Submission Title: Texas Instruments Impulse Radio UWB Physical Layer Proposal
Date Submitted: 04 May, 2009

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Re: Response to IEEE 802.15.6 call for proposals

Abstract: This document describes the Texas Instruments impulse radio UWB physical layer proposal for IEEE 802.15.6.

Purpose: For discussion by IEEE 802.15 TG6

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Texas Instruments Impulse Radio UWB
Physical Layer Proposal

June Chul Roh, Anuj Batra, Sudipto Chakraborty,
Srinath Hosur, and Timothy Schmidl

Texas Instruments
May 2009
Outline

• Motivation

• Details about the impulse radio UWB PHY:
  – Frequency Band of Operation
  – Frame Format: Preamble, Header, PSDU
  – Symbol Structure
  – Burst Position Modulation with Time-Hopping
  – Time-Hopping Sequence
  – FEC: BCH Codes
  – System Parameters

• Performance Results:
  – Link Budget and Receiver Sensitivity
  – Simulation Results in AWGN and 15.3a CM1,2
  – Performance with Co-channel Interference
  – Complexity and Power Consumption

• Summary and Conclusions
Overview of Proposal

- **Goal:** Design a low-power, low-complexity UWB PHY for BAN

- **Start by re-using some aspects of IEEE 802.15.4a PHY:**
  - Preamble structure
  - Burst position modulation and time-hopping (BPM-TH)

- **Add new features that reduce complexity and lower power consumption:**
  - More efficient symbol structure – eliminate unnecessary overheads
  - A new time-hopping sequence that supports new symbol structure
  - Limit modulation scheme to BPM-TH – simplifies receiver
  - Limit systems to a single bandwidth of 512 MHz – simplifies receiver
  - Limit systems to higher frequency bands – eliminates need for complex DAA algorithms
  - Replace RS codes with low-complexity binary BCH codes
  - Add support for simultaneous operation of at least 12 piconets
Improvements over 15.4a

- New frequency band plan
  - Use only the UWB high band → does not require power-hungry DAA or LDC
  - Each band has 512 MHz bandwidth

- New symbol structure and time-hopping sequence
  - No fixed guard interval for improved PHY efficiency
  - Time-hopping sequence is designed to avoid inter-symbol interference (ISI)

- Binary burst position modulation with time-hopping (BPM-TH)
  - Binary BPM → simple non-coherent receiver in mind
  - BPSK of 802.15.4a is not supported in this proposal → want ultra-simple receivers

- Low-complexity binary FEC codes
  - BCH (31, 16, t = 3), BCH (63, 51, t = 2), BCH (63, 57, t = 1)
WW Regulations on UWB Band

- Low Band*
  - DAA or LDC is a must (except USA) after 2010
  ⇒ DAA results in huge penalty on complexity and power for BAN transceivers

- High Band*
  - DAA is not required
  ⇒ Ideal for low-complexity, low-power BAN
  - Concern: only 1.25GHz bandwidth is common worldwide
  ⇒ Solution: new proposed band plan

