Submission Title: [Merger#2 Proposal DS-CDMA ]
Date Submitted: [17 September 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.]

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

- Communication Research Lab (CRL)
- XtremeSpectrum, Inc
- ParthusCeva
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SANYO Electric Co., Ltd.
Science University of Tokyo
Taiyo Yuden Co., Ltd.
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Tokyo Denki University
Tokyo Institute of Technology
Tokyo Institute of Technology
With an appropriate diplexer, the multi-band mode will support full-duplex operation (RX in one band while TX in the other).

3 Spectral Modes of Operation:

- **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
- **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

<table>
<thead>
<tr>
<th>Optimized SSA</th>
<th>Additional Mode for new merger with CRL</th>
<th>Previous merger proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Single band</td>
<td>• Dual-band</td>
<td>• Dual-band</td>
</tr>
<tr>
<td>Ex.: Modulated Hermitian pulses</td>
<td>Ex.: Modulated order-0 modified Hermitian pulse</td>
<td>Designed wavelet pulse shape</td>
</tr>
</tbody>
</table>

**Pulse shape**

**Time [nsec]**

**Low band**

**High band**

Ex.: Modulated Hermitian pulses

Ex.: Modulated order-0 modified Hermitian pulse

Low band

High band
<table>
<thead>
<tr>
<th>Modulation</th>
<th><strong>Optimized SSA</strong></th>
<th><strong>Merger #2 proposal</strong></th>
<th><strong>Initial Merger proposal with CRL</strong></th>
</tr>
</thead>
</table>
| **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

FH-OFDM
DS-CDMA

DS-CDMA is more benign

Volts

μs
### Fixed Transmitter Spec

**Scalable Receivers Across Applications**

<table>
<thead>
<tr>
<th>watts/ performance/ dollars</th>
<th>Implementation Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit-only applications</td>
<td>No IFFT DAC – super low power</td>
</tr>
<tr>
<td></td>
<td>Ultra simple yet capable of highest speeds</td>
</tr>
<tr>
<td>Big Appetite</td>
<td>RF sampling</td>
</tr>
<tr>
<td></td>
<td>Growth with DSP</td>
</tr>
<tr>
<td></td>
<td>MUD, digital RFI nulling, higher MBOK</td>
</tr>
<tr>
<td></td>
<td>Gets easier as IC processes shrink</td>
</tr>
<tr>
<td>Medium Appetite</td>
<td>Analog with few RAKE</td>
</tr>
<tr>
<td></td>
<td>1X, 2X, or 4X chip rate sampling</td>
</tr>
<tr>
<td></td>
<td>Digital RAKE &amp; MBOK</td>
</tr>
<tr>
<td>Smallest Appetite</td>
<td>Symbol-rate sampling with 1 RAKE</td>
</tr>
</tbody>
</table>
Scaleable power/cost/performance
Adaptable to broad application classes

**Symbol Rate ADC**
Simple/cheap Analog Emphasis

- Demod
- Analog Correlator Bank
- ADC
- SAP
- 57 Msps

**Chip Rate ADC**
Higher Performance some DSP-capable

- Filter
- Demod
- ADC
- Digital Correlator Bank
- SAP
- 1.368 Gsps

**RF Nyquist Rate ADC**
Highest Performance most DSP-capable

- Filter
- ADC
- Digital Demod & Correlator Bank
- SAP
- 20 Gsps
# Link Budgets for 110+ Mbps

