High Performance CMOS Radio Design for Multi Band OFDM UWB

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August 22, 2004

Acknowledgements

We would like to thank the authors of Texas Instruments’ Formal UWB Proposal. In addition, we would like to thank the designers involved in TI’s UWB RFIC Program.

– Jaiganesh Balakrishnan
– Anuj Batra
– Anand Dabak
– Ranjit Gharpurey
– Paul Fontaine
– Jerry Lin
– Simon Lee
– Danielle Griffith
– Joel Garza
Scope of Presentation

- A Brief Overview of UWB
- Multi-band OFDM System Characteristics
  - Non-Linearity
  - Band Width
  - Noise
- Architectures for VCO, Synthesizer, RX & TX
  - Frequency Generation Solutions, VCO & PLL
    - Spurs & Multi Pico Nets
  - Base Band Filters
  - Receive RF, Analog & ADC
  - Transmit RF, Analog & DAC
- RF Digital Isolation for SOC Implementation
  - Cross Talk

MBOA UWB Band Plan

"Lowest 3 Band" Solutions
- Best Channel Characteristics
- Simplest Off-Chip Filtering Requirements
  ➔ Earliest Introduction to Market
Overview of Multi-band OFDM

- Basic idea: divide the spectrum into channels that are 528 MHz wide.
- Transmitter and Receiver Process Smaller Bandwidth Signals (528 MHz).
- Insert a 2nS Guard Interval Between OFDM Symbols to Allow Sufficient Time to Switch RFIC Between Channels.
- Each Channel has 128 Sub Carriers 4.25MHz Apart
- 3X Power 1/3 of the Time

Low Power & Low Noise RF CMOS

4GHz: $\text{NF}_{\text{min}} < 1\, \text{dB} @ 16\, \text{dB Gain}$

RF CMOS Higher Reactive Impedances
- Narrower Band Widths Improve RF
  - $V_0 \sim V_{\text{IN}}Q_{\text{IN}}$
  - $V_1 \sim I_{\text{SIG}}Q_{\text{L}}$
  - Input S/N $\sim V_0 \sim Q$
  - Gain $\sim V_1 \sim Q$
  - $I_{\text{Bias}} \sim 1/Q$
- Inductors ($Q = 2$) Can Improve Noise and Lower Power

Inductively Biased Nodes Allow
- Voltage Swings Outside the Supply Rails
- Higher Dynamic Range

Base Band Op Amps Use Feed Back To Improve Performance
- Narrower Band Widths

Easy Migration to System on a Chip
Low Power & Low Noise RF SiGe

RF SiGe: Lower-Q, Smaller RF Impedances \( \rightarrow \) High Performance

RF Well Suited for Broad Band

- \( V_0 \sim V_{\text{IN}}XQ_{\text{IN}} \)
- \( V_1 \sim I_{\text{SIG}}XQ_{\text{L}} \)
- Input S/N \( \sim V_0 \sim Q \)
- Gain \( \sim V_1 \sim Q \)
- \( I_{\text{Bias}} \sim 1/Q \)

Inductors (\( Q = 2 \)) Can Still Improve Noise and Lower Power

Inductively Biased Nodes Support Voltage Swings Outside the Supply Rails

\( \rightarrow \) Higher Dynamic Range

Very Good Base Band Amps with Low Gains & Broad Band Widths

\( \rightarrow \) Lower Amounts of Feed Back

UWB Solutions: 3168MHz to 4752GHz

- Narrow Instantaneous RF Band Widths
- Lower Converter Sampling Rates
- Base Band Filters/VGA’s
  - Lower-Q
  - Smaller Band Width
- 4.25 MHz Carrier Spacing/No Zero Tone
  - No 1/f Noise

\( \rightarrow \) CMOS Friendly System Requirements
**MBOA UWB: Distortion Floor for TX/RX**

2nd and 3rd Order “Beats” Set Inter-Modulation

Distortion Floor in MBOA UWB

\[ V_{in} = V_A \cos(a) + V_B \cos(b) + V_C \cos(c) \]

\[ V_{out} = k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 \]