* Tables from P802.15-08-0034

<table>
<thead>
<tr>
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<th>PSD</th>
<th>Frequency Bands</th>
<th>Remarks</th>
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<tr>
<td>Australia</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>EU</td>
<td>-41.3 dBm/MHz</td>
<td>3.1 - 4.8 GHz</td>
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<td>4.2 - 4.8 GHz</td>
<td>By Dec. 31, 2010</td>
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<td>Japan</td>
<td>-41.3 dBm/MHz</td>
<td>3.4 – 4.8 GHz</td>
<td>DAA is needed</td>
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<td></td>
<td></td>
<td>4.2 – 4.8 GHz</td>
<td>By Dec. 31, 2010</td>
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<tr>
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<td>-41.3 dBm/MHz</td>
<td>3.1 - 4.8 GHz</td>
<td>LDC or DAA is needed</td>
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<td>By Dec. 31, 2010</td>
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<tr>
<td>USA</td>
<td>-41.3 dBm/MHz</td>
<td>3.1-10.6 GHz</td>
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<table>
<thead>
<tr>
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<th>PSD</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>Australia</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>EU</td>
<td>6 - 8.5 GHz</td>
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<td>Japan</td>
<td>7.25 – 10.25 GHz</td>
<td>-41.3 dBm/MHz</td>
<td></td>
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<tr>
<td>Korea</td>
<td>7.2 -10.2 GHz</td>
<td>-41.3 dBm/MHz</td>
<td></td>
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<tr>
<td>USA</td>
<td>3.1 -10.6 GHz</td>
<td>-41.3 dBm/MHz</td>
<td></td>
</tr>
<tr>
<td>Common</td>
<td>7.25 -8.5 GHz</td>
<td>-41.3 dBm/MHz</td>
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</table>
Frequency Bands of Operation

- Channelization:

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Supported Region</th>
<th>BW (MHz)</th>
<th>Low Freq. (MHz)</th>
<th>Center Freq. (MHz)</th>
<th>High Freq. (MHz)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>US, EU</td>
<td>512</td>
<td>6400</td>
<td>6656</td>
<td>6912</td>
</tr>
<tr>
<td>2</td>
<td>US, EU</td>
<td>512</td>
<td>6912</td>
<td>7168</td>
<td>7424</td>
</tr>
<tr>
<td>3</td>
<td>US, EU, Japan, Korea</td>
<td>512</td>
<td>7424</td>
<td>7680</td>
<td>7936</td>
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<tr>
<td>4</td>
<td>US, EU, Japan, Korea</td>
<td>512</td>
<td>7936</td>
<td>8192</td>
<td>8448</td>
</tr>
<tr>
<td>5</td>
<td>US, Japan, Korea</td>
<td>512</td>
<td>8448</td>
<td>8704</td>
<td>8960</td>
</tr>
</tbody>
</table>

- All bands are located in UWB high band
- At least 3 bands available per country: 4 SOPs per band
- Center frequencies are integer multiples of 512 MHz: $512 \times [13, 14, 15, 16, 17]$
- PLL is easier to implement than PLL for 802.15.4a
PLCP Frame Format

- PPDU compromised of three components:
  - PLCP Preamble: used for packet detection, timing acquisition, carrier frequency offset estimation, etc
  - PLCP Header: convey information about to decode PSDU
  - PSDU: MAC Header + MAC Frame Body (information) + FCS

- Structure:
PLCP Preamble

- Reuse the 802.15.4a preamble signal structure

- Use the length 31 ternary codes (of 802.15.4a) with following band assignment
  - Define 4 preamble codes per band
  - Assign different preambles to adjacent bands, minimizes false alarms due to adjacent channel energy leaking into the desired band

<table>
<thead>
<tr>
<th>Code index</th>
<th>Code sequence</th>
<th>Band number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0000+0-0+++0+-000+-++++0-+0-00</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>2</td>
<td>0+0-0+000-+++0-++++-00+00++00</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>3</td>
<td>++0++000-+++00++00-0000-0+0-</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>4</td>
<td>0000++00-00-++++0+++0000+0-0++0-</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>5</td>
<td>-0+-0+++0+-00+-++++-0+0000-000</td>
<td>2, 4</td>
</tr>
<tr>
<td>6</td>
<td>++0000---+0+++000+0+-0+0000</td>
<td>2, 4</td>
</tr>
<tr>
<td>7</td>
<td>+0000+-0+00+00000+0++---0-++0+</td>
<td>2, 4</td>
</tr>
<tr>
<td>8</td>
<td>0+00-0-0+++000-+-00-0+++0++++00</td>
<td>2, 4</td>
</tr>
</tbody>
</table>
PLCP Header

- Proposed PLCP Header Structure (31 bits)

