 2: 4 full-rate piconets (optional)
    - Both require use of 3 lowest bands
    - Acquisition occurs in lower 3 bands
    - Mode 1 and Mode 2 devices operating together provide no additional SOP benefit (acquisition limited)

Example High Band Modes

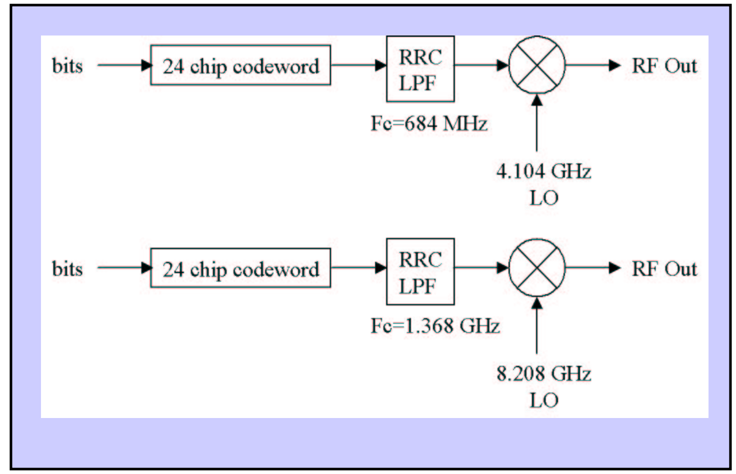
Info. Data Rate	Constellation	Symbol Rate	Quadrature	FEC Rate
25 Mbps	2-BOK	57	No	R = 0.44
50 Mbps	2-BOK	114	No	R = 0.44
114 Mbps	4-BOK	114	No	R = 0.50
112 Mbps	64-BOK	85.5	No	R = 0.44
200 Mbps	4-BOK	114	Yes	R = 0.44
224 Mbps	64-BOK	85.5	No	R = 0.44
450 Mbps	64-BOK	85.5	Yes	R = 0.44
900 Mbps	64-BOK	85.5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

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

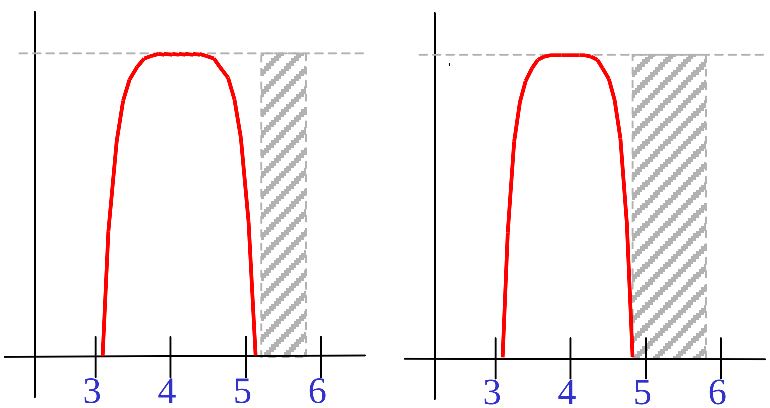
R=0.44 is concatenated ½ convolutional code with RS(55,63)
R=0.50 convolutional code
R=0.87 is RS(55,63)

Spectral Flexibility and Scalability

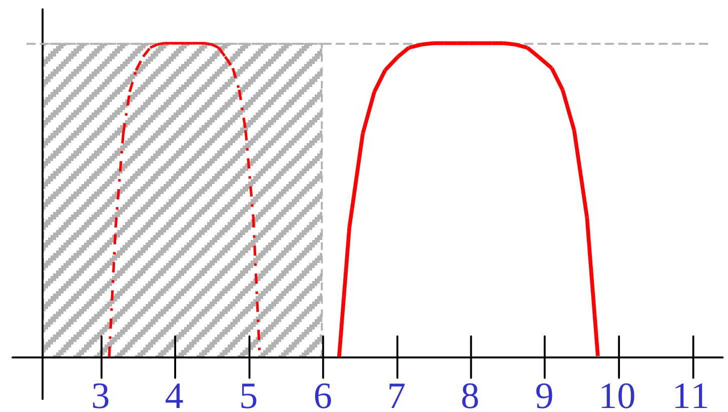
- PHY Proposal accommodates alternate spectral allocations
  - Center frequency and bandwidth are adjustable
  - Supports future spectral allocations
  - Maintains UWB advantages (i.e. wide bandwidth for multipath resolution)
  - **No changes to silicon**



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:

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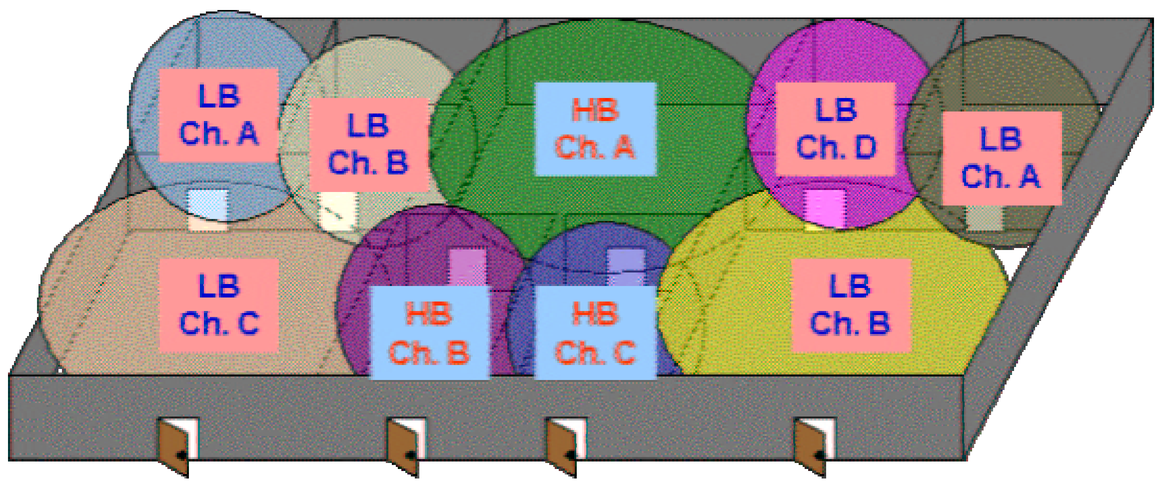
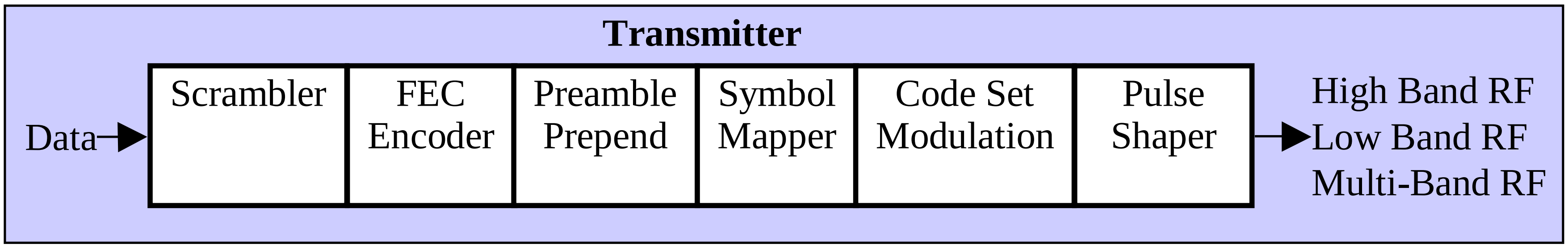