**3rd Order Inter Modulation Floor: 128 Sub Carriers**

\[ V_{IN} = A \cos(a) + B \cos(b) + C \cos(c) \]

\[ V_{OUT} = k_1 V_{IN} + k_2 V_{IN}^2 + k_3 V_{IN}^3 \]

\[ k_3 V_{IN}^3 = k_3 \left[ \frac{1}{4} A^3 \cos(3a) + \frac{1}{4} B^3 \cos(3b) + \frac{1}{4} C^3 \cos(3c) + \frac{3}{4} A^2 B \cos(2a + b) + \frac{3}{4} A^2 C \cos(2a - b) + \frac{3}{4} B^2 C \cos(2b + a) + \frac{3}{4} B^2 C \cos(2b - a) + \frac{3}{4} A C^2 \cos(2c + a) + \frac{3}{4} A C^2 \cos(2c - a) \right] \]

- Triple beats are 6dB higher than two-tone IM3 products
- Many more triple beats than IM3 products
- \( \sim 3N^2/8 \) beats near middle of band
- \( \sim N^2/4 \) product terms near edge of band
- \( CTB(dBc) = IM3(dBc) + 6 + 10 \log(3N^2/8) \)
UWB Second Order Inter Modulation Floor

\[
V_{in} = A \cos(a) + B \cos(b) + C \cos(c)
\]

\[
V_{out} = k_2 V_{in}^2 + k_3 V_{in}^3
\]

\[
k_2 V_{in}^2 = \frac{1}{2} k_2 A^2 + \frac{1}{2} k_2 B^2 + \frac{1}{2} k_2 C^2
\]

\[
+ k_2 A \cos(a +/ - b) + k_2 B \cos(a +/ - c) + k_2 C \cos(b +/ - c)
\]

\[
+ \frac{1}{2} k_3 A^2 \cos(2a) + \frac{1}{2} k_3 B^2 \cos(2b) + \frac{1}{2} k_3 C^2 \cos(2c)
\]

- CSO products are out of band in RF path
- Generate Signal dependent DC offsets at LNA output
- Reduced By Low-Q L-C Filtering Before Down Conversion

Multi-Band OFDM System Parameters

<table>
<thead>
<tr>
<th>Modulation/Constellation</th>
<th>Info. Data Rate: 110 Mbps</th>
<th>200 Mbps</th>
<th>400 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFDM/QPSK</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>FFT Length</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
<td>242.4 ns</td>
</tr>
<tr>
<td>Coding Rate (K=7)</td>
<td>R = 11/32</td>
<td>R = 5/8</td>
<td>R = 3/4</td>
</tr>
<tr>
<td>Spreading Rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Information Tones</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Data Tones</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Info. Length</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
<tr>
<td>Cyclic Prefix</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
<td>9.5 ns</td>
</tr>
<tr>
<td>Symbol Length</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
<td>312.5 ns</td>
</tr>
<tr>
<td>Channel Bit Rate</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
<td>640 Mbps</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>3188 – 4752 MHz</td>
<td>3188 – 4752 MHz</td>
<td>3188 – 4752 MHz</td>
</tr>
<tr>
<td>Multi-path Tolerance</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
<td>60.6 ns</td>
</tr>
</tbody>
</table>

1) Tolerant of Inter-Mods, Image, and Synthesizer Noise
2) Fast Synthesizer 9.5nS for System   ~ 2nS for RFIC
3) Short “In-Channel” Settling Times for RFIC
4) Frequencies Readily Obtained on CMOS RFIC
1) Very Low TX Power ➞ Fully Integrated PA
2) 6.5dB for switch + filter + receiver ➞ ~ 4.5dB for RFIC
3) Tolerant of Inter-Mods, Image, and Synthesizer Noise

### Link Budget and Receiver Sensitivity

Assumption: AWGN and 0 dBi gain at TX/RX antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Data Rate</td>
<td>110 Mbps</td>
<td>200 Mbps</td>
<td>480 Mbps</td>
</tr>
<tr>
<td>Average TX Power</td>
<td>-10.3 dBm</td>
<td>-10.3 dBm</td>
<td>-10.3 dBm</td>
</tr>
<tr>
<td>Total Path Loss</td>
<td>64.2 dB (@10 meters)</td>
<td>56.2 dB (@4 meters)</td>
<td>50.2 dB (@2 meters)</td>
</tr>
<tr>
<td>Average RX Power</td>
<td>-74.5 dBm</td>
<td>-66.5 dBm</td>
<td>-60.5 dBm</td>
</tr>
<tr>
<td>Noise Power Per Bit</td>
<td>-30.6 dBm</td>
<td>-91.0 dBm</td>
<td>-87.2 dBm</td>
</tr>
<tr>
<td>RX Noise Figure</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
<td>6.6 dB</td>
</tr>
<tr>
<td>Total Noise Power</td>
<td>-87.0 dBm</td>
<td>-84.4 dBm</td>
<td>-80.8 dBm</td>
</tr>
<tr>
<td>Required Eb/N0</td>
<td>4.0 dB</td>
<td>4.7 dB</td>
<td>4.9 dB</td>
</tr>
<tr>
<td>Implementation Loss</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
</tr>
<tr>
<td>Link Margin</td>
<td>5.5 dB</td>
<td>10.2 dB</td>
<td>12.2 dB</td>
</tr>
<tr>
<td>RX Sensitivity Level</td>
<td>-40.0 dBm</td>
<td>-76.7 dBm</td>
<td>-72.7 dBm</td>
</tr>
</tbody>
</table>