- Format the PHY header as shown in figure based on data provided by the MAC
- Calculate the 2-bit HCS value over the PHY header
  - CRC-2 polynomial: \( g(x) = 1 + x + x^2 \)
- Apply a BCH (31,16) code to PHY header + HCS

- The resulting encoded bits are modulated using the lowest data rate
Burst Position Modulation with Time-Hopping

• Basic concept:
  – Binary PPM based modulation
  – Multiple pulses are continuously transmitted in a symbol
  – Time-hopping for multiple access (symbol-rate hopping)
  – Random pulse polarity changes within a pulse burst

• Signal for \( k \)-th symbol interval may be mathematically expressed*:

\[
x^{(k)}(t) = \sum_{n=0}^{N_{cpb}-1} s_{kN_{cpb}+n} p(t - d^{(k)}T_{BPM} - h^{(k)}T_{burst} - nT_c)
\]

\[p(t)\] : transmitted pulse shape at the antenna input,
\[s_{kN_{cpb}+n} \in \{-1,1\}\] : chip scrambling code used during the \( k \)-th symbol interval,
\[d^{(k)} \in \{0,1\}\] : \( k \)-th data symbol carrying information,
\[h^{(k)} \in \{0,1,\ldots,N_{hop}-1\}\] : time-hopping position for the burst during the \( k \)-th symbol interval,
\[N_{cpb}\] : number of chips per burst,
\[T_{burst} = N_{cpb}T_c\] : slot time (or burst time),
\[T_c\] : chip time,
\[T_{BPM} = N_{hop}T_{burst}\] : BPM (burst position modulation) interval.  

* For proposed symbol structure (slide 15).
802.15.4a Symbol Structure

- 802.15.4a symbol structure:

  ![Diagram](image)

  - 50% of symbol duration is reserved as guard interval (GI): 50% of symbol is *overhead*!
  - GI is unnecessarily large compared to typical channel delay spread for data rates of interest
  - Why two guard intervals in 15.4a?
    - 1st GI avoids interference from symbol ‘0’ to symbol ‘1’ region
    - 2nd GI prevents inter-symbol interference (ISI)
Elimination of 1st Guard Interval

- 1st guard interval (GI) of 15.4a is unnecessary as BPM-TH inherently provides GI
  - Since \((N_{\text{hop}}-1)T_{\text{burst}} > \tau_{\text{max}}\) for data rates of interest (\(\tau_{\text{max}}\): max expected delay spread of channel)

- ‘Fixed-length’ 2nd GI with \(T_{\text{GI}} > \tau_{\text{max}}\) can be used to prevent ISI

- Leads to a more efficient symbol structure, less overhead

- Q: Can we do better?
Proposed Optimal Symbol Structure (1)

- A: Yes, we can!

- We only need a guard interval when transmitting a ‘1’ on previous symbol at the end of the symbol, and when transmitting a ‘0’ on current symbol at the beginning of the symbol ⇒ ISI

- Example:

  ![Diagram](image1)

  - Can eliminate these cases from happening by designing the time-hopping sequence properly!

  ![Diagram](image2)
Proposed Optimal Symbol Structure (2)

- New proposed symbol structure:
  - Completely eliminate the two fixed guard intervals of 15.4a
  - Time-hopping sequence provides embedded guard interval *only when* necessary
    - ISI can happen when two consecutive hop locations are the last slot and the first slot
    - Design time-hopping to avoid the ISI condition
  - Increased channel efficiency can be used for
    - Increasing the overall possible data rates (*increase channel efficiency*), and/or
    - Providing better interference mitigation capability by increasing $N_{hop}$
Time-Hopping Sequence

- Time-hopping sequence design constraint to avoid ISI:

\[
h^{(k)} \geq h^{(k-1)} - (N_{hop} - N_{ch} - 1) \quad \text{for } k \geq 1
\]  \hspace{1cm} (1)

- An intuitive example:
  - Let \( N_{hop} = 8 \) and \( N_{ch} = 4 \)
Time-Hopping Sequence Generation

1. Generate a random number $z(k) \in \{0,1,\ldots,N_{\text{hop}}-1\}$ by tapping $m = \log_2(N_{\text{hop}})$ shift registers of the 802.15.4a LFSR. For each symbol interval, the LFSR shall be clocked $N_{\text{cpb}}$ times.