An environment depicting multiple collocated piconets

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

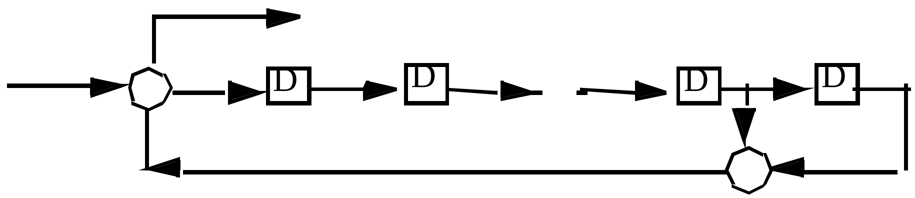
This PHY proposal is based upon proven and common communication techniques



- **Multiple bits/symbol via MBOK coding**
- **Data rates from 25 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**

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
  - Convolutional code
    - ½ rate K=7, (171, 133)
    - Convolutional interleaver
  - Reed-Solomon code
    - RS(63,55)
  - Concatenated FEC code (RS + Convolutional Code)

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 3 dB repetition gain for reliable link establishment

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
- Pulse filtering/shaping 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

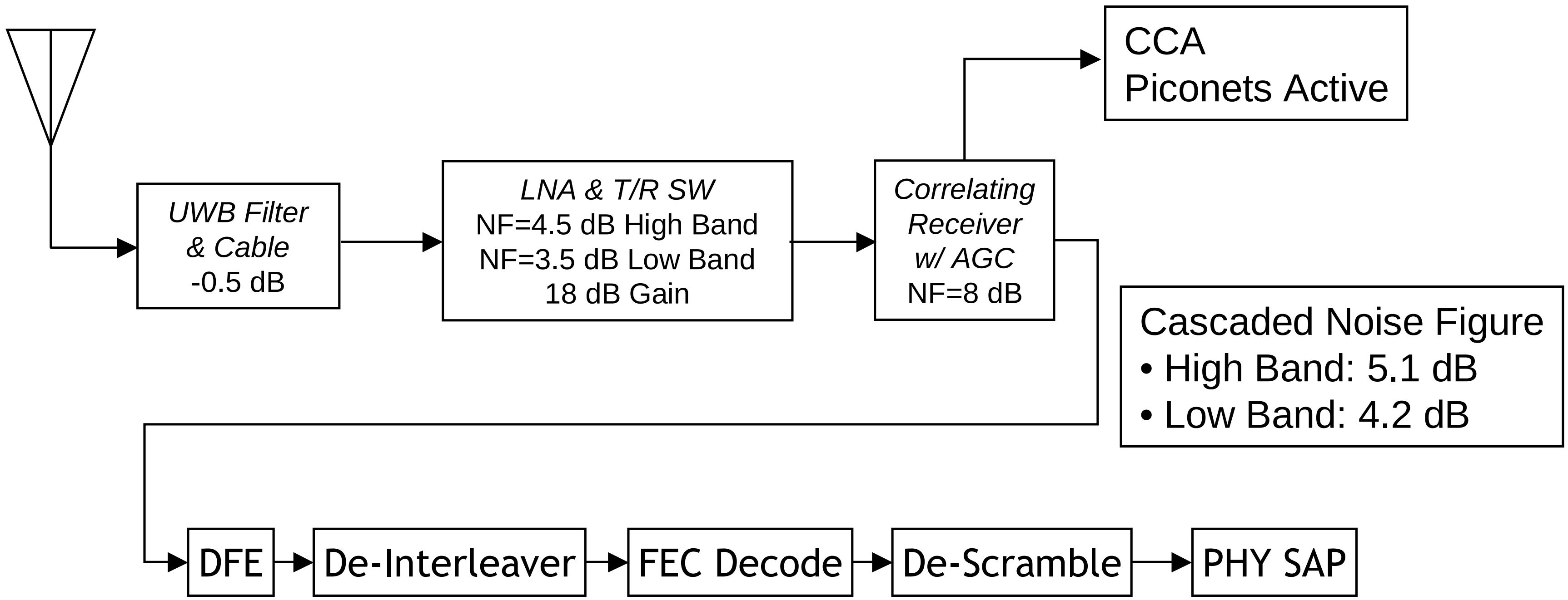
	RRC BW	Chip Rate	Code Length	Symbol Rate
Low Band	1.368 GHz	1.368 GHz (±1 MHz, ± 3 MHz)	24 or 32 chips/symbol	57 or 42.75 MS/s
High Band	2.736 GHz	2.736 GHz (±1 MHz, ± 3 MHz)	24 or 32 chips/symbol	114 or 85.5 MS/s

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



- 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

Link Budgets for 200+ Mbps

Parameter	Value	Value	Value
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 (@ 4 meters)	56.5 dB (@ 4 meters)	56.2 dB (@ 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

