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

Abstract: []

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

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

• Summary of FCC’s Part 15 rules on UWB
  – A UWB frequency hopper must be tested for compliance with the hopping turned off and the signal "parked" or held stationary at one band of frequencies. (First R&O at para. 32.)
  – The bandwidth must be at least 500 MHz with the hopping turned off.
  – The device must comply with all emissions limits with the hopping turned off.

• Therefore
  – A hopper is NOT allowed to put as much energy as a non-hopper (both covering the same total range of frequencies)
  – The maximum permitted power is reduced in proportion to the number of hops

• Therefore the performance of FH systems is seriously degraded.
  – N=number of hops
  – Range is reduced by $1/\sqrt{N}$ assuming $1/R^2$ propagation
  – Data-rate is reduced by $1/N$ assuming all else is equal.
  – Example - 10 m range is reduced to 5.8 m range using three hops

• None of the submissions proposing Multiband OFDM have factored this reduction into their performance analysis.
Frequency Hoppers and FCC UWB Rules

• The issue today is NOT whether or not there is more or less interference

• The issue is, what are the rules.
  – Side interest is WHY did NTIA and FCC specifically write rules for frequency hoppers

• The next issues regard changing the rules
  – What is the process for the rules to be changed
  – How long would this process typically take
What do FCC documents say about why FH systems are have specifically different rules?

• The WB R&O states “The current measurement procedures require that measurements of swept frequency devices be made with the frequency sweep stopped. The sweep is stopped because no measurement procedures have been proposed or established for swept frequency devices nor has the interference aspects of swept frequency devices been evaluated .... Similarly, measurements on a stepped frequency or frequency hopping modulated system are performed with the stepping sequence or frequency hop stopped.
See 47 C.F.R. §15.31(c).
 Avg Pwr = 1/3 of “hopping-on” Power

Avg Pwr in band w/ hopping off = 3X higher than hopping-on
Which way should this be measured if the requirement is to have “hopping stopped”? Is it (A) this way:

![Diagram A: avg Pwr in band w/ hopping-off = 3X higher than hopping-on]

Or is it (B) this way:

![Diagram B: avg Pwr in band w/ hopping off = same as when hopping on]
• UWB is a highly unusual regulation as it allows devices to radiate in bands specifically allocated to other services.

• As a result, the proceeding was one of the most contentions in the history of the FCC (having over 1000 filings).

• FCC and NTIA (representing DOD, DOT, FAA etc) through-out the proceeding specifically addressed FH as being a different class device.

• The specific rules were clearly intended to change the certification measurement result.
  – Any interpretation that makes the measurement come out the same regardless of whether hopping is turned on or off, would make the language superfluous, which was clearly not the intent of the language.
• Examples of FH systems that the FH rules could have been meant to address include:
  – Random hopping - which could put too much energy in a particular band.
  – Hopping where the hop-bands overlap – which could put too much energy into an overlap region
  – Hopping where sidelobe energy of neighboring hops could put too much energy into a band.
• The FCC does not have separate rules or measurement procedures to address hoppers with orthogonal pulses, hoppers with overlapping pulses, hoppers with sequential/periodic pulses, or hoppers with pseudo-random pulses, or combinations of these.
• All frequency hoppers must follow the same rule: measurements “are performed with the stepping sequence or frequency hop stopped.”
Illustration of how to test a compliant UWB FH radio

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

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

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
- Frequency
  - Hopping ON
    - Symbols in different bands
  - Frequency
    - Burst
      - Band B
    - Quiet
      - Band B
    - Time
      - Band A
    - Band B
    - Band A
    - Band B
    - Time

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
- Frequency
  - Hopping Stopped
    - All Symbols/Pulses in same band
    - Energy from other bands are concentrated into one band
  - Frequency
    - Burst
      - Band B
    - Quiet
      - Band B
    - Time
      - Band A
    - Band B
    - Band B
    - Band B
    - Band B
    - Band B
    - Time
Conclusion

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

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

4 Spectral Modes of Operation

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

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

- **Duplex-Band**
  - 3.1 to 5.15 GHz
  - 5.825 to 10.6 GHz
  - Up to 1.2 Gbps
  - Independent data in each band