2. Calculate related parameters: $\alpha = h^{(k-1)} - \gamma$, $N_{\text{reduced}} = N_{\text{hop}} - \alpha$

   where $\gamma = N_{\text{hop}} - N_{\text{ch}} - 1$ is known (pre-calculated) for each data rate.

3. Generate time-hopping sequence as follows:

   $$h^{(k)} = \begin{cases} z^{(k)}, & \text{if } h^{(k-1)} \leq \gamma \\ \left[ (z^{(k)} + c^{(k)}) \mod N_{\text{reduced}} \right] + \alpha, & \text{if } h^{(k-1)} > \gamma \end{cases}$$

   where $c^{(k)}$ is a 7-bit counter when $N_{\text{hop}} = 16$, or a 6-bit counter when $N_{\text{hop}} = 8$. 
BCH Encoder

- BCH (31,16) code: \( g(x) = 1 + x + x^2 + x^3 + x^5 + x^7 + x^8 + x^9 + x^{10} + x^{11} + x^{15} \)

- Low-complexity, low-power implementation:

- BCH (63, 51): \( g(x) = 1 + x^3 + x^4 + x^5 + x^8 + x^{10} + x^{12} \)

- BCH (63, 57): \( g(x) = 1 + x + x^6 \)
Process for BCH Encoding

1. Compute the number of bits in the PSDU:
   \[ N_{PSDU} = (N_{MAC header} + N_{payload} + N_{FCS}) \times 8 \]

2. Calculate the number of BCH codewords:
   \[ N_{CW} = \left\lceil \frac{N_{PSDU}}{k} \right\rceil \]

3. Compute the total number of shortening bits*:
   \[ N_{shorten} = N_{CW} \times k - N_{PSDU} \]

4. Calculate the number of shortening bits needed per codeword:
   \[ N_{spcw} = \left\lceil \frac{N_{shorten}}{N_{CW}} \right\rceil \]

5. Distribute shortening bits uniformly over codewords:
   a. Each of the first \( \text{rem}(N_{shorten}, N_{cw}) \) codewords have \( N_{spcw} + 1 \) shortened bits
   b. Remaining codewords have \( N_{spcw} \) shortened bits