### Direct Conversion UWB Transceiver

Low Power, Low Noise ~ 4dB, Low Cost, 480MBPS

Channel Switching Time ~ 2nS (~10,000 Times Faster Than 802.11)

- Complex Frequency Synthesis & Frequency Conversion
- Low TX Power ~ -10dBM RMS
- Fully Integrated PA
- Very Low Noise RFIC Required NF ~ 4dB
**Direct Conversion UWB Transceiver**

Low Power, Low Noise ~ 4dB, Low Cost, 480MBPS

- Channel Switching Time ~ 2nS, Two RF LO Frequencies Needed
  - Unique Frequency Synthesis & Frequency Conversion
- Low TX Power ~ -10dBm RMS
  - Fully Integrated PA
- More Complex Dual Stage RX/TX → Simpler Frequency Synthesis

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**MBOA UWB: Frequency Synthesis**

- Fast Frequency Hopping
  - Necessary condition for multi-band proposals
  - Frequency switching time < 2ns
- Standard Closed Loop PLL Design is Far Too Slow
- Frequency Synthesis Using Single-Sideband Generation
- All Frequencies Derived From Multiples of 16MHz
  - All IC cells fully synchronous
    - ADC outputs, mixer LOs, RX & TX digital base band, …
Frequency Synthesis
(Generating 3 Frequencies from 1)

• VCO center frequency = 4224MHz = 264 x 16MHz
  – 4224 MHz ÷ 4 output = 1056MHz, ÷ 16 output = 264MHz

• Single sideband generation principle: \(2\sin(\omega t) = \text{Sine Wave}\)
  – \(\cos(\omega t)\cos(\omega t) - \sin(\omega t)\sin(\omega t) = \cos((\omega_1 + \omega_2)t)\)
  – \(\cos(\omega t)\sin(\omega t) + \sin(\omega t)\cos(\omega t) = \sin((\omega_1 + \omega_2)t)\)
  – \(\cos(\omega t)\sin(\omega t) - \sin(\omega t)\cos(\omega t) = \cos((\omega_1 - \omega_2)t)\)
  – \(\cos(\omega t)\cos(\omega t) + \sin(\omega t)\sin(\omega t) = \cos((\omega_1 + \omega_2)t)\)
  – Unwanted Frequency Rejected ~ 30dB

• All three frequencies can be generated rapidly
  – 792MHz = 1056MHz – 264MHz
  – Channel 1: 4224 - 792 = 3432MHz
  – Channel 2: 4224 - 264 = 3960MHz
  – Channel 3: 4224 + 264 = 4488MHz

Quadrature Voltage Controlled Oscillators

Ring Oscillator
• Quadrature Output VCO
  – No Separate Phase Splitter
• Lower Operating Frequency
  – Better Yield?
• Variable MOS capacitors set frequency to 4224MHz

2f Oscillator

2f Oscillator (8448MHz)
• Reduced 1/f Radiation
• Reduced VCO Pulling
• Smaller Implementation
• Higher Inductor Q’s

Two-Stage \(D_{\text{Flip-Flop}}\) Dividers
• Divided Clocks in Quadrature
UWB Synthesizer Dual Output Frequency
Channel Select ~2nS; Outputs: \( f_1 = 4224 \text{MHz} \), \( f_2 = +/\pm 264 \text{ Or 792MHz} \)