<table>
<thead>
<tr>
<th>Parameter</th>
<th>4-BOK</th>
<th>MERGER</th>
<th>64-BOK</th>
<th>MB-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Data Rate</td>
<td>114 Mb/s</td>
<td>114 Mb/s</td>
<td>112 Mb/s</td>
<td>110 Mb/s</td>
</tr>
<tr>
<td>Average TX Power</td>
<td>-9.9 dBm</td>
<td>-9.9 dBm</td>
<td>-9.9 dBm</td>
<td>-10.3 dBm</td>
</tr>
<tr>
<td>Total Path Loss</td>
<td>64.4 dB</td>
<td>64.4 dB</td>
<td>64.4 dB</td>
<td>64.2 dB</td>
</tr>
<tr>
<td>( @ 10 meters)</td>
<td></td>
<td>( @ 10 meters)</td>
<td>( @ 10 meters)</td>
<td></td>
</tr>
<tr>
<td>Average RX Power</td>
<td>-74.4 dBm</td>
<td>-74.4 dBm</td>
<td>-74.4 dBm</td>
<td>-74.5 dBm</td>
</tr>
<tr>
<td>Noise Power Per Bit</td>
<td>-93.4 dBm</td>
<td>-93.4 dBm</td>
<td>-93.5 dBm</td>
<td>-93.6 dBm</td>
</tr>
<tr>
<td>CMOS RX Noise Figure</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
</tr>
<tr>
<td>Total Noise Power</td>
<td>-86.8 dBm</td>
<td>-86.8 dBm</td>
<td>-86.9 dBm</td>
<td>-87.0 dBm</td>
</tr>
<tr>
<td>Required Eb/N0</td>
<td>4.4 dB</td>
<td>2.9 dB</td>
<td>2.4 dB</td>
<td>4.0 dB</td>
</tr>
<tr>
<td>Implementation Loss</td>
<td>2.5 dB</td>
<td>2.5 dB</td>
<td>4.0 dB</td>
<td>2.5 dB</td>
</tr>
<tr>
<td>Link Margin</td>
<td>5.6 dB</td>
<td>7.1 dB</td>
<td>6.1 dB</td>
<td>6.0 dB</td>
</tr>
<tr>
<td>RX Sensitivity Level</td>
<td>-78.9 dBm</td>
<td>-78.9 dBm</td>
<td>-80.5 dBm</td>
<td>-80.5 dBm</td>
</tr>
</tbody>
</table>
FIR Gate count for example FIR implementation
Example Matched Filter Configuration
Serial FIR implementation

Input rate $S \cdot m$

Filter rate $S$

$S = 1368\text{MHz}$

Too fast for current processes

$S = \text{chip rate}$

$m = \text{over-sampling factor}$

Decimated Output rate $S$
Parallel FIR implementation

Input rate $S \times m$

Filter rate $S/n$

Output rate $S$
Filter rate

- $S=1368$, $m=4$
- $n = 16 \Rightarrow \text{Filter rate} = 86\text{MHz}$
- Filter spread $60\text{ns} = 300/(4*1368\text{MHz})$
- Taps per filter $= 300$
- Number of taps $= n \times 300 = 4800$
- No. 1$^{\text{st}}$ 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
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

<table>
<thead>
<tr>
<th>Info. Data Rate</th>
<th>Constellation</th>
<th>Symbol Rate</th>
<th>Quadrature</th>
<th>FEC Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Mbps</td>
<td>2-BOK</td>
<td>57</td>
<td>No</td>
<td>R = 0.44</td>
</tr>
<tr>
<td>50 Mbps</td>
<td>2-BOK</td>
<td>114</td>
<td>No</td>
<td>R = 0.44</td>
</tr>
<tr>
<td>114 Mbps</td>
<td>4-BOK</td>
<td>114</td>
<td>No</td>
<td>R = 0.50</td>
</tr>
<tr>
<td>112 Mbps</td>
<td>64-BOK</td>
<td>85.5</td>
<td>No</td>
<td>R = 0.44</td>
</tr>
<tr>
<td>200 Mbps</td>
<td>4-BOK</td>
<td>114</td>
<td>Yes</td>
<td>R = 0.44</td>
</tr>
<tr>
<td>224 Mbps</td>
<td>64-BOK</td>
<td>85.5</td>
<td>No</td>
<td>R = 0.44</td>
</tr>
<tr>
<td>450 Mbps</td>
<td>64-BOK</td>
<td>85.5</td>
<td>Yes</td>
<td>R = 0.44</td>
</tr>
<tr>
<td>900 Mbps</td>
<td>64-BOK</td>
<td>85.5</td>
<td>Yes</td>
<td>R = 0.87</td>
</tr>
</tbody>
</table>

*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)*
• 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

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

- Forward error correction options
  - Convolutional code
    - $\frac{1}{2}$ rate $K=7$, $(171, 133)$
    - Convolutional interleaver
  - Reed-Solomon code
    - RS(63,55)
  - Concatenated FEC code (RS + Convolutional Code)