6. Shortened bits are \textit{not} transmitted on-air, but receiver \textit{will} re-insert them into known locations

* Shortened bits are message bits that are set to zero
# System Parameters

<table>
<thead>
<tr>
<th>MCS number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>Chip rate (MHz)</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
</tr>
<tr>
<td>Chip time (ns), $T_c$</td>
<td>1.953125</td>
<td>1.953125</td>
<td>1.953125</td>
<td>1.953125</td>
<td>1.953125</td>
<td>1.953125</td>
<td>1.953125</td>
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<td>Modulation</td>
<td>BPM-TH</td>
<td>BPM-TH</td>
<td>BPM-TH</td>
<td>BPM-TH</td>
<td>BPM-TH</td>
<td>BPM-TH</td>
<td>BPM-TH</td>
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<tr>
<td>BCH code rate, $r$</td>
<td>16/31</td>
<td>16/31</td>
<td>16/31</td>
<td>16/31</td>
<td>51/63</td>
<td>57/63</td>
<td>57/63</td>
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<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td># hop bursts, $N_{hop}$</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>8</td>
<td>8</td>
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<tr>
<td># of chips in burst, $N_{cpb}$</td>
<td>64</td>
<td>32</td>
<td>16</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>3</td>
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<tr>
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<td>2048</td>
<td>1024</td>
<td>512</td>
<td>256</td>
<td>192</td>
<td>80</td>
<td>48</td>
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<tr>
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<td>125.0000</td>
<td>62.5000</td>
<td>31.2500</td>
<td>15.6250</td>
<td>11.7188</td>
<td>9.7656</td>
<td>5.8594</td>
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<td>Symbol period (ns), $T_s$</td>
<td>4000.00</td>
<td>2000.00</td>
<td>1000.00</td>
<td>500.00</td>
<td>375.00</td>
<td>156.25</td>
<td>93.75</td>
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<tr>
<td>Symbol rate (kps), $R_s$</td>
<td>250.00</td>
<td>500.00</td>
<td>1000.00</td>
<td>2000.00</td>
<td>2666.67</td>
<td>6400.00</td>
<td>10666.67</td>
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<tr>
<td>Data rate (kbps), $R_b$</td>
<td>129.03</td>
<td>258.06</td>
<td>516.13</td>
<td>1032.26</td>
<td>2158.73</td>
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<td>9650.79</td>
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<td>16.00</td>
<td>16.00</td>
<td>16.00</td>
<td>16.00</td>
<td>32.00</td>
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<td>$N_{ch}$ for TH sequence</td>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
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Energy-Detection Based Non-coherent Receiver

- Low complexity and low power-consumption receiver

- Other non-coherent receiver structures are also possible
## Link Budget and Receiver Sensitivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Unit</th>
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<tr>
<td>Bit rate ($R_b$)</td>
<td>129.03</td>
<td>1032.26</td>
<td>9650.79</td>
<td>kbps</td>
</tr>
<tr>
<td>Center frequency ($f_c$)</td>
<td>8704</td>
<td>8704</td>
<td>8704</td>
<td>MHz</td>
</tr>
<tr>
<td>Bandwidth ($B$)</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>MHz</td>
</tr>
<tr>
<td>Average Tx power</td>
<td>-16.21</td>
<td>-16.21</td>
<td>-16.21</td>
<td>dBm</td>
</tr>
<tr>
<td>Tx/Rx switch loss</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>dB</td>
</tr>
<tr>
<td>Average Tx power before Tx Ant ($P_T$)</td>
<td>-17.21</td>
<td>-17.21</td>
<td>-17.21</td>
<td>dBm</td>
</tr>
<tr>
<td>Tx antenna gain ($G_T$)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>dBi</td>
</tr>
<tr>
<td>Distance ($d$)</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>m</td>
</tr>
<tr>
<td>Path loss at $d$ meter ($L$)</td>
<td>60.77</td>
<td>60.77</td>
<td>57.25</td>
<td>dB</td>
</tr>
<tr>
<td>Rx antenna gain ($G_R$)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>dBi</td>
</tr>
<tr>
<td>Rx power ($P_R = P_T + G_T + G_R - L$)</td>
<td>-77.98</td>
<td>-77.98</td>
<td>-74.46</td>
<td>dBm</td>
</tr>
<tr>
<td>Average noise power per bit ($N = -174 + 10*\log_{10}R_b$)</td>
<td>-122.89</td>
<td>-113.86</td>
<td>-104.15</td>
<td>dBm</td>
</tr>
<tr>
<td>Rx noise figure ($N_F$)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>dB</td>
</tr>
<tr>
<td>Total noise power per bit ($P_N = N + N_F$)</td>
<td>-112.89</td>
<td>-103.86</td>
<td>-94.15</td>
<td>dBm</td>
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<tr>
<td>Received SNR</td>
<td>34.91</td>
<td>25.88</td>
<td>19.69</td>
<td>dB</td>
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<tr>
<td>Minimum required $E_b/N_0$ ($S$)</td>
<td>17.82</td>
<td>14.49</td>
<td>13.03</td>
<td>dB</td>
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<tr>
<td>Implementation loss ($I$)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>dB</td>
</tr>
<tr>
<td><strong>Link margin ($M = P_R - P_N - S - I$)</strong></td>
<td><strong>14.09</strong></td>
<td><strong>8.39</strong></td>
<td><strong>3.67</strong></td>
<td>dB</td>
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<tr>
<td>Proposed min Rx sensitivity level</td>
<td>-92.07</td>
<td>-86.37</td>
<td>-78.13</td>
<td>dBm</td>
</tr>
</tbody>
</table>
Justification for IEEE 802.15.3a Channel Model (1)