UWB Synthesizer: Single Output Frequency
Channel Select ~2nS; Outputs: 3432, 3960 Or 4488MHz
**Single sideband generation principle:** \( f_1 = \frac{f}{2\pi} \text{= Square wave} \)

\[
\begin{align*}
\cos(\omega_1 t) &\times \cos(\omega_2 t) \times \sin(\omega_3 t) \\
+ \cos(\omega_1 t) &\times \cos(3\omega_2 t) + \sin(\omega_3 t) \\
+ \cos(5\omega_2 t) &\times \sin(\omega_3 t) \\
\Rightarrow f_{264} &\approx 264\text{MHz} &\Delta -792\text{MHz} 1320\text{MHz} &\ldots \\
\Rightarrow f_{792} &\approx 792\text{MHz} 2376\text{MHz} &\ldots
\end{align*}
\]

- Channel 1 Output = 3432MHz, 6600MHz, 264MHz,…
- Channel 2 Output = 3960MHz, 5016MHz, 2904MHz,…
- Channel 3 Output = 2376MHz, 3432MHz, 4488MHz,…

**LO Spurious & Multiple Pico Nets**

<table>
<thead>
<tr>
<th>Desired LO Output</th>
<th>Actual LO Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**LO Spurious**
- Mix Channel 1 on Top of Channel 3
- Transmit on Channel 1 When Channel 3 is Selected
  ➔ Prevent Coexistence of Multiple Pico-Nets
- Mix Undesired Wireless Standards Into UWB Receive Bands
- Transmits UWB Data Into Spectrum Allocated to Other Standards
  ➔ Hampers Coexistence with Other Wireless Standards
Base Band Filters

RX Channel Select Filter (528MSPS ADC)
- 3\textsuperscript{rd} Order All Pole Response
- $F_c \approx 250$MHz
- On-Chip Auto Tuning of Filter Corner
- Filter can be integrated into the VGA
  - Real pole at Output of Mixer
  - Complex pole can be combined with VGA Op-Amp

TX Image Reject Filter (1056MSPS DAC)
- Second Order Response
- +0 to +1dB @ 250MHz
- Auto Tuning of Filter Corner

MBOA UWB Base Band Filters
(One-Half of Differential Section Shown)

Sallen & Key
- Low-Q
- Stable
- Moderate power
- Requires Buffer
- No Voltage Gain

Op-Amp Based
- Higher-Q
- Stability Issues
- Moderate Power
- Has Gain

L-C
- Moderate-Q
- Most Stable
- Zero power
- Requires Buffer
- No Gain
Base Band Self-Calibration: Example

Base Band Filter

Tuned Capacitor

Filter Self-Calibration

- Higher Yield & Lower Costs
- Higher Realized Performance
- RF/Analog Self Testing at DC Probe

ADC Spec/Issues for UWB Receiver

- ADC:
  - 5bits/528MHz
  - Power Hungry Component in UWB
- VGA & Base Band Filters
  - Large Gain Range
  - Flat Response to ~ 240MHz
  - Can Combine Base Band Filters With Gain Blocks
  - May Need 50Ω Drive
- More Complex Synthesizer \(\rightarrow\) LO Spurs
- Standard Receive Mixers
- Gain Step in LNA
ADC Spec/Issues for UWB Receiver

- **ADC:**
  - 5bits/528MHz
  - Power Hungry Component in UWB
- **VGA & Base Band Filters**
  - Large Gain Range
  - Flat Response to ~ 240MHz
  - Can Combine Base Band Filters With Gain Blocks
  - May Need 50Ω Drive
- **Less Complex Synthesizer**
- **Dual Stage Receive Mixers**
  - LO Spurs
- **Gain Step in LNA**

Basic Flash ADC

Continuous time signal with infinite resolution

Discrete time signal with finite resolution

**Structure**
- Input Capacitance ~ $2^n$ of Bits
- Pre-Amps & Comparators ~ $2^n$ of Bits
  - Area & Power ~ $2^n$ of Bits
- Sample & Hold Not Required

**Performance Issues**
- Input Feed-Through to Reference
- Comparator Kickback
- Clock Jitter
Transmitter 1 for MBOA UWB

Requirements
- DAC: 5bits @ 1.056GHz Sampling Rate
- Low pass Filter
  - Flat To ~ 240MHz
  - Suppresses (1056 – 264)MHz and Beyond
- Simple Up-Conversion Mixers
- A Single RF Output Synthesizer
  - Shared with DAC & Receiver
  - Higher Complexity LO Generation \( \rightarrow \) LO Spurs

