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

**Submission Title:** [XtremeSpectrum CFP Presentation]

**Date Submitted:** [July 2003]

**Source:** [Matt Welborn] Company [XtremeSpectrum, Inc.]
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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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Compliant Frequency Hoppers suffer degraded performance under current FCC UWB Rules\(^1\)

- FCC has expressed deep reservations about FH systems at every stage of UWB proceeding.
- To date, no interference studies have been done using FH modulations.
- FCC’s Part 15 rules on FH UWB are clear on their face:
  - A UWB frequency hopper must be tested for compliance with the hopping turned **off** and the signal "parked" or held stationary at one band of frequencies. (First R&O at para. 32.)
  - The bandwidth must be at least 500 MHz with the hopping turned off.
  - The device must comply with the emissions limits with the hopping turned off.

*Result:* The performance of compliant FH systems is seriously degraded because a hopper is NOT allowed to put as much energy as a non-hopper (both covering the same total range of frequencies).
- The maximum permitted power is reduced in proportion to the number of hops
- N=number of hops
- Range is reduced by \(1/\sqrt{N}\) assuming \(1/R^2\) propagation
- Data-rate is reduced by \(1/N\) assuming all else is equal.
- Example - 10 m range is reduced to 5.8 m range using three hops

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Note 1: Reference doc IEEE802.15-03/271
Illustration of how to test a compliant UWB FH radio

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

- Pulses/Symbols always come out at same rate
- The total average power is the same with or without hopping stopped
- With hopping stopped all power is concentrated in one band instead of N bands
- Switch is synchronized to the PFN/symbol maker
- Switch rotates to hop the >500 MHz bandwidth pulse (or symbol) to a different center frequency
- Switch stops rotating to stop hopping

A compliant FH system has only 1/N th the power of a non-hopping system so that it meets the emission limits with hopping turned off
Timing versus Power and Frequency Diagrams
for frequency hoppers

Hopping on (normal operation)
- Symbols cycle across bands over time
- Average power (dBm/MHz) in Band-B with Hopping ON must be 1/N times emission limit
- Pulse Burst is within FCC emission limit

Hopping off (for compliance testing)
- All Symbols/Pulses in same band
- Average Power (dBm/MHz) in Band-B with Hopping OFF must meet emission limit

Turning hopping off concentrates the energy so a compliant FH system has only 1/N th the power of a non-hopping system
Power versus Frequency Diagrams
For Frequency Hoppers

FH systems have only 1/N th the power of a non-hopping systems

The performance of FH systems is seriously degraded.

N=number of hops
Range is reduced by $1/\sqrt{N}$ assuming $1/R^2$ propagation
Data-rate is reduced by 1/N assuming all else is equal.
Example - 10 m range is reduced to 5.8 m range using three hop system
Two Band DS-CDMA

Low Band

- Low Band (3.1 to 5.15 GHz)
  - 28.5 Mbps to 400 Mbps
  - Supports low rate, longer range services

High Band

- High Band (5.825 to 10.6 GHz)
  - 57 Mbps to 800 Mbps
  - Supports high rate, short range services

Multi-Band

- Multi-Band (3.1 to 5.15 GHz plus 5.825 GHz to 10.6 GHz)
  - Up to 1.2 Gbps
  - Supports low rate, longer range, high rate, short range services

With an appropriate diplexer, the multi-band mode will support full-duplex operation (RX in one band while TX in the other)
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
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 28.5 Mbps to 1.2 Gbps
- Multiple access via ternary CDMA coding
- Support for CCA by exploiting higher order properties of BPSK/QPSK
- Operation with up to 8 simultaneous piconets
Scrambler and FEC Coding

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

  \[ g(D) = 1 + D^{14} + D^{15} \]