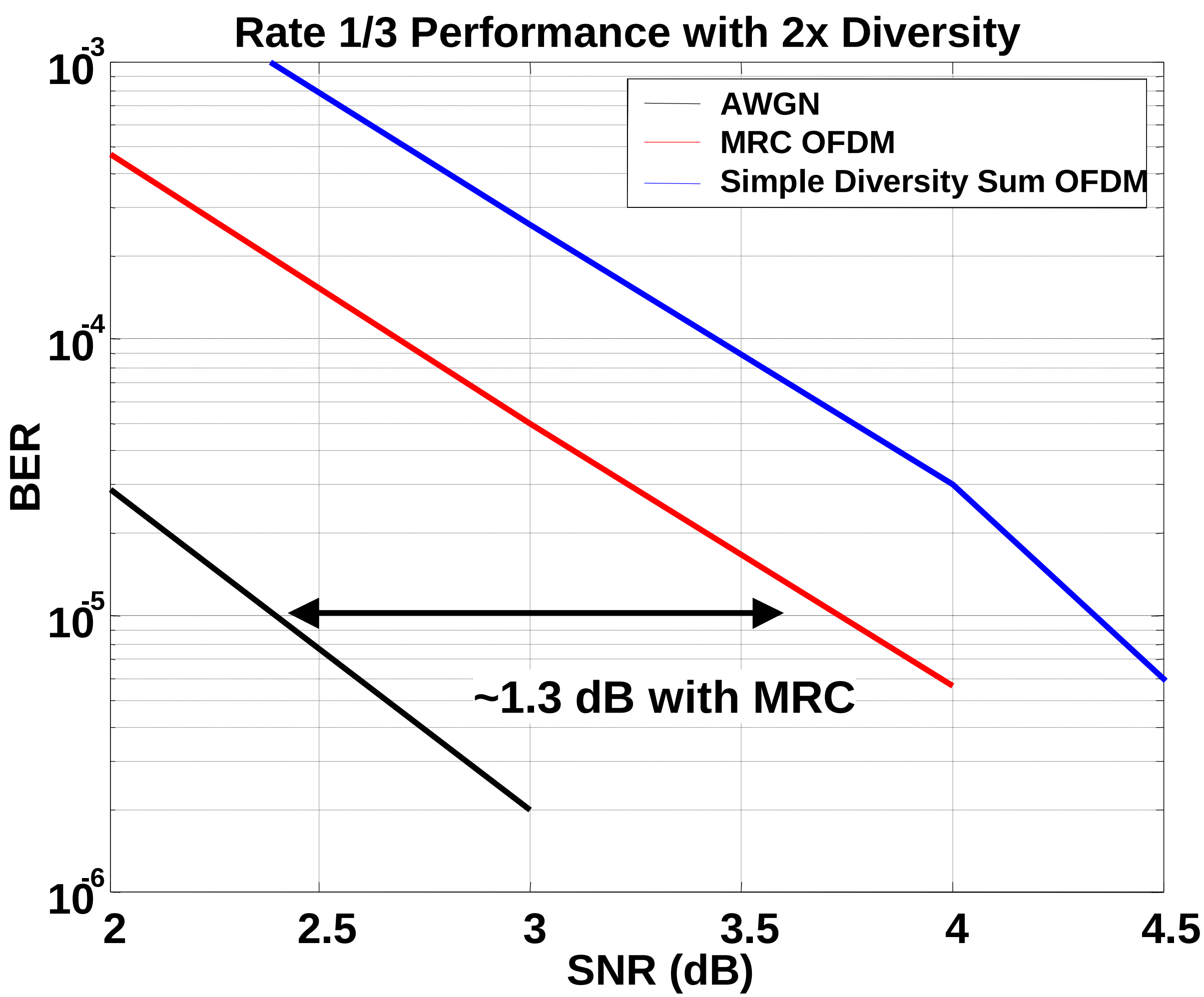
AWGN Link Budgets for Higher Rates

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 (@ 2 meters)	50.2 dB (@ 2 meters)
Average RX Power	-60.4 dBm	-60.5 dBm
Noise Power Per Bit	-87.2 dBm	-87.2 dBm
CMOS RX Noise Figure	6.6 dB	6.6 dB
Total Noise Power	-80.6 dBm	-80.6 dBm
Required Eb/N0	4.4 dB	4.9 dB
Implementation Loss	4.0 dB	2.5 dB
Link Margin	12.1 dB	12.2 dB
RX Sensitivity Level	-72.5 dBm	-72.7 dB

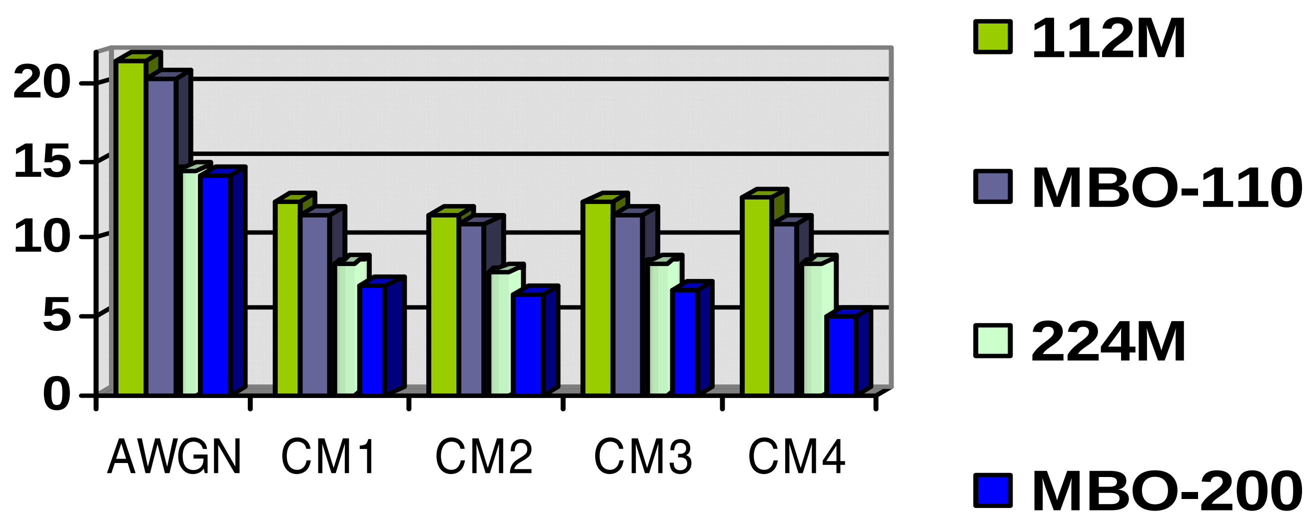
Impact of Rayleigh Fading Analysis Modifies AWGN Budget