$g(D)=1+D^{14}+D^{15}$
PHY Preamble and Header

- 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

<table>
<thead>
<tr>
<th></th>
<th>RRC BW</th>
<th>Chip Rate</th>
<th>Code Length</th>
<th>Symbol Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Band</strong></td>
<td>1.368 GHz</td>
<td>1.368 GHz</td>
<td>24 or 32</td>
<td>57 or 42.75</td>
</tr>
<tr>
<td></td>
<td>(±1 MHz, ±3 MHz)</td>
<td></td>
<td>chips/symbol</td>
<td>MS/s</td>
</tr>
<tr>
<td><strong>High Band</strong></td>
<td>2.736 GHz</td>
<td>2.736 GHz</td>
<td>24 or 32</td>
<td>114 or 85.5</td>
</tr>
<tr>
<td></td>
<td>(±1 MHz, ±3 MHz)</td>
<td></td>
<td>chips/symbol</td>
<td>MS/s</td>
</tr>
</tbody>
</table>
## Code Set Spectral Back-off and Cross-correlation

<table>
<thead>
<tr>
<th>Backoff Type</th>
<th>2-BOK</th>
<th>4-BOK</th>
<th>8-BOK</th>
<th>64-BOK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Pk-to-Avg Backoff</td>
<td>2.2 dB</td>
<td>2.1 dB</td>
<td>1.7 dB</td>
<td>&lt;1 dB</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Data Rate</td>
<td>200 Mb/s</td>
<td>224 Mb/s</td>
<td>200 Mb/s</td>
</tr>
<tr>
<td>Average TX Power</td>
<td>-9.9 dBm</td>
<td>-9.9 dBm</td>
<td>-10.3 dBm</td>
</tr>
<tr>
<td>Total Path Loss</td>
<td>56.5 dB (4 m)</td>
<td>56.5 dB (4 m)</td>
<td>56.2 dB (4 m)</td>
</tr>
<tr>
<td>Average RX Power</td>
<td>-66.4 dBm</td>
<td>-66.4 dBm</td>
<td>-66.5 dBm</td>
</tr>
<tr>
<td>Noise Power Per Bit</td>
<td>-91.0 dBm</td>
<td>-91.0 dBm</td>
<td>-91.0 dBm</td>
</tr>
<tr>
<td>CMOS RX Noise Figure</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
</tr>
<tr>
<td>Total Noise Power</td>
<td>-84.4 dBm</td>
<td>-83.9 dBm</td>
<td>-84.4 dBm</td>
</tr>
<tr>
<td>Required Eb/N0</td>
<td>6.8 dB</td>
<td>2.4 dB</td>
<td>4.7 dB</td>
</tr>
<tr>
<td>Implementation Loss</td>
<td>2.5 dB</td>
<td>4.0 dB</td>
<td>2.5 dB</td>
</tr>
<tr>
<td>Link Margin</td>
<td>8.7 dB</td>
<td>11.1 dB</td>
<td>10.7 dB</td>
</tr>
<tr>
<td>RX Sensitivity Level</td>
<td>-75.1 dBm</td>
<td>-77.5 dBm</td>
<td>-77.2 dBm</td>
</tr>
</tbody>
</table>
### AWGN Link Budgets for Higher Rates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Data Rate</td>
<td>448 Mb/s</td>
<td>480 Mb/s</td>
</tr>
<tr>
<td>Average TX Power</td>
<td>-9.9 dBm</td>
<td>-10.3 dBm</td>
</tr>
<tr>
<td>Total Path Loss</td>
<td>50.5 dB</td>
<td>50.2 dB</td>
</tr>
<tr>
<td>( @ 2 meters)</td>
<td></td>
<td>( @ 2 meters)</td>
</tr>
<tr>
<td>Average RX Power</td>
<td>-60.4 dBm</td>
<td>-60.5 dBm</td>
</tr>
<tr>
<td>Noise Power Per Bit</td>
<td>-87.2 dBm</td>
<td>-87.2 dBm</td>
</tr>
<tr>
<td>CMOS RX Noise Figure</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
</tr>
<tr>
<td>Total Noise Power</td>
<td>-80.6 dBm</td>
<td>-80.6 dBm</td>
</tr>
<tr>
<td>Required Eb/N0</td>
<td>4.4 dB</td>
<td>4.9 dB</td>
</tr>
<tr>
<td>Implementation Loss</td>
<td>4.0 dB</td>
<td>2.5 dB</td>
</tr>
<tr>
<td>Link Margin</td>
<td>12.1 dB</td>
<td>12.2 dB</td>
</tr>
<tr>
<td>RX Sensitivity Level</td>
<td>-72.5 dBm</td>
<td>-72.7 dB</td>
</tr>
</tbody>
</table>
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