- **802.15.6 CM3: Average Power Decay Profile**
  - PDP decays 30dB at $\tau = 200$ ns
  - Mean excess delay: 26.3 ns
  - RMS delay spread: 19 ns

- **802.15.6 CM4: Average Power Decay Profile**
  - PDP decays 30dB at $\tau = 180$ ns
  - Mean excess delay: 40.9 ns
  - RMS delay spread: 42 ns
Justification for IEEE 802.15.3a Channel Model (2)

- 802.15.3a CM1 (0–4m, LOS): Average PDP
  - PDP decays 30dB at $\tau = 40$ ns
  - Mean excess delay: 5.2 ns
  - RMS delay spread: 6 ns

- 802.15.3a CM2 (0–4m, NLOS): Average PDP
  - PDP decays 30dB at $\tau = 50$ ns
  - Mean excess delay: 9.6 ns
  - RMS delay spread: 8 ns
Simulation Parameters

- PSDU = 256 bytes

- Transmit pulse: root-raised cosine pulse ($f_{cutoff} = 240$ MHz and $\alpha = 0.6$)

- Channel
  - AWGN
  - Multipath channel: 802.15.3a CM1 and CM2 (0–4m, LOS, NLOS)
  - PER results in multipath channel are averaged over 95% best channels

- Receiver
  - Energy-detection based non-coherent demodulator
  - Assume perfect packet detection and header decoding
  - Ideal timing, zero carrier-frequency offset
Packet Error Performance in AWGN

- AWGN results:
Packet Error Performance in Multi-path

- CM1

- CM2
Performance in SOP Co-channel Interference (1)

- 4 SOPs in a band → 3 interfering piconets:
  - Each piconet uses a unique time-hopping sequence
  - Asynchronous between signals from multiple piconets
  - 3 interferers continuously transmitting
  - All users transmit at 1Mbps
  - Interferers $d_{\text{Inf}}$ from reference receiver

- Path loss model:
  - Free-space path loss model ($\exp \alpha = 2$)
  - $\text{SIR} = 10 \log_{10}(d_{\text{Inf}}/d_{\text{Ref}})^\alpha$ [dB] for a single interferer

- Channel:
  - Each signal passes through an independent multipath channel (15.3a CM1)

- Receiver: non-coherent receiver based on energy-detection
Performance in SOP Co-channel Interference (2)

- SOP results:

\[ \frac{d_{\text{Intf}}}{d_{\text{Ref}}} = 1.55 \] (to maintain a PER = 10%)
## Power Consumption

<table>
<thead>
<tr>
<th>Data rate</th>
<th>1032.26 kbps</th>
<th>9650.79 kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analog Tx</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak power (mW)</td>
<td>40</td>
<td>27</td>
</tr>
<tr>
<td>Idle power (mW)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Average power (mW)</td>
<td>1.6</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Analog Rx</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak power (mW)</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Idle power (mW)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Average power (mW)</td>
<td>1.4</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Tx Total (mW)</strong></td>
<td><strong>2.1</strong></td>
<td><strong>3.2</strong></td>
</tr>
<tr>
<td><strong>Rx Total (mW)</strong></td>
<td><strong>1.9</strong></td>
<td><strong>2.9</strong></td>
</tr>
</tbody>
</table>