- There are differences in receiver fading statistics seen by the MB-OFDM and DS-CDMA proposal
- Initial results (without MRC combining for low rates) in Document 03/344
  - 2 dB for rate 1/3, 3.5 dB for rate 5/8, 7.5 dB for rate ¾
  - We indicated 0.5 to 1 dB better with MRC
  - Our “2-carrier diversity” is the same as the MB-OFDM “Spread rate” – should be “apples-to-apples”
  - Feedback that MRC should be feasible
- Theoretically achievable results with MRC at 1e-5 BER
  - 1 dB for rate 1/3, 2 dB for rate 5/8, 6 dB for rate ¾
- MB-OFDM differences from AWGN are minimal at lower rates, but degrade as FEC is punctured & with no diversity

Rayleigh Fading Updated Results



Distance achieved for worst packet error rate of best 90% = 8% (Digital implementation)



Mean PER = 8%	AWGN	CM1	CM2	CM3	CM4
112Mbps	21.6 m (20.5 m)	12.4 m (11.5 m)	11.5 m (10.9 m)	12.5 m (11.6 m)	12.7 m (11.0 m)
224Mbps	14.5 m (14.1m)	8.4 m (6.9 m)	7.9 m (6.3 m)	8.5 m (6.8 m)	8.5 m (5.0 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.

Complexity - Area/Gate count, Power consumption

	Gate equiv	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	0.13	10	10	10
Matched filter	75k	0.58	40	80	-
Channel estimation	24k extra	0.15	-	-	80
Viterbi Decoder (k=7) RS decoders (55/63)	90k	0.55	45	15	-
Rest of Baseband Section	65k	0.40	25	60	25
Total	256k	4.50mm^2	180mW	225mW	175mW

- These figure are for a standard cell library implementation in 0.13µm CMOS

Scalability with technology

- Process shrinks
  - 130nm -> 90nm -> 65nm
- Matched filter
  - 75k gates -> 38k gates -> 20k gates
  - 1 bit samples -> 2 bits -> 3 bits
  - 60ns spread -> 120ns -> 240ns
- ADC
  - 1 bit samples -> 2bits -> 3bits

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

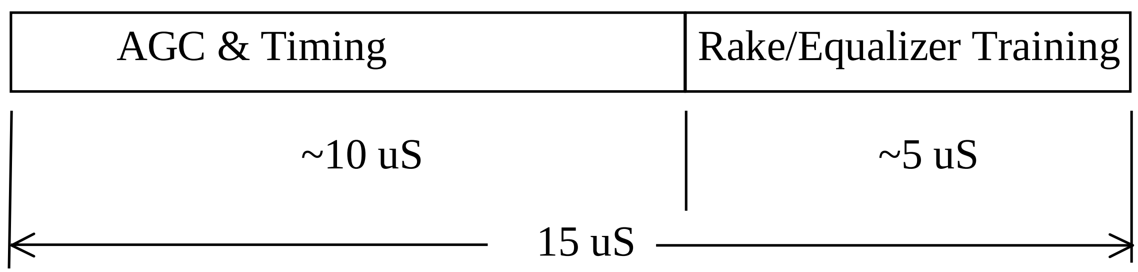
Note 1: http://www.xtremespectrum.com/PDF/xsi_trinity_brief.pdf

PHY Synchronization Preamble Sequence

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

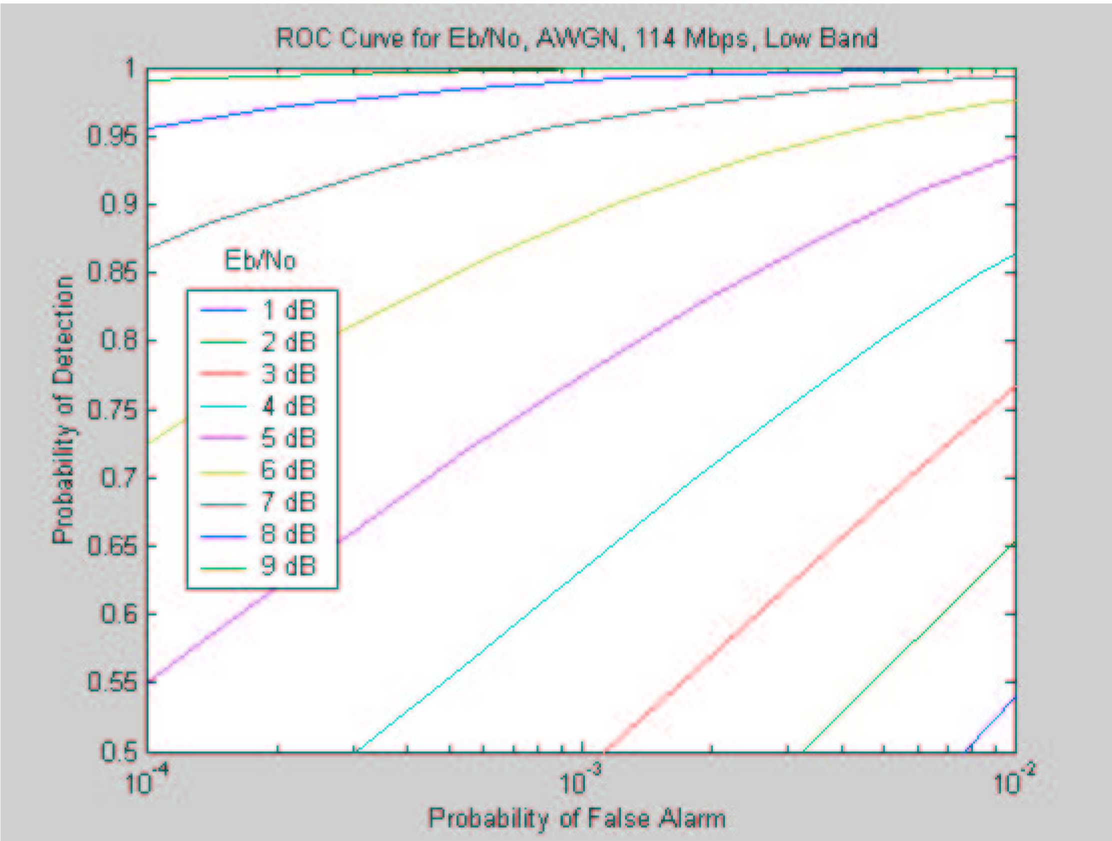
JNJNB5ANB6APAPCPANASASCNJNASK9B5K6B5K5D5D5B9ANASJPJNK5MNCP
ATB5CSJPMTK9MSJTCTASD9ASCTATASCSANCSASJSJSB5ANB6JPN5DAASB9K
5MSCNDE6AT3469RKWAVXM9JFEZ8CDS0D6BAV8CCS05E9ASRWR914A1BR