Rate 1/3 Performance with 2x Diversity

- AWGN
- MRC OFDM
- Simple Diversity Sum OFDM

\[ \text{BER} \]

\[ \text{SNR (dB)} \]

~1.3 dB with MRC
Distance achieved for worst packet error rate of best 90% = 8%
(Digital implementation)

<table>
<thead>
<tr>
<th></th>
<th>AWGN</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>112Mbps</strong></td>
<td>21.6 m (20.5 m)</td>
<td>12.4 m (11.5 m)</td>
<td>11.5 m (10.9 m)</td>
<td>12.5 m (11.6 m)</td>
<td>12.7 m (11.0 m)</td>
</tr>
<tr>
<td><strong>224Mbps</strong></td>
<td>14.5 m (14.1 m)</td>
<td>8.4 m (6.9 m)</td>
<td>7.9 m (6.3 m)</td>
<td>8.5 m (6.8 m)</td>
<td>8.5 m (5.0 m)</td>
</tr>
</tbody>
</table>

Mean PER = 8%

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

<table>
<thead>
<tr>
<th></th>
<th>Gate equiv</th>
<th>Area (mm²)</th>
<th>Power mW Rx Data @ 120Mbps</th>
<th>Power mW Rx Data @ 450Mbps</th>
<th>Power mW Preamble Rx</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF section (Up to and incl. A/D - D/A)</td>
<td>-</td>
<td>2.8</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>RAM - 24kbits</td>
<td>22k</td>
<td>0.13</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Matched filter</td>
<td>75k</td>
<td>0.58</td>
<td>40</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>24k extra</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>Viterbi Decoder (k=7) RS decoders (55/63)</td>
<td>90k</td>
<td>0.55</td>
<td>45</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Rest of Baseband Section</td>
<td>65k</td>
<td>0.40</td>
<td>25</td>
<td>60</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>256k</td>
<td>4.50mm²</td>
<td>180mW</td>
<td>225mW</td>
<td>175mW</td>
</tr>
</tbody>
</table>

- 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 -> 2 bits -> 3 bits
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 set¹
  • DFE with M-BOK is efficient and proven technology (ref. 802.11b CCK devices)
  • DFE Die Size Estimate: <0.1 mm²
  • 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 medium length sequence)

JNJNB5ANB6APAPCPANASASCNJNASK9B5K6B5K5D5D5B9ANASJPJNK5MNCP
ATB5CSJPMTK9MSJCTCTASD9ASCTATASCSANCSASJSJSB5ANB6JPN5DAASB9K
5MSCNDE6AT3469RKWAVXM9JFEZ8CDS0D6BAV8CCS05E9ASRWR914A1BR

Notation is Base 32

<table>
<thead>
<tr>
<th>AGC &amp; Timing</th>
<th>Rake/Equalizer Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>~10 uS</td>
<td>~5 uS</td>
</tr>
<tr>
<td>15 uS</td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>114 Mbps Eb/No</th>
<th>Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 dB</td>
<td>1.0</td>
</tr>
<tr>
<td>8 dB</td>
<td>0.999</td>
</tr>
<tr>
<td>7 dB</td>
<td>0.994</td>
</tr>
<tr>
<td>6 dB</td>
<td>0.976</td>
</tr>
<tr>
<td>5 dB</td>
<td>0.935</td>
</tr>
<tr>
<td>4 dB</td>
<td>0.865</td>
</tr>
<tr>
<td>3 dB</td>
<td>0.770</td>
</tr>
<tr>
<td>2 dB</td>
<td>0.655</td>
</tr>
<tr>
<td>1 dB</td>
<td>0.540</td>
</tr>
</tbody>
</table>

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)
### 6.1 General Solution Criteria

