Multi-Band OFDM UWB RF System

Issues

Lawrence Larson, Daniel Li, Mahim Ranjan

UCSD Center for Wireless Communications

larson@ece.ucsd.edu
Outline

• **Introduction to UWB**

• **UWB Transmitter Design**
  – *I/Q mismatch in UWB transmitter*
  – *LO impurity in UWB transmitter*
  – *LO Leakage in UWB transmitter*

• **UWB Receiver Design**
  – *System Specs.*
  – *LNA Design*
  – *Mixer Design*

• **Future Work**
Introduction to UWB

- **UWB uses unlicensed 3.1 –10.6GHz band**
- **Provides a wireless PAN with data payload communication capabilities of 55, 80, 110, 160, 200, 320, and 480 Mb/s.**
- **We follow the TI and Intel proposal Multi-band OFDM System proposal**
- **OFDM advantages:**
  - OFDM has been adopted for several technologies
  - OFDM is spectrally efficient.
  - Good performance in narrowband interference.
  - Robustness in multi-path environments.


**Introduction to UWB**

- **Multi-band OFDM TX Architecture:**
  
  ![Diagram of Multi-band OFDM TX Architecture]
  
  - The bit stream format is defined by PLCP sublayer
  - Scrambler uses Pseudo random binary sequence generator: \( g(D) = 1 + D^{14} + D^{15} \)
    
    \[
    S_n = I_n \oplus x_n \\
    x_n = x_{n-14} \oplus x_{n-15}
    \]
    
    Where \( S_n, I_n \) are the output & input of the scrambler, \( x_n \) is the random binary sequence
  
  - Convolutional Encoder provides Forward Error Correction (FEC)
Introduction to UWB

- **Multi-band OFDM TX Architecture (continued):**
  - **Puncturer:**
    - A procedure of omitting some of the encoded bits
    - Reduce total number of bits transmitted
    - Increase the coding rate (from 1/3) to 11/32, ½, 5/8, ¾, etc
  - **Interleaving: An efficient method against burst errors**
    - Symbol interleaving: Permutates the bits across OFDM symbols for frequency diversity
    - Tone interleaving: Bits across tones in one symbol for robustness against narrow-band interference
  - **QPSK mapping:** 2 bits map to a complex number, a tone of OFDM symbol

<table>
<thead>
<tr>
<th>Input bits (b0 b1)</th>
<th>I</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>01</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
**Introduction to UWB**

- **Multi-band OFDM TX Architecture (continued):**
  - 128 tones per OFDM symbol
    - 100 Information tones (or 50 independent tones use 100 position for freq. Spreading)
    - 12 Pilot Tones for coherent detection against freq. offset and phase noise
    - 10 Guard tones, relax filters design or other purpose
    - 6 null tones,

- **IFFT:** Convert 128 tones to 128 time-domain samples
- **Add zero-pad prefix (60.6ns=32 sample time) to remove PSD ripple**
- **and 5 sample time guard intervals for switch between bands**
Introduction to UWB

- Multi-band OFDM TX Architecture (continued):
  - OFDM symbols are modulated to UWB bands

- Band plan

- Mode 1 device uses Group A
- Mode 2 device uses Group A and Group C
- Group B and D are reserved for future
## Multi-Band OFDM System Parameters*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>110 Mbps</th>
<th>200 Mbps</th>
<th>480 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Info. Data Rate</strong></td>
<td>110 Mbps</td>
<td>200 Mbps</td>
<td>480 Mbps</td>
</tr>
<tr>
<td><strong>Modulation/Constellation</strong></td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
<td>OFDM/QPSK</td>
</tr>
<tr>
<td><strong>FFT Size</strong></td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td><strong>Coding Rate (K=7)</strong></td>
<td>R = 11/32</td>
<td>R = 5/8</td>
<td>R = 3/4</td>
</tr>
<tr>
<td><strong>Spreading Rate</strong></td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Information Tones</strong></td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td><strong>Data Tones</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Info. Length</strong></td>
<td>242.4 ns</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
</tr>
<tr>
<td><strong>Cyclic Prefix</strong></td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
<tr>
<td><strong>Guard Interval</strong></td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
</tr>
<tr>
<td><strong>Symbol Length</strong></td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
</tr>
<tr>
<td><strong>Channel Bit Rate</strong></td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
</tr>
<tr>
<td><strong>Frequency Band</strong></td>
<td>3168 – 4752 MHz</td>
<td>3168 – 4752 MHz</td>
<td>3168 – 4752 MHz</td>
</tr>
<tr>
<td><strong>Multi-path Tolerance</strong></td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
</tbody>
</table>

* From TI proposal
UWB Transmitter Simulation

A snapshot:

UWB - Multiband OFDM - 200 Mb/s Mode

This version is based on an IEEE 802.15.3a proposal, dated 15 September 2005 (Doc: IEEE P802.15-03/0681)

Double click to see documentation

Other colors:
- Floating point override
- Analysis/Visualization
- Settings/Information
- Binary data processing
- Digital baseband processing (fixed point)
- Baseband model of analog front-end and channel

UWB Channel

Frequency Hopping and Filtering

IQ Imbalance

Frequency Demodulation

Binary

Rate 6/8 Encoder

IQ Encoder

Interleaver

IQ Demodulator

Viterbi Decoder

Error Rate Calculation

Deinterleaver

Error Rate Calculation

Other colors:
UWB System Simulation

• **Goal:** Make the simulation as realistic as possible
• **Current Model Assumptions**
  • Random data transmission (no data scrambling used)
  • Fixed (selectable) number of data symbols per packet
  Continuous frame-to-frame operation (no coder state resetting via tail bits)
  • Fixed transmit power level; link-SNR specified, No PA
  • Assume perfect receiver, Idealized timing/frequency acquisition
  • Only simulate the highest mandatory rate 200Mbps
• **The following non-idealities are introduced to the simulation**
  • I/Q mismatch
  • LO impurity
    • Spurs
    • Phase noise
  • LO leakage
**IQ imbalance in UWB transmitter**

**IQ imbalance in QPSK system (no OFDM)**

- IQ magnitude error
- IQ phase error

- Cause EVM (Error Vector Magnitude)
- Degrade Signal-to-noise ratio
IQ imbalance in UWB transmitter

IQ imbalance in QPSK with OFDM

Ideal complex modulation carrier waveform:
\[ y(t) = x_I(t) \cos(\omega t) + x_Q(t) \sin(\omega t) \]

IQ imbalanced modulated waveform:
\[ y(t) = x_I(t) \cos(\omega t) + \lambda x_Q(t) \sin(\omega t + \theta) \]
\[ = (x_I(t) + \lambda x_Q(t) \sin \theta) \cos(\omega t) + (\lambda x_Q(t) \cos \theta) \sin(\omega t + \theta) \]
IQ imbalance in UWB transmitter

**IQ magnitude imbalance test results for UWB:**

- **Channel mode:** CM2, non-line of sight, distance 0-4m
- **Channel index:** 50
- **I/Q imbalance** is defined as $20 \times \log_{10} \left( \frac{I}{I-Q} \right)$

• **BER is determined by channel SNR when IQ imbalance is above 20dB**
• **IQ imbalance starts to affect BER when less than 20dB**

![BER vs IQ Imbalance graph](chart.png)
LO impurity in UWB Transmitter

LO from frequency synthesizer comes with Spurs and phase noise

Ideal LO

Non-ideal LO

Non-ideal LO effect in the Mixer:

Baseband signal

RF signal
LO impurity in UWB Transmitter

Simulation of LO impurity impact on UWB transmitter

- **Two cases**: A: Spurs at $0.98*fc$ & $1.02*fc$  B: Spurs at $0.9*fc$ & $1.1*fc$
- **Channel mode**: non-line-of-sight, distance 0-4m, Channel index: 50
- **LO Spurs has little impact on BER when less than –20dB**
- **The closer the spurs to LO, the more impact it has**
LO Leakage in UWB Transmitter

LO leakage causes:
- **DC offset at receiver**
- **Interference to other receivers using the same band**

- **Baseband signal**
- **Transmitted RF signal**
- **Received RF signal**
- **Received baseband signal With DC offset**
LO Leakage in UWB Transmitter

Simulation of LO Leakage on UWB transmitter

• LO Leakage magnitude is specified in dB w.r.t. LO magnitude
• Channel mode: non-line-of-sight, distance 0-4m,
• Channel index: 50

When LO leakage
• >-30dB, BER is mainly affected by LO leakage
• <-50dB, BER is mainly affected by SNR
• Between –30 and –50dB, both SNR and LO leakage affect BER
Multi-Band OFDM Receiver Architecture*

• Block diagram of an example RX architecture:

* From TI Proposal
## Link Budget and Receiver Sensitivity*

- **Assumption:** AWGN and 0 dBi gain at TX and RX antennas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Information Data Rate</strong></td>
<td>110 Mb/s</td>
<td>200 Mb/s</td>
<td>480 Mb/s</td>
</tr>
<tr>
<td><strong>Average TX Power</strong></td>
<td>-10.3 dBm</td>
<td>-10.3 dBm</td>
<td>-10.3 dBm</td>
</tr>
<tr>
<td><strong>Total Path Loss</strong></td>
<td>64.2 dB</td>
<td>56.2 dB</td>
<td>50.2 dB</td>
</tr>
<tr>
<td></td>
<td>(@ 10 meters)</td>
<td>(@ 4 meters)</td>
<td>(@ 2 meters)</td>
</tr>
<tr>
<td><strong>Average RX Power</strong></td>
<td>-74.5 dBm</td>
<td>-66.5 dBm</td>
<td>-60.5 dBm</td>
</tr>
<tr>
<td><strong>Noise Power Per Bit</strong></td>
<td>-93.6 dBm</td>
<td>-91.0 dBm</td>
<td>-87.2 dBm</td>
</tr>
<tr>
<td><strong>RX Noise Figure</strong></td>
<td>6.6 dB</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
</tr>
<tr>
<td><strong>Total Noise Power</strong></td>
<td>-87.0 dBm</td>
<td>-84.4 dBm</td>
<td>-80.6 dBm</td>
</tr>
<tr>
<td><strong>Required Eb/N0</strong></td>
<td>4.0 dB</td>
<td>4.7 dB</td>
<td>4.9 dB</td>
</tr>
<tr>
<td><strong>Implementation Loss</strong></td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
</tr>
<tr>
<td><strong>Link Margin</strong></td>
<td>5.5 dB</td>
<td>10.2 dB</td>
<td>12.2 dB</td>
</tr>
<tr>
<td><strong>RX Sensitivity Level</strong></td>
<td>-80.0 dBm</td>
<td>-76.7 dBm</td>
<td>-72.7 dB</td>
</tr>
</tbody>
</table>

* From TI Proposal
## Key Block Specifications

<table>
<thead>
<tr>
<th></th>
<th>NF (dB)</th>
<th>Gain (dB)</th>
<th>IIP3 (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA</td>
<td>4</td>
<td>10</td>
<td>-2</td>
</tr>
<tr>
<td>Mixer</td>
<td>10</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Filter</td>
<td>10</td>
<td>0</td>
<td>18</td>
</tr>
</tbody>
</table>

### Assumptions:

- Min distance of operation = 0.1m
- Maximum of three UWB systems operating concurrently
- External Notch filter filters out non-Multi-Band OFDM jammers (802.11a/b/g, Bluetooth, PCS etc)
Other Considerations

• **DC Offset:** Important for direct conversion systems: Multi-Band OFDM system rejects the sub-carrier at DC.

• **1/f noise:** Sub-carrier at DC is rejected, subcarrier spacing = 4.125 MHz which is far away from the 1/f noise corner frequency. Impact of 1/f noise is low.

• **IIP2:** Completely differential design to increase IIP2

• **LO Re-radiation:** Use cascode LNA to improve isolation and reduce carrier leakage
Paths to Broadband LNA

• **Resistive Load, Resistive Input Match**
  - Good Broadband Gain and Input Match
  - High Noise Figure
  - Headroom

• **LC Match**
  - Broadband match possible using multiple LC sections
  - Good noise performance
  - Requires on-chip inductors for tuning: High cost
Design Methodology

• **Load Tuning**
  - LC Tune LNA load for 6GHz-8GHz band using package bondwire inductance and on-chip capacitors
  - Switch in extra capacitance to tune to 3GHz-4.5GHz band
  Allows for a broad-band load without the use of resistors or on-chip inductors. Fixed LC tuning would require multiple LC sections and therefore on-chip inductors.

• **Input match**
  - Use package bondwires to match input
  - Add RC feedback
  - Size devices for best input match (as opposed to sizing for best NF): Increases NF, but allows for input matching without on-chip inductors

Load tuning also provides extra filtering and eases IP2 spec on mixer

\[ \omega_{high} = \frac{1}{\sqrt{L_{bond}.C_{dev}}} \]

\[ \omega_{low} = \frac{1}{\sqrt{L_{bond}.(C_{dev} + C_l)}} \]
LNA Design
## Simulation Results - I

<table>
<thead>
<tr>
<th>Freq (MHz)</th>
<th>Gain (dB)</th>
<th>NF (dB)</th>
<th>Return Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3432</td>
<td>11</td>
<td>3.25</td>
<td>-4.6</td>
</tr>
<tr>
<td>3960</td>
<td>11.8</td>
<td>3.3</td>
<td>-4.9</td>
</tr>
<tr>
<td>4488</td>
<td>14</td>
<td>3.4</td>
<td>-5.2</td>
</tr>
<tr>
<td>6336</td>
<td>18.53</td>
<td>3.4</td>
<td>-5.9</td>
</tr>
<tr>
<td>6864</td>
<td>21</td>
<td>3.5</td>
<td>-6.1</td>
</tr>
<tr>
<td>7392</td>
<td>21.9</td>
<td>3.65</td>
<td>-5.9</td>
</tr>
<tr>
<td>7920</td>
<td>20.8</td>
<td>3.8</td>
<td>-5.4</td>
</tr>
</tbody>
</table>