- **Joint-Band**
  - 3.1 to 4.9 GHz
  - 6.3 to 8.1 GHz
RX Implementation Considerations
(Analog vs. Digital)

Scaleable power/cost/performance
Adaptable to broad application classes

**Symbol Rate ADC**
*Simple/cheap Analog Emphasis*
- 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
Split Band DS-CDMA

Low Band

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

High Band

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

3 Modes Span
Analog and Digital Implementations

- Up to 1.2 Gbps
- Independent data in each band
New Joint-band Spectrum

- Bandwidth: 3.2GHz
- 1m Receive level: -52.9dBm
- Sample Rate 7.7GHz
• Bandwidth: 3.85GHz
• 1m Receive level: -53dBm
• Sample Rate: 7.7GHz
After sampling at 6.4GHz

- Bandwidth: 3.2GHz
- 1m Receive level: -52.9dBm
Joint Band Reception on Single ADC
## Joint-Band Benefits

<table>
<thead>
<tr>
<th></th>
<th>Single Band</th>
<th>Dualband</th>
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<tbody>
<tr>
<td>Rx Power</td>
<td>-54dBm</td>
<td>-53.9dBm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>3.85GHz</td>
<td>3.2GHz</td>
</tr>
<tr>
<td>Filter Rate</td>
<td>7.7GHz</td>
<td>6.4GHz</td>
</tr>
<tr>
<td>Relative Complexity</td>
<td>100%</td>
<td>70%</td>
</tr>
<tr>
<td>Relative Power</td>
<td>100%</td>
<td>70%</td>
</tr>
</tbody>
</table>
Matched Filter configuration

\[ C_n \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow 1 \rightarrow D_i \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow C_{n+N} \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow D_{i-N} \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow C_{n+1} \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow D_{i-1} \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow C_{n+N+1} \rightarrow 4 \rightarrow 4x \rightarrow 4 \rightarrow D_{i-N-1} \]

\[ \cdots \]

\[ 4 \text{ bit adder} \]

\[ 5 \text{ bit adder} \]
Rate 4/6 Convolutional coder

Map every 6 bits to one of 64 biorthogonal codewords
Joint Time Frequency Wavelet Family

Long Wavelet

Mid Wavelet

Example Duplex Wavelet
Spectral Flexibility and Scalability

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

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

Example 2: Support for hypothetical “above 6 GHz” UWB definition

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

- Forward error correction options
  - Rate 2/3 trellis code for operation with 64 BOK
  - Convolutional FEC code (<200 Mbps – 2002 technology)
    - 1/2 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)

\[ g(D) = 1 + D^{14} + D^{15} \]
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>Band</th>
<th>RRC BW</th>
<th>Chip Rate</th>
<th>Code Length</th>
<th>Symbol Rate</th>
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<tbody>
<tr>
<td>Low Band</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>
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<tr>
<td>High Band</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>
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<tr>
<td>Joint Band</td>
<td>912 /1596 / 2128 MHz</td>
<td>24/32 chips/symbol</td>
<td>Various</td>
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</table>
- CDMA via low cross-correlation ternary code sets ($\pm 1, 0$)
- 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): $4 \times 8 = 32$
  - RMS cross-correlation $<-15$ dB in a flat fading channel
- CCA via higher order techniques
  - Squaring circuit for BPSK, fourth-power circuit for QPSK
  - Operating frequency detection via collapsing to a spectral line
- Each piconet uses a unique center frequency offset
  - Four selectable offset frequencies, one for each piconet
    - +/- 3 MHz offset, +/- 9 MHz offset
### 4x8 Code Set

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

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Submission
### 4x8 Code Set (Cont.)