* Power analysis is based on low-voltage, low-leakage 130 nm CMOS technology.
## Comparison Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Proposed Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Regulatory</td>
<td>Compliant with TG6 regulatory document in UWB frequency band</td>
</tr>
<tr>
<td>2. Raw PHY data rate</td>
<td>129 kbps to 9.65 Mbps supported between node and hub</td>
</tr>
<tr>
<td>3. Transmission distance</td>
<td></td>
</tr>
<tr>
<td>4. Packet error rate</td>
<td>PER and link budget shown to support 10% PER for 256 octet PSDU at 3 meters within all operating frequency bands proposed.</td>
</tr>
<tr>
<td>5. Link budget</td>
<td></td>
</tr>
<tr>
<td>6. Power emission level</td>
<td>-16.21 dBm maximum EIRP</td>
</tr>
<tr>
<td>7. Interference and coexistence</td>
<td>Channelization: 5 channels total, at least 3 frequency bands available in each region</td>
</tr>
<tr>
<td></td>
<td>4 SOP supported per band, at least 12 SOP piconets supported in each region</td>
</tr>
<tr>
<td></td>
<td>Time-hopping and pulse polarization scrambling used to mitigate interference</td>
</tr>
<tr>
<td>8. Security</td>
<td>Can be combined with MAC providing security</td>
</tr>
<tr>
<td>9. Reliability</td>
<td>Link margin sufficient in 802.15.3a UWB channel model.</td>
</tr>
<tr>
<td>10. Quality of Service</td>
<td>-</td>
</tr>
<tr>
<td>11. Scalability</td>
<td>Scalable data rate from common symbol rates.</td>
</tr>
<tr>
<td>12. MAC transparency</td>
<td>-</td>
</tr>
<tr>
<td>13. Power Efficiency</td>
<td>To be added</td>
</tr>
<tr>
<td>14. Topology</td>
<td>Star topology, broadcast beacon supported. Maximum number of nodes supported via multiple access mechanisms.</td>
</tr>
<tr>
<td>15. Bonus Point</td>
<td>-</td>
</tr>
</tbody>
</table>
Summary and Conclusions

- Reuse the strengths of 802.15.4a PHY as much as possible

- Proposed a new frequency band plan → simplifies receiver, no DAA requirements

- New symbol structure, time-hopping sequence → eliminates ISI w/o needing a GI

- Low complexity and low power-consumption standard
  - Binary burst position modulation with time-hopping (BPM-TH) → non-coherent Rx
  - Low-complexity binary BCH codes

- Wide range of data rates are supported: 129 kbps to 9.65 Mbps

- Supports for 12 simultaneously operating piconets
Acronyms and Abbreviations

- BCH Code: Bose, Ray-Chaudhuri, Hocquenghem Code
- BPM: Burst Position Modulation
- DAA: Detection And Avoidance
- FCS: Frame Check Sequence
- GI: Guard Interval
- HCS: Header Check Sequence
- ISI: Inter-Symbol Interference
- LDC: Low Duty Cycle
- LFSR: Linear Feedback Shift Register
- MAC: Media Access Control
- PDP: Power Decay Profile
- PHY: Physical Layer
- PLCP: Physical Layer Convergence Protocol
- PPDU: Physical Layer Protocol Data Unit
- PRF: Pulse Repetition Frequency
- PSDU: Physical Service Data Unit
- SOP: Simultaneously Operating Piconet
- TH: Time-Hopping
- UWB: Ultra-Wide Band
Backup
Better Channel Efficiency with Proposed Symbol Structure

- 15.4a symbol structure
- Proposed symbol structure: \( N_{hop} \) doubled
- Proposed symbol structure: data rate doubled

* For all the cases, the number of chips per burst \( N_{cpb} \) is the same.
Time-Hopping Sequence Generation (2)

- Conditional distributions from simulation: $N_{hop} = 8$ and $N_{ch} = 4$