Transmitter 2 for MBOA UWB

Requirements
- DAC: 5bits @ 1.056GHz Sampling Rate
- Low pass Filter
  - Flat To ~ 240MHz
  - Suppresses (1056 – 264)MHz and Beyond
- Two Stage Up-Conversion Mixers
  - Spurious Issues
- Simpler Dual RF Output Synthesizer
  - Shared with DAC & Receiver
  - Switching Time < 2ns
Band Set #1 Emission Mask Proposal

TX Base Band Output Spectrum: No Filter

- High level simulation (DAC and mixer)
- 2nd left sided image in GPS band Violates TX Mask
**Base Band Output Spectrum with Filtering**

- Simple Low-pass filter \(\rightarrow\) 5dB Margin
- Additional RF Filtering Improves Margin

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**UWB Transceiver Design Approach**

Digital Baseband

<table>
<thead>
<tr>
<th>ADC</th>
<th>DAC</th>
</tr>
</thead>
</table>

1GHz

6bits

CMOS RFIC

Next Generation (SoC)

<table>
<thead>
<tr>
<th>Baseband</th>
<th>CMOS RFIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>DAC</td>
</tr>
</tbody>
</table>

Multi-Chip to Full System on a Chip
- Self Calibration: RF/VCO/Analog Base Band
- Cross Talk Suppression: System & Design Level
System on a Chip

Advantages
- Reduced Implementation Cost
- Improved Vendor Acceptance

Challenges
- Cost of Lower Yield
- Device Modeling
- Cross Talk

Cross Talk

On-Chip Coupling
- TX Output/Harmonics Pull VCO
- Strong RF Input/Harmonics Pull VCO
- Digital Contaminates Base Band or RF
- Digital Over-Drives RF or Base Band Input
- TX Output Over-Drives RX Input (UMTS)
- TX/RX Mode Changes “Kick” VCO
- VCO Feed Though Violates FCC Max Power
**Inductive Cross Talk**

**Inductive Vector Potential:**

\[
E(f, \rho, z) \approx I \int_0^\infty dk_\rho k_\rho J_0(k_\rho \rho) \left( e^{ik_\rho \rho} + A e^{-ik_\rho \rho} \right), \quad f = \frac{c}{2\pi} \sqrt{k_\rho^2 + k_z^2}
\]

\[
E(2GHz, \rho, z) \Rightarrow \frac{6 \cdot 10^3 V}{\rho (\mu m)}
\]

**Static Component**

**Dynamic Component:** Weakly Spatially Dependent

---

**Magneto Static Cross Talk**

(No Simple Board Level Solution)

**Standard Layout**

**Field Cancellation**

*VCO Currents*

*Electric Field*

*Input Matching Inductors*
**Cross Talk Suppression**

**Electro Magnetic Isolation**

- Standard Layout
- Anti-Symmetric Layout

Anti-Symmetric Layout: ~ 20dB More Isolation

**System Level & On-Chip Cross Talk Suppression**
- Digital Spectral Content Far From RF
- VCO Electromagnetically Isolated and Resistant to LF Pulling
- LNA Input Narrow Band and Electromagnetically Isolated
- Layout/Floor Plan Optimized with Electromagnetic Solver

---

**Electrostatic Cross Talk**

**Shielded Scalar Potential:**

\[ \phi_i \sim q \int \frac{1}{|\vec{r}_i - \vec{r}_j|} \frac{1}{|\vec{r}_i - \vec{r}_j - 2z\hat{z}|} d\vec{l}_j \]

- Frequency Independent
- Decreases Rapidly for \(|r_i - r_j| > 2z \sim 1\mu m|

**Shielding Requirements:**

\[ R_{\text{Shield}} \ll R_{\text{Substrate}} \quad \text{with} \quad C_{\text{parasitic}} \frac{R_{\text{Shield}}}{|R_{\text{Substrate}}|} \ll (2\pi f)^{-1} \]

\[ R_{\text{Substrate}} \sim \frac{\rho_{\text{Substrate}}}{4\pi} \int_{|r|}^{\infty} \frac{1}{r^2} dr \]

Parasitic Currents are Shunted to Ground Through Low Loss Substrate Shielding

- Improves Q
- Greatly Reduces Cross Talk
### Conclusion

- MBOA UWB Was Developed for a High Performance CMOS Implementation.
- VCO Core Requirements & Many RX/TX Requirements are More Relaxed Than Other Wireless Standards.
- LO Spurious Requirements for MBOA UWB and Base Band Bandwidth are the Primary Design Challenges
- MBOA UWB Was Developed for a Direct Migration to Full, Low-Cost System on a Chip