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**PNC4**

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

4x8 Code Set (Cont.)
### 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</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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<tr>
<td>Backoff</td>
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</table>

**Worst Case Synchronized Cross-correlation Coefficient within a group**

2/22

**Average RMS Cross Correlation between groups**

Channel dependent but generally looks like $10 \times \log_{10}(1/24)$ noise due to center frequency offset and chipping rate frequency offset

---

### Submission

*Slide 32*

*Welborn, XtremeSpectrum, Inc.*
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

- **T_xpow** = -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 GHz¹</th>
<th>Range AWGN</th>
<th>Acquisition Range</th>
<th>10 meter margin</th>
<th>RX Sensitivity²</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</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</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>

¹ Center frequency determined as geometric mean in accordance with 03031r9, clause 5.6
² Based upon corrected Eb/No of 9.6 dB after application of all coding gain

**Coding Gain References:**
- [http://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)

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

Submission: IEEE 802.15-03/153r9
# High Band Symbol Rates and Link Budget

T\textsuperscript{xpow}=-6.9 \text{ dBm}; Coded Eb/No=9.6 \text{ dB}, 3 \text{ dB implementation loss, 0 dB RAKE gain, NF}=5.1 \text{ dB}, 1/2 rate code gain: 5.2 \text{ dB}, 2/3 rate code gain: 4.7 \text{ dB}, 3/4 rate code gain: 4 \text{ dB}, RS code gain: 3 \text{ dB}, concatenated gain: 6.3 \text{ dB}, 8-BOK coding gain: 1.4 \text{ dB}, 16-BOK coding gain: 2.4 \text{ dB}, 2-BOK PSD Backoff: 2.2 \text{ dB}, 4-BOK PSD Backoff: 2.1 \text{ dB}, 8-BOK PSD Backoff: 1.7 \text{ dB}, 16-BOK PSD Backoff: 1.3 \text{ dB}

<table>
<thead>
<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</td>
<td>BPSK</td>
<td>4-BOK (2 bits/symbol)</td>
<td>1/2 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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
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<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
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

- 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
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></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meters Distance</strong></td>
<td>15.0</td>
<td>13.5</td>
<td>11.5</td>
<td>10.0</td>
</tr>
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</table>

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

<table>
<thead>
<tr>
<th></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Averaged Outage Range</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coexistence Ratios – 1 MUI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ref</th>
<th>Int</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>0.60</td>
<td>0.58</td>
<td>0.53</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>CM2</td>
<td>0.67</td>
<td>0.65</td>
<td>0.59</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>CM3</td>
<td>0.71</td>
<td>0.69</td>
<td>0.62</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>CM4</td>
<td>0.83</td>
<td>0.80</td>
<td>0.73</td>
<td>0.69</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meters Distance</strong></td>
<td>11.1</td>
<td>10.0</td>
<td>8.8</td>
<td>7.5</td>
</tr>
</tbody>
</table>

**200 Mbps, 16-BOK, R-S FEC**

<table>
<thead>
<tr>
<th></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Averaged Outage Range</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coexistence Ratios – 1 MUI</strong></td>
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<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Ref</th>
<th>Int</th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM1</td>
<td>0.55</td>
<td>0.53</td>
<td>0.48</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>CM2</td>
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</tr>
<tr>
<td>CM3</td>
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<td>0.65</td>
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</tr>
<tr>
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<td>0.67</td>
<td>0.64</td>
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</table>
### Multiple User Separation Distance – CM1 to CM4

**July 2003**  
**doc.: IEEE 802.15-03/153r9**

**Continuing**

#### Coexistence Ratios – 2 MUI

<table>
<thead>
<tr>
<th></th>
<th>Ref</th>
<th>Int</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>
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</tr>
<tr>
<td>CM2</td>
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<td>0.91</td>
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</tr>
<tr>
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<td>0.97</td>
<td>0.88</td>
<td>0.84</td>
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<tr>
<td>CM4</td>
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<td>1.13</td>
<td>1.03</td>
<td>0.97</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
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<th>Ref</th>
<th>Int</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>
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</tr>
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<td>0.72</td>
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<td></td>
</tr>
<tr>
<td>CM3</td>
<td>0.95</td>
<td>0.91</td>
<td>0.83</td>
<td>0.79</td>
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<td></td>
</tr>
<tr>
<td>CM4</td>
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<td>1.05</td>
<td>0.96</td>
<td>0.90</td>
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</tr>
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</table>

#### Coexistence Ratios – 3 MUI

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

<table>
<thead>
<tr>
<th></th>
<th>Ref</th>
<th>Int</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>
<td></td>
<td></td>
</tr>
<tr>
<td>CM2</td>
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<td>1.03</td>
<td>0.94</td>
<td>0.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM3</td>
<td>1.16</td>
<td>1.12</td>
<td>1.02</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM4</td>
<td>1.33</td>
<td>1.28</td>
<td>1.17</td>
<td>1.11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• 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\textsuperscript{1})