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*	+

Additional Technical Slides

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

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

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

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

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

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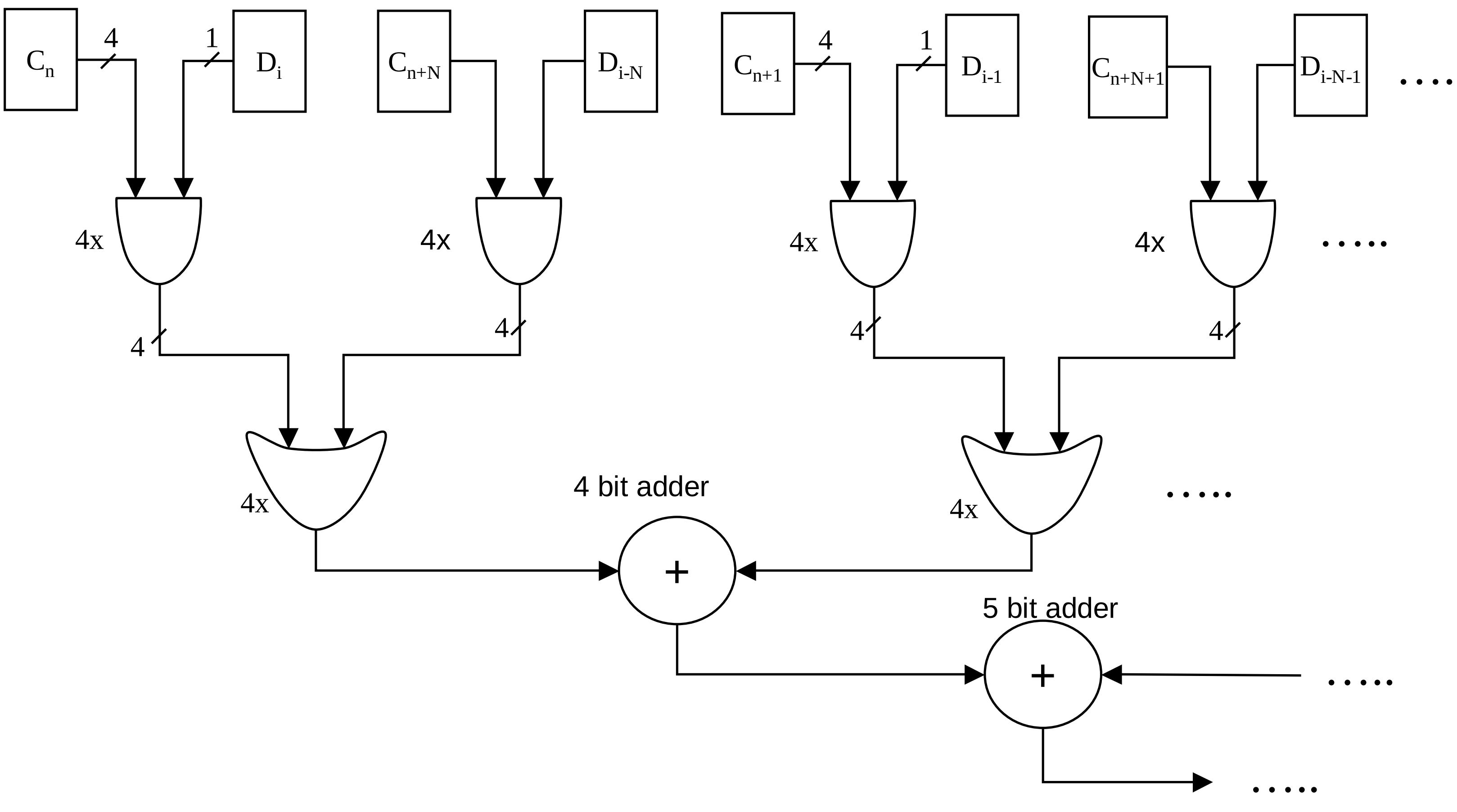
Example Matched Filter Configuration