- **Noise Figure**: 3.8dB (worst case)
- **Input IP3**: -3 dBm
- **Input IP2**: +40 dBm with 5% device mismatch
  +30 dBm with 5% device mismatch AND 10% bondwire mismatch
- **Current Consumption**: 8mA (from a 2.7V supply)
- **Frequency band switching time**: 3nS

10 dB gain step between bands. VGA will need to compensate.
Mixer

Simulation Results
- Noise Figure = 7dB
- Gain = 6dB
- Current Consumption = 4mA (from a 2.7V supply)

Gilbert cell mixer with resistive loads and degeneration
Mixer Spur Performance

- IIP2 quantifies “wide-band” distortion.

  Ex.: $F_{spur}=4.1\text{GHz}$, $F_{interest}=8.2\text{GHz}$, $F_{lo}=8\text{GHz}$
  then $F_{interest\_OUT}=200\text{MHz}$
  $2XF_{spur} - F_{lo}=200\text{MHz}$ !!

LNA is frequency selective (Gain at 4.1GHz is different from gain at 8.2GHz). IIP2 for mixer not a true figure of merit for the system as it assumes the gain for 4.1GHz is the same as that for 8.2GHz.
Mixer Spur Simulation Strategy

• Simulate Mixer+LNA
• Inject Minimum Detectable Signal at input of LNA at freq of interest
• Inject spur(s) which would create a signal close to frequency of interest
• Make sure the spur output is at least 10dB below signal of interest
# LNA+Mixer Spur Results

RF signal power = -73dBm, Spur power = -30dBm

5% device mismatch, 10% bondwire mismatch

<table>
<thead>
<tr>
<th>Signal of interest</th>
<th>Spur</th>
<th>LO</th>
<th>Mixing Product</th>
<th>Fout Spur</th>
<th>Fout interest</th>
<th>Spur Rej (dBc)</th>
<th>Spur Rej LNA with Resistive Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1G</td>
<td>4.1G</td>
<td>8G</td>
<td>2.Fspur-Flo</td>
<td>200M</td>
<td>100M</td>
<td>17.2</td>
<td>10.1</td>
</tr>
<tr>
<td>4.1G</td>
<td>8.2G</td>
<td>4G</td>
<td>Fspur-2.Flo</td>
<td>200M</td>
<td>100M</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>7.1G</td>
<td>4.1G,3.1G</td>
<td>7G</td>
<td>Fspur1+Fspur2-Flo</td>
<td>200M</td>
<td>100M</td>
<td>14.5</td>
<td>8.6</td>
</tr>
</tbody>
</table>
Filter Specification

- Need a low pass filter to filter out adjacent channels from other UWB systems
- Required adjacent channel suppression > 30dB (500MHz from center frequency) => at least 4\textsuperscript{th} order LPF
- Minimum noise contribution
- No inductors
Filter Topologies

Currently investigating different filter topologies
• Sallen-Key filter with unity gain buffer

• Gm-C filter
Sallen-Key Filter

- Low current
- No inductors
- Good noise performance
- Low complexity

- Finite Zout of source follower introduces a zero which limits rejection (particularly problematic for MOS due to low Gm)

\[
H(s) = \frac{K}{s^2C_1C_2R_1R_2 + s[C_1(R_1 + R_2) + C_2R_1(1-K)] + 1}
\]

Zero output impedance

\[
H(s) = \frac{s^2C_1C_2R_1r_o + sC_2r_o + K}{s^3C_1C_2R_1R_2 + s[C_1C_2'(R_1 + R_2)] + s[C_1(R_1 + R_2) + C_2(r_o + (1-K)R_1)] + 1}
\]

Finite output impedance
Techniques for Enhancing Rejection of Sallen-Key

- Extra buffer "isolates" source follower $Z_{out}$ and pushes the zero to a higher frequency

- Band-width could be reduced due to limited band-width of extra buffer
2 Pole Sallen-Key Filter Response: Preliminary Simulation Results

- ~17 dB improvement in rejection at 2 GHz by using extra buffer
- ~10 dB rejection of adjacent band with extra buffer
- Bandwidth reduced due to finite bandwidth of buffer

Still To Evaluate
- Noise Performance
- Input IP3
- Group Delay
Conclusions

- **UWB Multi-Band OFDM** offers significant data rate enhancements over existing 802.11 systems.
  - **What is the performance?**
  - **What is the cost?**
  - **What are the markets?**

- **TBD!!!**