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

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

<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 (±1 MHz, ±3 MHz)</td>
<td>24 chips/symbol</td>
<td>57 MS/s</td>
</tr>
<tr>
<td><strong>High Band</strong></td>
<td>2.736 GHz</td>
<td>2.736 GHz (±1 MHz, ±3 MHz)</td>
<td>24 chips/symbol</td>
<td>114 MS/s</td>
</tr>
</tbody>
</table>
• CDMA via low cross-correlation ternary code sets (±1, 0)
• Four logical piconets per sub-band (8 logical channels over 2 bands)
• Up to 16-BOK per piconet (4 bits/symbol bi-phase, 8 bits/symbol quad-phase)
  • 1 sign bit and 3 bit code selection per modulation dimension
  • 8 codewords per piconet
• Total number of 24-chip codewords (each band): 4x8=32
  • RMS cross-correlation < -15 dB in a flat fading channel
• CCA via higher order techniques
  • Squaring circuit for BPSK, fourth-power circuit for QPSK
  • Operating frequency detection via collapsing to a spectral line
• Each piconet uses a unique center frequency offset
  • Four selectable offset frequencies, one for each piconet
    • +/- 3 MHz offset, +/- 9 MHz offset
RX Implementation Considerations
(Analog vs. Digital)

Scaleable power/cost/performance
Adaptable to broad application classes

Symbol Rate ADC
Simple/cheap Analog Emphasis

Analog Correlator Bank
ADC
57 Msps
Demod
SAP

Chip Rate ADC
Higher Performance some DSP-capable

Filter
Demod
ADC
Digital Correlator Bank
1.368 Gsps
SAP

RF Nyquist Rate ADC
Highest Performance most DSP-capable

Filter
ADC
Digital Demod & Correlator Bank
20 Gsps
SAP
4x8 Code Set

PNC1 =

| -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 | -1 | 1 | -1 | 1 | 1 |
| 0 | -1 | 1 | 1 | 1 | -1 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | -1 | 1 | -1 | 1 |
| -1 | 0 | 1 | -1 | -1 | -1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 |
| -1 | 0 | -1 | 1 | -1 | 1 | -1 | 1 | 0 | 1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | 1 | 1 |
| -1 | -1 | -1 | -1 | -1 | 1 | 1 | 0 | -1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 | 1 |
| -1 | 1 | -1 | -1 | -1 | 1 | -1 | 0 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | -1 | 0 | 1 | 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
16-BOK uses all codes

PNC2 =

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

Submission Slide 15 Welborn, XtremeSpectrum, Inc.
### 4x8 Code Set (Cont.)

#### PNC3 =

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#### PNC4 =

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### 4x8 Code Set Statistics

<table>
<thead>
<tr>
<th></th>
<th>2-BOK</th>
<th>4-BOK</th>
<th>8-BOK</th>
<th>16-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>1.3 dB</td>
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</table>

<table>
<thead>
<tr>
<th>Worst Case Synchronized Cross-correlation Coefficient within a group</th>
<th>2/22</th>
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</thead>
<tbody>
<tr>
<td>Average RMS Cross Correlation between groups</td>
<td>channel dependent but generally looks like $10 \times \log_{10}(1/24)$ noise due to center frequency offset and chipping rate frequency offset</td>
</tr>
</tbody>
</table>
RX Link Budget Performance

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

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

CCA
Piconets Active

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

DFE
De-Interleaver
FEC Decode
De-Scramble
PHY SAP
### Low Band Symbol Rates and Link Budget

**July 2003**

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

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

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

\textsuperscript{1} Center frequency determined as geometric mean in accordance with 03031r9, clause 5.6

\textsuperscript{2} Based upon corrected Eb/No of 9.6 dB after application of all coding gain

**Coding Gain References:**

- [http://grouper.ieee.org/groups/802/16/tg1/phy/contrib/802161pc-00_33.pdf](http://grouper.ieee.org/groups/802/16/tg1/phy/contrib/802161pc-00_33.pdf)
### High Band Symbol Rates and Link Budget

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

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

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

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

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

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

Our CCA scheme allows monitoring channel activity during preamble acquisition to minimize probability of false alarm acquisition attempts.
Multiple User Separation Distance – CM1 to CM4