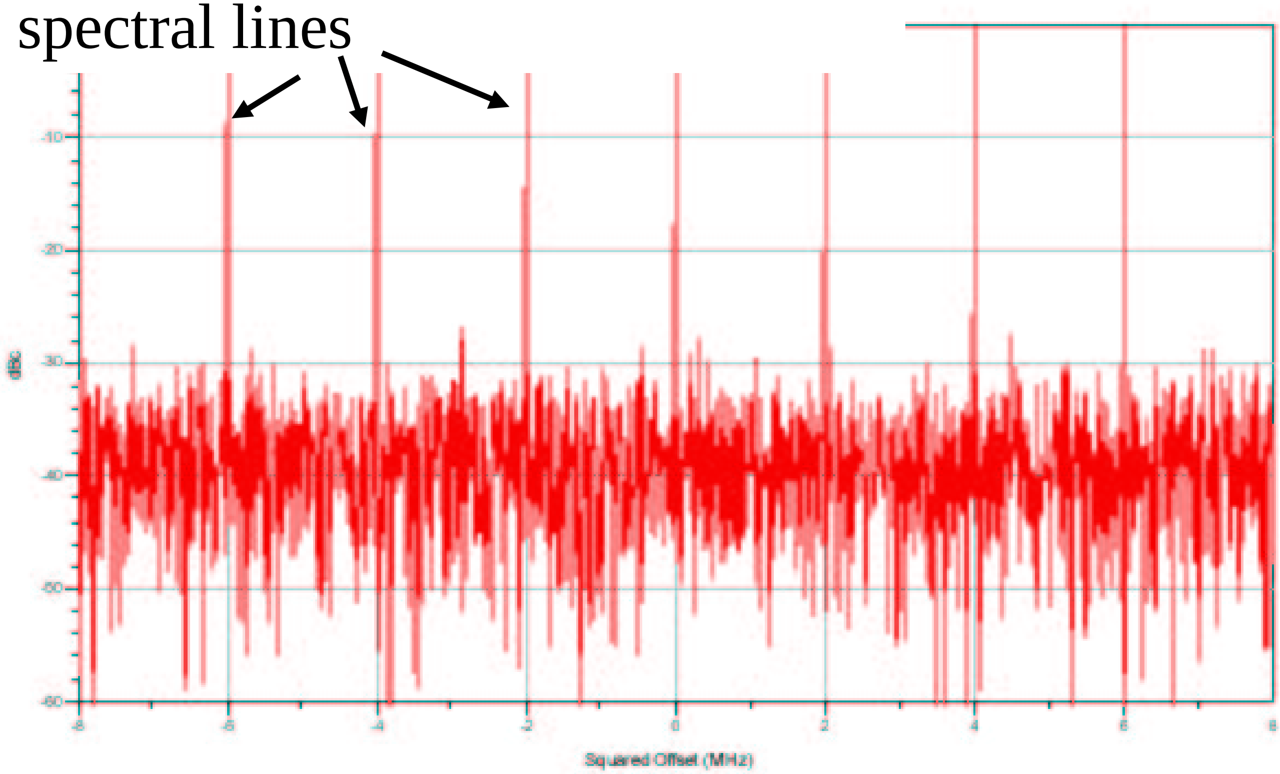


Strong Support for CSMA/CCA

- 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

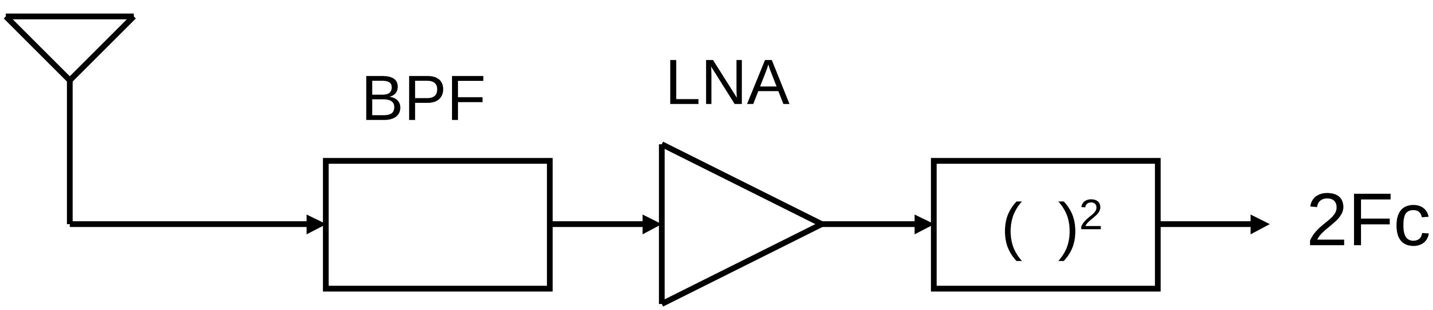
Output of the Squaring Circuit

Piconets clearly identified by spectral lines



How it Works

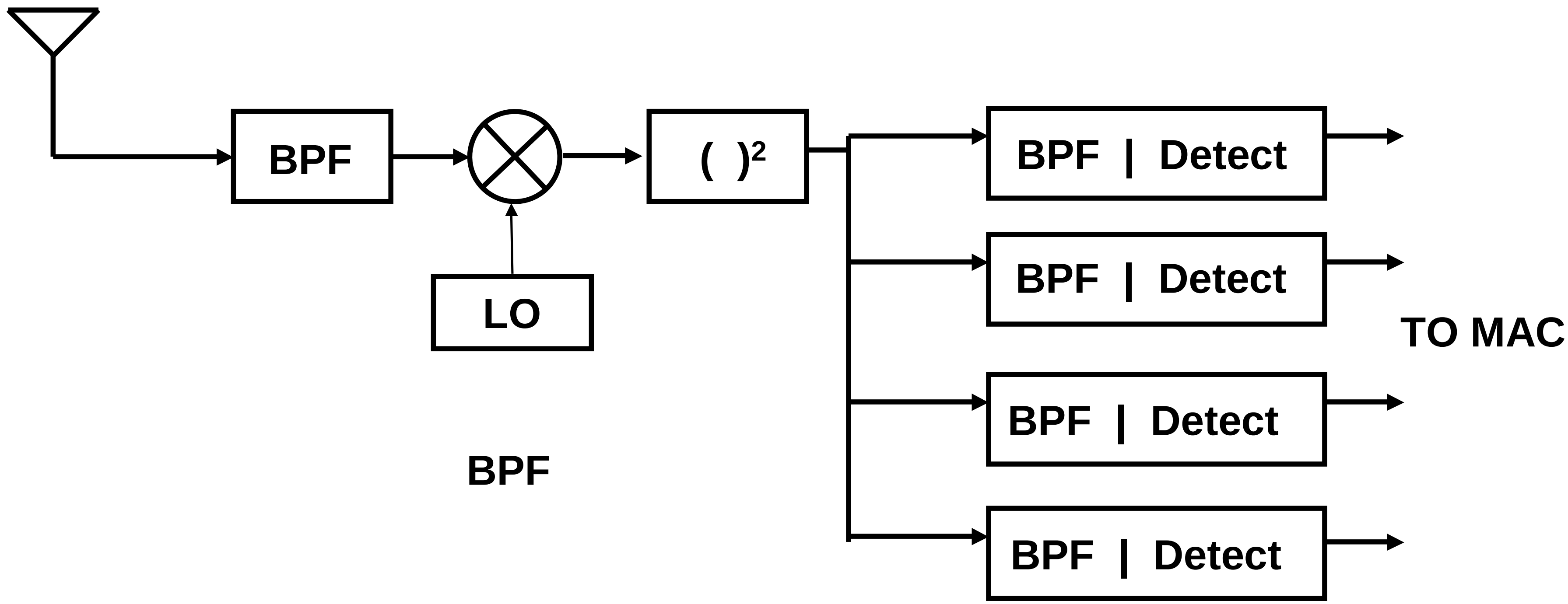
- Fc = wavelet center frequency = 3x chip rate
- Piconet ID is chip rate offset of ±1 or ±3 MHz