JNJNB5ANB6APAPCPANASASCNJNAS\textsuperscript{K}9B5K6B5K5D5D5B9ANASJPJ\textsuperscript{K}5MNCPATB5CSJPM\textsuperscript{T}TK9MSJTCT\textsuperscript{A}SD9\textsuperscript{A}SCTATASC\textsuperscript{S}ANCSASJSJSB5ANB6JPN5DAASB9K5MSCNDE6AT3469RK\textsuperscript{V}XM9JFEZ8CDS0D6BA\textsuperscript{V}8CCS05E9AS\textsuperscript{R}WR914A1BR

Notation is Base 32

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

\textsuperscript{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>1.0</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

Acquisition time is a compromise between:

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

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

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
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<tr>
<td>FEC conv concat.conv</td>
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<tr>
<td>FEC conv R/S</td>
<td>200</td>
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<tr>
<td>FEC conv R/S</td>
<td>400</td>
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<tr>
<td>FEC symbol rate</td>
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</tr>
<tr>
<td>BOK</td>
<td>2</td>
</tr>
<tr>
<td>BPSK/QPSK</td>
<td>BPSK</td>
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</tr>
<tr>
<td>BPSK/QPSK</td>
<td>BPSK</td>
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<tr>
<td>Payload FEC rate</td>
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<td>T_HCS_INITIAL</td>
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<td>T_PHYHDR_CONT</td>
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</tr>
<tr>
<td>T_FCS</td>
<td>1.122807</td>
</tr>
<tr>
<td>T_SIFS</td>
<td>5</td>
</tr>
<tr>
<td>T_FEC_OH</td>
<td>12.80702</td>
</tr>
<tr>
<td>T_MIFS</td>
<td>0</td>
</tr>
<tr>
<td>T_ONE_FRAME</td>
<td>327.6842</td>
</tr>
<tr>
<td>Throughput_1</td>
<td>24.99968</td>
</tr>
<tr>
<td>T_FIVE_FRAMES</td>
<td>1498.772</td>
</tr>
<tr>
<td>Throughput_5</td>
<td>27.32304</td>
</tr>
</tbody>
</table>

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

Low Band Results,
See 03154r3 for High Band Results
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,</td>
<td>3.4</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>Channelization – physical or coded, Complexity, Range, Frequency of Operation, Bandwidth of Operation, Power Consumption)</td>
<td></td>
<td></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>
### 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
Strong Support for CSMA/CCA

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

- $F_c = \text{wavelet center frequency} = 3 \times \text{chip rate}$
- 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
Output of the Squaring Circuit

Piconets clearly identified by spectral lines
How it Works

- Can also be done at baseband:

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

- **Handoff**
  - What piconets are around
  - How big they are (refresh every 5 us)

- **PHY** provides all required info to efficiently support CCA/CSMA MAC functionality
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.
## Scalability Across Applications

<table>
<thead>
<tr>
<th>watts/ performance/ dollars</th>
<th>Implementation Scaling</th>
</tr>
</thead>
</table>
| 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

- **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
Location Awareness and the 802.15.3a ALT PHY

• The FCC recognized that UWB offers a unique high-precision location potential
• This ranging capability is recognized by the wireless industry
• Ranging/Location Awareness were identified as requirements for TG3a ALT PHY
• The choice of the waveform for the 15.3a ALT PHY will impact the ranging and location capability of a 15.3a WPAN systems
Location Awareness and the 802.15.3a ALT PHY

• There is significant interest
• Safety of life etc.
• On Monday of this week numerous presentations were made before 802.15 interest group on ranging/location applications for WPAN technology
## Companies List Ranging As Important

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

Source: Document 04/266r0
## Typical Range/Location Accuracy Requirements for WPAN in TG4 IG

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

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

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Home Theatre</th>
<th>Portable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranging/Location Awareness</td>
<td>Location awareness is desirable: range 10m, resolution &lt;30cm</td>
<td>Location awareness is highly desirable: range 10m, resolution &lt;30cm</td>
</tr>
</tbody>
</table>
Ranging Resolution Depends on Signal Bandwidth