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

<table>
<thead>
<tr>
<th>114 Mbps, 8-BOK, 2/3 Rate FEC</th>
<th>200 Mbps, 16-BOK, R-S FEC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Averaged Outage Range</strong></td>
<td><strong>Averaged Outage Range</strong></td>
</tr>
<tr>
<td>CM1</td>
<td>CM2</td>
</tr>
<tr>
<td>Meters Distance</td>
<td>15.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Coexistence Ratios – 1 MUI</strong></th>
<th><strong>Coexistence Ratios – 1 MUI</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>Int</td>
</tr>
<tr>
<td>CM1</td>
<td>0.60</td>
</tr>
<tr>
<td>CM2</td>
<td>0.67</td>
</tr>
<tr>
<td>CM3</td>
<td>0.71</td>
</tr>
<tr>
<td>CM4</td>
<td>0.83</td>
</tr>
</tbody>
</table>
## Multiple User Separation Distance – CM1 to CM4

**July 2003**

**doc.: IEEE 802.15-03/153r7**

### Continuing

#### Coexistence Ratios – 2 MUI

<table>
<thead>
<tr>
<th>Ref</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>0.85</td>
<td>0.82</td>
<td>0.74</td>
<td>0.70</td>
</tr>
<tr>
<td>CM2</td>
<td>0.94</td>
<td>0.91</td>
<td>0.83</td>
<td>0.78</td>
</tr>
<tr>
<td>CM3</td>
<td>1.01</td>
<td>0.97</td>
<td>0.88</td>
<td>0.84</td>
</tr>
<tr>
<td>CM4</td>
<td>1.17</td>
<td>1.13</td>
<td>1.03</td>
<td>0.97</td>
</tr>
</tbody>
</table>

#### Coexistence Ratios – 3 MUI

<table>
<thead>
<tr>
<th>Ref</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>1.04</td>
<td>1.00</td>
<td>0.91</td>
<td>0.86</td>
</tr>
<tr>
<td>CM2</td>
<td>1.16</td>
<td>1.12</td>
<td>1.02</td>
<td>0.96</td>
</tr>
<tr>
<td>CM3</td>
<td>1.24</td>
<td>1.19</td>
<td>1.08</td>
<td>1.03</td>
</tr>
<tr>
<td>CM4</td>
<td>1.43</td>
<td>1.38</td>
<td>1.26</td>
<td>1.19</td>
</tr>
</tbody>
</table>

#### Coexistence Ratios – 2 MUI

<table>
<thead>
<tr>
<th>Ref</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>0.78</td>
<td>0.75</td>
<td>0.68</td>
<td>0.65</td>
</tr>
<tr>
<td>CM2</td>
<td>0.87</td>
<td>0.84</td>
<td>0.77</td>
<td>0.72</td>
</tr>
<tr>
<td>CM3</td>
<td>0.95</td>
<td>0.91</td>
<td>0.83</td>
<td>0.79</td>
</tr>
<tr>
<td>CM4</td>
<td>1.09</td>
<td>1.05</td>
<td>0.96</td>
<td>0.90</td>
</tr>
</tbody>
</table>

#### Coexistence Ratios – 3 MUI

<table>
<thead>
<tr>
<th>Ref</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>0.96</td>
<td>0.92</td>
<td>0.84</td>
<td>0.79</td>
</tr>
<tr>
<td>CM2</td>
<td>1.06</td>
<td>1.03</td>
<td>0.94</td>
<td>0.88</td>
</tr>
<tr>
<td>CM3</td>
<td>1.16</td>
<td>1.12</td>
<td>1.02</td>
<td>0.96</td>
</tr>
<tr>
<td>CM4</td>
<td>1.33</td>
<td>1.28</td>
<td>1.17</td>
<td>1.11</td>
</tr>
</tbody>
</table>
PHY Preamble and Header

