A 19pJ/pulse UWB Transmitter with Dual Capacitively-Coupled Digital Power Amplifiers

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Outline

- Architectural Motivation
- Generating UWB Pulses Digitally
- Transmitter Design
- Measurement Results
- Conclusions
Research Vision

• Ubiquitous wireless nodes for Body Area Networks

• Key requirements:
  – Long battery life
  – Small form factor (< 1cm³)

• Key characteristics:
  – Low data rate (< 500kbps)
  – Short range (1-10m)
Energy-Efficient/Low Area Design

- Need a system-level view to meet low energy and area requirements

<table>
<thead>
<tr>
<th>System observations and/or requirements</th>
<th>Questions</th>
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<tbody>
<tr>
<td>Low data rates</td>
<td>Can we reduce circuit complexity at the expense of sensitivity?</td>
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<tr>
<td>Duty cycling</td>
<td>Can we shut off circuits for extended periods of time?</td>
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<tr>
<td>No off-chip components</td>
<td>Can we filter on-chip without consuming too much area?</td>
</tr>
<tr>
<td>Digital, digital, digital</td>
<td>Can we design with scalable single-ended digital circuits?</td>
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<tr>
<td>Clocking</td>
<td>Can we use poor quality oscillators and no PLLs?</td>
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</tbody>
</table>
UWB System Architecture

- **Non-coherent pulsed-UWB** can answer many of these questions

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Simple, low-power</td>
<td>Inherently less performance</td>
</tr>
<tr>
<td>Oscillator accuracy relaxed</td>
<td>Localization accuracy reduced</td>
</tr>
<tr>
<td>Fast turn-on times</td>
<td>Long preambles often required</td>
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Generating UWB Pulses Digitally

- **Simplified transmitter:**
  
  ![Simplified transmitter diagram](image)

  - Data can be modulated using OOK or **PPM**:
    
    ![Modulation example](image)

  - Symbol Rep. Period = $1/(Symbol Rate)$
Spectral Problems

- Spectral lines
- Large sidelobes
- Large low frequency components

![Graph showing spectral characteristics with FCC mask](image-url)
Spectral Scrambling

- BPSK scrambling to eliminate spectral lines
- Still have RF sidelobes + low frequency content

![Power Spectral Density (PSD) graph]

10dB reduction
Pulse Shaping

- Reduces sidelobes at RF
  - E.g.: raised-cosine shaping
  - Still have low-frequency content

![Graph showing pulse shaping and its implications](chart.png)
Dealing with Low Freq. Content

• Ideally, we want RF pulses with zero DC components

• We only have two levels to work with in single-ended digital CMOS (GND and VDD)
AC-Coupling: Freq. Domain

- First order filtering does not provide the required attenuation
  - Filter must have steep roll-off filter to meet FCC
  - Large off-chip component likely necessary
Eliminating Low-Freq. Content

- Dual paths capacitively combined:
  - Paths start off with *opposite* DC commons-modes
  - Generate differential low-frequency pulses

Capacitors charge and discharge at the same rate – net zero voltage change on output
Eliminating Low-Freq. Content

- Now, add in-phase RF tones to each path
  - In-phase RF signals propagate to output

Opposite common-modes cancel, close to zero low frequency content on the output
Dual Digital Power Amplifiers

Keeper transistors set the common modes during idle mode.

Pulse shaping achieved by dynamically enabling tri-state inverters.
Transmitter Architecture

All digital!

31.2MHz CLK

Start TX

Off-chip

E/L Detector

Freq. Tuning

Counter

DCO

LFSR

Pulse Shaping

CM High

CM Low

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Digitally Controlled Oscillator

- Single-ended structure
- Tunable from 3-to-5GHz
- Accurate to within 2800ppm (good enough for non-coherent)
Measured Transient Waveform

- Burst of five UWB pulses, individually BPSK-modulated

No large visible turn-on/off low-frequency transients
Measured Spectra

- Overlaid spectra in the 3.5, 4.0, and 4.5GHz channels

[Diagram showing overlaid spectra with FCC Indoor and Outdoor Mask regions and a note indicating all channels are FCC compliant.]
Measured Spectra

- Overlaid spectra with and without shaping and/or capacitive combining

Pulse shaping achieves 15-20dB of sidelobe attenuation
# Measurement Results

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Technology</td>
<td>90nm CMOS</td>
</tr>
<tr>
<td>$V_{\text{DD}}$</td>
<td>1.0V</td>
</tr>
<tr>
<td>Core area</td>
<td>0.07mm$^2$</td>
</tr>
<tr>
<td>Max Data Rate</td>
<td>15.6Mbps</td>
</tr>
<tr>
<td>Power Consumption (100kbps–15.6Mbps)</td>
<td>180µW – 4.8mW</td>
</tr>
<tr>
<td>Nominal Leakage Power</td>
<td>124 µW</td>
</tr>
<tr>
<td>Energy per pulse (16 pulses per burst)</td>
<td>19pJ/pulse</td>
</tr>
<tr>
<td>RF Voltage Swing</td>
<td>165 mV$<em>{pp}$ – 710 mV$</em>{pp}$</td>
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<tr>
<td>Turn-on time</td>
<td>7.2 ns</td>
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Figure of Merit

Energy/pulse [pJ] vs. Symbol Rate [Hz]

- Leakage
- This work
Conclusions

• All-digital Ultra-Wideband transmitter
  – Made possible by relaxed frequency tolerances
  – No static bias currents

• Energy efficient → 19pJ/pulse

• Small area → 0.07mm²

• No external filters required for FCC compliance

• Highly scalable in advanced CMOS processes
  – Future work: synthesizable transmitters

Acknowledgements: DARPA, NSERC
IC fabrication provided by STMicroelectronics