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

• OFDM self-reported support for Location Awareness:
  – “The TFI-OFDM system has the capability to determine the relative location of one device with respect to another. The relative location information can be obtained by estimating the round trip delay between the devices. As the bandwidth of each sub-band in the TFI-OFDM system is 528 MHz, the minimum resolvability between the multi-path fingers is 1.9 ns. Hence, the minimum level of accuracy that can be obtained for the location awareness is 57 cm.” (TFI-OFDM Proposal, 03/142r2 page 56)

• Mechanism to do this was not disclosed
Location Awareness Support for DS-CDMA PHY Proposals

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

XtremeSpectrum has demonstrated high resolution ranging capability to better than 10 cm resolution at 20 m range
Measured Multipath Resolution with an Operating XtremeSpectrum Radio

- Earliest arriving path
- Optimal lock path for radio
- 14 dB lower power
- 10 ns earlier

Time in nanoseconds (time reversed)
Conclusions on Location Awareness

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

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>XSI</th>
<th>MBOA-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CMOS</td>
<td>RF &amp; Digital Proven in .18u</td>
<td>Projected in 90nm – no advantage</td>
</tr>
<tr>
<td></td>
<td>Scales to better performance in 90 nm</td>
<td></td>
</tr>
<tr>
<td>Simple Antenna</td>
<td>Simple etch on PCB – multiple choices</td>
<td>Same – no advantage</td>
</tr>
<tr>
<td>Early time to market</td>
<td>Production ICs here today</td>
<td>Chips no earlier than 2005</td>
</tr>
<tr>
<td>Early market adoption</td>
<td>Production ICs here today</td>
<td>Chips no earlier than 2005</td>
</tr>
<tr>
<td>Robust to multipath &amp; Complexity</td>
<td>2-RAKE equal to OFDM performance</td>
<td>More complex for same perf</td>
</tr>
<tr>
<td></td>
<td>5-RAKE superior to OFDM perf</td>
<td>Same complexity for less perf</td>
</tr>
<tr>
<td>CSMA Support</td>
<td>No Preamble – Data independent</td>
<td>Requires Preamble</td>
</tr>
<tr>
<td></td>
<td>5us ID, mag of all neighboring nets</td>
<td></td>
</tr>
<tr>
<td>Could work with 802.11 MAC</td>
<td>YES – CSMA support allows this</td>
<td>NO – SNR much lower</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Requires Preamble</td>
</tr>
<tr>
<td>PSD Backoff</td>
<td>1.3 to 2.2 dB</td>
<td>1.3 dB</td>
</tr>
<tr>
<td>Xmit Only</td>
<td>Very Simple, Very Low Power</td>
<td>Full DAC and IFFT required</td>
</tr>
<tr>
<td>US Reg’s Compliance</td>
<td>Assured</td>
<td>Questionable at best.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FH hopping rules may drop range by almost 1/2</td>
</tr>
</tbody>
</table>
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 Efficient¹
  – Meet Regulations and Coexists with others
    • Proven — 802.11a,b – Cordless & Cell Phones (.9, 2.4, 5.8 GHz) – Microwave ovens – GPS
  – Modulation results low Eb/No – Highest data-rate & range versus TX emission level.
  – Coded modulation method allows future growth

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

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

M=4

\[ \begin{align*}
00 & \rightarrow C1=\text{Code-1} \\
01 & \rightarrow C1 \\
10 & \rightarrow X \\
11 & \rightarrow C2
\end{align*} \]

\[ \begin{align*}
\Sigma \rightarrow \text{Data Out} & \rightarrow \text{MSB} \\
\Sigma \rightarrow \text{Data Out} & \rightarrow \text{LSB}
\end{align*} \]
MBOK Coding Gain

- MBOK used to carry multiple bits/symbol
- MBOK exhibits coding gain compared to QAM
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 10^-5; so while the lower bound is exact at 10^-5, it is only an estimate above 10^-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
ROP: receiver operating characteristics
Pi: Probability of False Alarm
Pd: Probability of Detection
RMS: Root-mean-square
PNC: Piconet Controller
MUI: Multiple User Interference