- Three Preamble Lengths (Link Quality Dependent)
  - Short Preamble (10 μs, short range <4 meters, high bit rate)
  - Medium Preamble (default) (15 μs, medium range ~10 meters)
  - Long Preamble (30 μs, long range ~20 meters, low bit rate)
  - Preamble selection done via blocks in the CTA and CTR

- PHY Header Indicates FEC type, M-BOK type and PSK type
  - Data rate is a function of FEC, M-BOK and PSK setup
  - Headers are sent with 3 dB repetition gain for reliable link establishment
PHY Synchronization Preamble Sequence
(low band medium length sequence\(^1\))

JNJNB5ANB6APAPCPANASASCNJNASK9B5K6B5K5D5D5B9ANASJPJNK5MNCP
ATB5CSJPMTK9MSJTCTASD9ASCTATASCANSASJSJSB5ANB6JPN5DAASB9K
5MSCNDE6AT3469RKAVVX9JFEZ8CDS0D6BAV8CCS05E9ASRWR914A1BR

Notation is Base 32

<table>
<thead>
<tr>
<th>AGC &amp; Timing</th>
<th>Rake/Equalizer Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>~10 (\mu)S</td>
<td>~5 (\mu)S</td>
</tr>
<tr>
<td>15 (\mu)S</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) see document 03/154r2 for sequences for the long, short and high band preambles
Acquisition ROC Curves

Acquisition ROC curve vs. Eb/No at 114 Mbps

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

<table>
<thead>
<tr>
<th>114 Mbps Eb/No</th>
<th>Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 dB</td>
<td>1.00</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

Acquisition time is a compromise between:

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

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

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

1. XSI - CDMA

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

2. Comparison to Multi-band OFDM NBI Approach

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

All rates in Mbps, times in µs

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY Header bits</td>
<td>24</td>
</tr>
<tr>
<td>MAC Header Bits</td>
<td>80</td>
</tr>
<tr>
<td>HCS bits</td>
<td>16</td>
</tr>
<tr>
<td>Header Bits</td>
<td>120</td>
</tr>
<tr>
<td>Payload Bytes</td>
<td>1024</td>
</tr>
<tr>
<td>Payload Bits</td>
<td>8192</td>
</tr>
<tr>
<td>FCS Bits</td>
<td>32</td>
</tr>
<tr>
<td>FEC Overhead symbols (conv)</td>
<td>730</td>
</tr>
<tr>
<td>FEC Overhead symbols (RS)</td>
<td>3112</td>
</tr>
<tr>
<td>Symbol Rate</td>
<td>57</td>
</tr>
<tr>
<td>Header equivalent &quot;FEC&quot; rate</td>
<td>0.333333</td>
</tr>
<tr>
<td>Header BOK bits per symbol</td>
<td>1</td>
</tr>
<tr>
<td>Initial PHY Header rate</td>
<td>19</td>
</tr>
</tbody>
</table>

### FEC

<table>
<thead>
<tr>
<th>Bit Rate</th>
<th>conv</th>
<th>conv</th>
<th>concat</th>
<th>conv</th>
<th>R/S</th>
<th>R/S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28.5</td>
<td>57</td>
<td>75</td>
<td>114</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>FEC symbol rate</td>
<td>57</td>
<td>114</td>
<td>171.5247</td>
<td>228</td>
<td>228.6996</td>
<td>457.3991</td>
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<tr>
<td>BOK</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>BPSK/QPSK</td>
<td>BPSK</td>
<td>BPSK</td>
<td>BPSK</td>
<td>BPSK</td>
<td>QPSK</td>
<td></td>
</tr>
<tr>
<td>Bits per symbol</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Payload FEC rate</td>
<td>0.5</td>
<td>0.5</td>
<td>0.437255</td>
<td>0.5</td>
<td>0.87451</td>
<td>0.87451</td>
</tr>
</tbody>
</table>

### Low Band Results

See 03154r3 for High Band Results

We've limited the number of correlators during acquisition to three. These results are for a 15 µS preamble length.
No significant MAC or superframe modifications required!