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>REF.</th>
<th>IMPORTANCE LEVEL</th>
<th>PROPOSER RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Manufacturing Complexity (UMC)</td>
<td>3.1</td>
<td>B</td>
<td>+</td>
</tr>
<tr>
<td><strong>Signal Robustness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interference And Susceptibility</td>
<td>3.2.2</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>Coexistence</td>
<td>3.2.3</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td><strong>Technical Feasibility</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturability</td>
<td>3.3.1</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>Time To Market</td>
<td>3.3.2</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>Regulatory Impact</td>
<td>3.3.3</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>Scalability (i.e. Payload Bit Rate/Data Throughput, Channelization – physical or coded, Complexity, Range, Frequencies of Operation, Bandwidth of Operation, Power Consumption)</td>
<td>3.4</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>Location Awareness</td>
<td>3.5</td>
<td>C</td>
<td>+</td>
</tr>
</tbody>
</table>
### 6.2 PHY Protocol Criteria

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

*Self-Evaluation (cont.)*
6.3  MAC Protocol Enhancement Criteria

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>REF.</th>
<th>IMPORTANCE LEVEL</th>
<th>PROPOSER RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC Enhancements And Modifications</td>
<td>4.1</td>
<td>C</td>
<td>+</td>
</tr>
</tbody>
</table>
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.

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

<table>
<thead>
<tr>
<th>PNC1 =</th>
<th>-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 1 -1 -1 0 -1 1 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 -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 0 1 1</td>
<td></td>
</tr>
<tr>
<td>-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</td>
<td></td>
</tr>
<tr>
<td>0 -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</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PNC2 =</th>
<th>-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 0 1 -1 -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 -1 -1 1 -1 -1 1 0 1 -1 1 1 -1 1 -1 1 -1 1 1 0 1 -1 -1</td>
<td></td>
</tr>
<tr>
<td>-1 1 -1 1 1 -1 1 0 1 1 1 -1 -1 1 1 -1 1 1 0 1 -1 -1 0 -1</td>
<td></td>
</tr>
<tr>
<td>0 -1 1 1 1 -1 -1 1 1 1 -1 1 1 1 -1 1 1 1 -1 1 1 0 -1 -1</td>
<td></td>
</tr>
</tbody>
</table>

Submission: September 2003

Slide 53

Welborn, XSI & Mc Laughlin, ParthuSceva & Ryuji Kohno, CRL
### 4x8 Code Set (Cont.)

**PNC3 =**

```
-1  1  -1  1 -1  1  0  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  0 -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  0  1  1 -1  1  0  1
```

**PNC4 =**

```
-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  1 -1 -1  1  1  0  0 -1  1
-1  1 -1  1  1  1 -1  0 -1 -1 -1  1 -1  0 -1 -1  1  0 -1
0 -1 -1 -1 -1 -1 -1  1  1  1 -1  1  1 -1  1 -1  1  1 -1
```
Ternary Orthogonal Length 32 Code Set
Example Matched Filter Configuration

Cₙ  4  1  Cₙ+N  4  1  Cₙ+1  4  1  Cₙ+N+1  4  1

Di  4  1  Dᵢ-N  4  1  Dᵢ-1  4  1  Dᵢ-N-1  4  1

4x  4x  4x  4x  4x  4x  4x

4 bit adder  5 bit adder

……  ……  ……  ……  ……  ……
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

- $F_c = \text{wavelet center frequency} = 3 \times \text{chip rate}$
- Piconet ID is chip rate offset of $\pm 1$ or $\pm 3$ 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:

\[
\text{BPF} \rightarrow (\cdot)^2 \rightarrow \text{BPF} \mid \text{Detect} \rightarrow \text{BPF} \mid \text{Detect} \rightarrow \text{BPF} \mid \text{Detect}
\]

- ID’s all operating piconets
- Completely Independent of Data Stream
- DOES NOT REQUIRE PREAMBLE/HEADER
- **5us** to ID or react to signal level changes
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.**
M-BOK (M=4) Illustration

M=4

C1=Code-1

C2=Code-2

Received Symbols

In

\[ \Sigma \]

\[ \Sigma \]

\[ ! \]

\[ \# \]

\[ \times \]

\[ \times \]

\[ \times \]

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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