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

How it Works

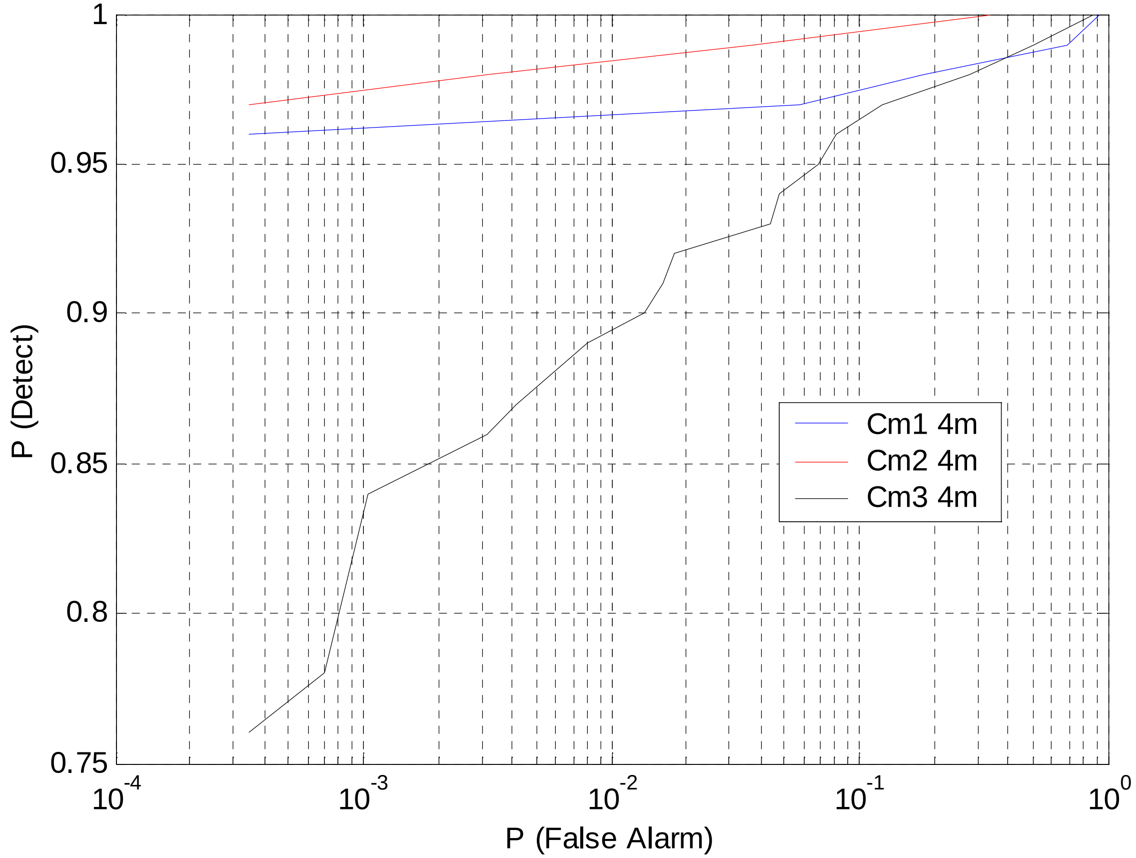
- Can also be done at baseband:



- 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

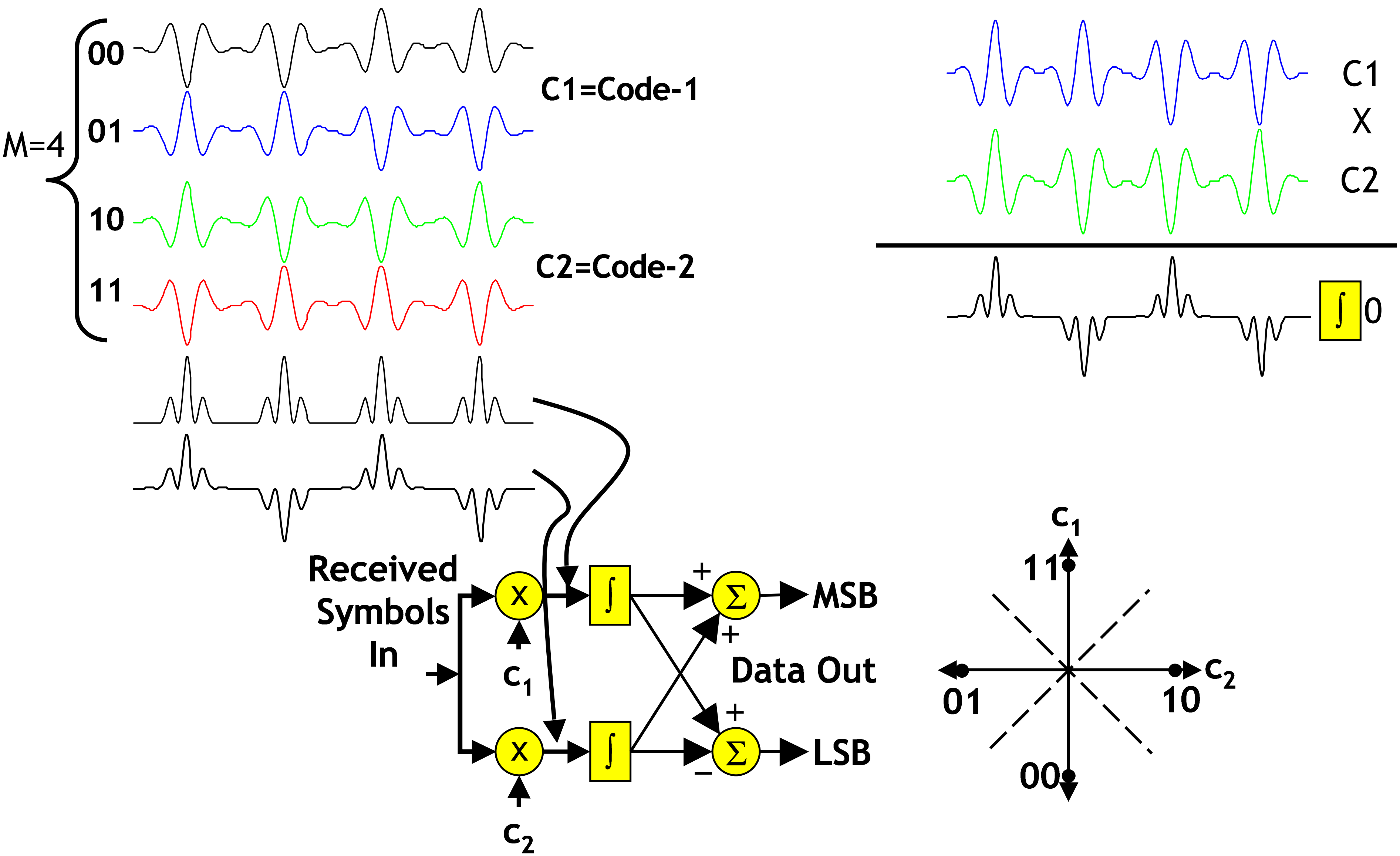
The following figure represents the CCA ROC curves for CM1, CM2 and CM3 at 4.1 GHz. This curve shows good performance on CM1 and CM2 with high probability of detection and low probability of false alarm (e.g. usage of a CAP CSMA based algorithm is feasible); however, on CM3 use of the management slots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



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

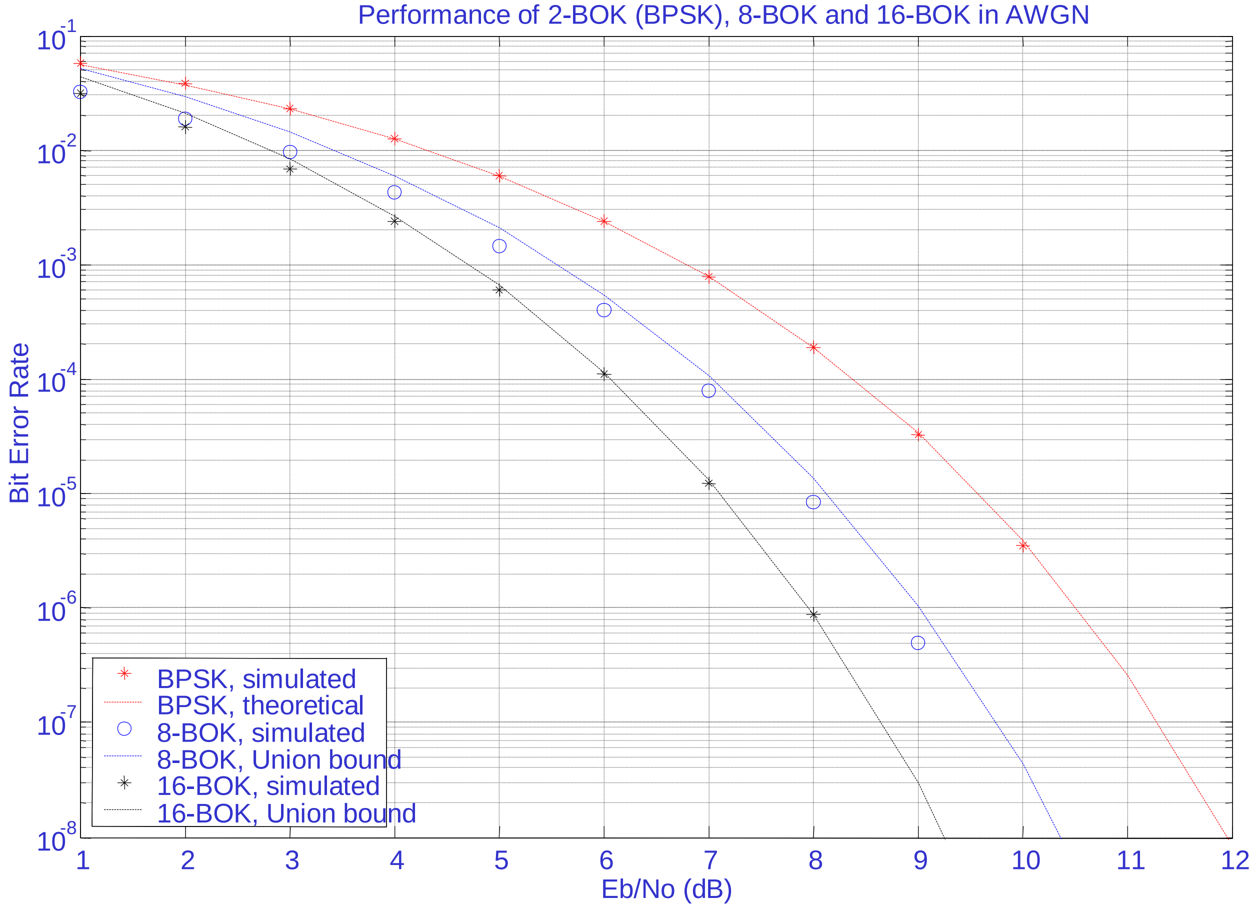
Our CCA scheme allows monitoring channel activity during preamble acquisition to minimize probability of false alarm acquisition attempts.

M-BOK (M=4) Illustration



MBOK Coding Gain

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



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