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

Proposal Offers MAC Enhancement Details (complete solution)

- PHY PIB
  - RSSI, LQI, TPC and CCA
- Clause 6 Layer Management Enhancements
  - Ranging MLME Enhancements
  - Multi-band UWB Enhancements
- Clause 7 MAC Frame Formats
  - Ranging Command Enhancements
  - Multi-band UWB Enhancements
- Clause 8 MAC Functional Description
  - Ranging Token Exchange MSC
Additional Information can be found in doc - 03/154r3 including XSI draft text for the standard (in the appendix of -03/154r3).
802.15.3a Early Merge Work

XtremeSpectrum will be cooperating with Motorola
## 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>
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<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>
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<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>
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<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>
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</tbody>
</table>
### 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>
Back-up Support Slides
Key Features Meet Application Requirements

• Multi-User (Multi-Piconet) Capable
  – Piconets are independent – my TV or PC doesn’t coordinate/sync with my neighbor’s
  – Every network supports full data-rate
    • Even at extended data rates
  – Allows very close adjacent piconets
    • Two apartments with antennas on opposite sides of the same wall

• Streaming Video Capable
  – High QOS, High Speed, Low Latency
  – Works In Home/Office/Warehouse RF environments -- Dense & High Multipath

• Low Complexity
  – Small Die Size, Low Parts Count – Low Cost
  – Low Power – Light-Weight Long-Life Batteries
Key Features Meet Application Requirements

• Spectrally Efficient\(^1\)
  – Meet Regulations and Coexists with others
    • Proven — 802.11a,b – Cordless & Cell Phones (0.9, 2.4, 5.8 GHz) – Microwave ovens – GPS
    – Modulation results low Eb/No – Highest data-rate & range versus TX emission level.
    – Coded modulation method allows future growth

• Growth Path To Higher Data Rates With Backward Compatibility
  – Architecture allows component (FEC, each receiver channel, etc) usage to be adjusted such that incremental hardware additions result in the highest incremental SNR improvement.

Note 1: Reference doc IEEE802.15-03/211
DFE (Decision Feedback Equalization) used for LOS channels and NLOS channels (dotted red line represents theoretical performance). Results shown for High Band, Symbol Duration=1/114e6 seconds.
M-BOK (M=4) Illustration

M=4

C1=Code-1

C2=Code-2

Received Symbols In

Data Out

MSB

LSB

01

10

00

11

C1

C2

X

X

X

X

Submission

Slide 43

Welborn, XtremeSpectrum, Inc.
- MBOK used to carry multiple bits/symbol
- MBOK exhibits coding gain compared to QAM

Performance of 2-BOK (BPSK), 8-BOK and 16-BOK in AWGN

Bit Error Rate vs. Eb/No (dB)

- BPSK, simulated
- BPSK, theoretical
- 8-BOK, simulated
- 8-BOK, Union bound
- 16-BOK, simulated
- 16-BOK, Union bound
16-BOK with $\frac{1}{2}$ Rate CC Coding Gain

We are falling above the lower bound ... this is due to sub-optimal soft decision mapping of the BOK symbols to bits. This is on-going work and we expect to have this resolved in the near future.
The lower bound estimate was actually done only at 10e-5; so while the lower bound is exact at 10e-5, it is only an estimate above 10e-5. Notice that with orthogonal codes we exactly fall on the lower bound.
Technical Feasibility

- BPSK operation with controlled center frequency has been demonstrated in the current XSI chipset with commensurate chipping rates at 10 meters.

- Current chipset uses convolutional code with Viterbi at 100 Mchip rate. We’ve traded-off Reed-Solomon vs. Viterbi implementation complexity and feel Reed-Solomon is suitable at higher data rates.

- Long preamble currently implemented in chipset … have successfully simulated short & medium preambles on test channels.

- DFE implemented in the current XSI chipset at 100 Mbps. Existence proof is that IEEE802.11b uses DFE with CCK codes, which is a form of MBOK … so it can be done economically.

- NBI filtering is currently implemented in the XSI chipset and has repeatedly been shown to work.

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