Low Power Low Cost RFIC Design for Pulse Based UWB

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2. Energy Efficient CMOS IR-UWB Transmitter/Receiver Design
3. Pulse based UWB for Radar
4. Future research direction
1. Introduction: UWB Signal

- Fractional bandwidth is greater than 0.2 or absolute bandwidth is greater than 500 MHz.
- Unlicensed spectrum 3.1 – 10.6 GHz.
- Low power emission ( < -41.3dBm/MHz) by FCC in 2002.

UWB Features

✓ Advantages
- Capability to deliver high data rate, proportional to bandwidth
- Low interference to existing applications due to low emission power
- Short range data communication (<10m)
- Robust to multipath, and fading (short pulse)
- Precise positioning (proportional to bandwidth)

✓ Challenges
- Wideband circuit techniques
- Power constraint design
- Interference from NB transmitters: How to alleviate interference while maximizing efficient use of the spectrum (notch filtering, spread spectrum, adaptive filtering, etc.)?
- Antenna design
Impulse radio UWB (IR-UWB)

Uses extremely short pulses with duration on the order of nanoseconds to transmit information

✓ Advantages:
- Low duty cycle of pulses, the transmitter power can be small
- Carrier modulation is not required, no up and down conversion
- No need of RF power amplifier
- Simple architecture, low cost
- Robust to multi-path fading

✓ Disadvantages:
- Difficult to generate and send extremely short pulses
- Timing accuracy for short pulse reception, synchronization in the receiver.

IR-UWB: Modulation

- PPM
- OOK
- PAM
- BPSK

Suitable for low data rate radio
UWB - Standard and Proposals

- Time Hopped UWB (IEEE 802.15.4a Standard)
  - Old concept (radar)
  - Impulse Radio (IR-UWB has been chosen for PHY)
  - Low/moderate data rate

- DS-CDMA UWB (IEEE 802.15.3a)
  - High data rate
  - UWB Forum supporting DS-UWB

- Multi-Band OFDM UWB (IEEE 802.15.3a)
  - High data rate
  - MBOA (MBO Alliance)

Applications of IR-UWB in WPAN

- Short range wireless communication, home network
- Sensor networks (USN)
- Radar and Sensing: for Transportation, Police, Medical imaging, Surveillance
- Tracking, localization like RF ID, TAG
FCC Spectrum Mask

- FCC Spectrum Mask and the frequency band of interest
- Three subbands with 520 MHz of bandwidth expected in this band

Choices of Architectures

- Motivation: Low Complexity, Low cost, Low power dissipation for low data rate communication

  - Conventional: Heterodyne or Direct conversion
    - High complexity
    - High power dissipation
    - Challenges in designing wideband building blocks

  - IR-UWB design approaches
    - Technology: CMOS
    - Transmitter: no need of power amplifier
    - No need of up/down conversion step
    - Receiver: Analog approach for low power, low complexity and high level of integration
Receiver Architecture Consideration for IR-UWB

- Coherent
  - Input signal distorted after antenna → template signal not matched with incoming signal
  - Synchronization issue → complex circuit

- RAKE
  - Require number of fingers (bank of correlators) to gather signal power

- Non-Coherent
  + Energy Detection
    Pros:  - OOK modulation, low complexity
          - Robust with clock jitter,
          - Relax distortion and phase non-linear requirement
    Cons:  - Decision problem regarding determine optimal threshold
           - Simplicity vs Noise
  + Transmitted Reference (Autocorrelation)
    Pros:  - 3dB better than ED
    Cons:  - Required long and precise delay time (for integration time)

2. CMOS Transceiver Design

Impulse Radio UWB Transceiver

- Proposed Pulse Generator
- Transmitter Design
- Energy Detection Receiver Design
A. IR-UWB System Approach

✓ Proposed non-coherent architecture for LDR IR-UWB

Link Budget: Loss

- Implementation loss budget

\[ NF = 12 \sim 14 \, \text{dB} \]

\[ LM = Pr - Pn - S(Eb/No) - I + PG \]

\[ P_{\text{min}} = Pr - LM \]

- Duty gain: \( BW/PRF \rightarrow \text{reduce average } NF \)
- Processing gain: \( PG=10\log(Np) \rightarrow \text{Improve SNR per symbol} \)
Design Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Unit</th>
<th>Target</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>3.1 ~ 5</td>
<td>Low UWB band</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>MHz</td>
<td>528</td>
<td>@ -10dB BW</td>
</tr>
<tr>
<td>PRF</td>
<td>MHz</td>
<td>16</td>
<td>Variable</td>
</tr>
<tr>
<td>Power Supply</td>
<td>V</td>
<td>1.5</td>
<td>TSMC 0.18um</td>
</tr>
<tr>
<td>Output Power</td>
<td>dBm</td>
<td>1.1</td>
<td>Peak Power</td>
</tr>
<tr>
<td>Amplitude</td>
<td>mV</td>
<td>150-200mV</td>
<td></td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ns</td>
<td>3~4</td>
<td>Real duration</td>
</tr>
<tr>
<td>Tx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>dB</td>
<td>36 ~ 60</td>
<td>-30dBm @ Squarer Input</td>
</tr>
<tr>
<td>Rx</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Primary goal is low power, low complexity, low cost

B. Tx Design: Issues

- Simplify architecture, only pulse generator without PA
- Support OOK modulation

Requirement
- Frequency range from 3.1 to 5.1GHz
- Three bands, 520MHz wide each

Challenges
- Satisfy FCC spectral mask
- Low power, low complexity
- Band switching capability
Pulse Generation Principle

✓ The key block in Tx

- Output pulse is generated by turning the oscillator ON/OFF
- Input square pulse train is used to control the oscillator operation
- Pulse BW is determined by input square pulse’s duration

“ The proposed Pulse Generator is Patent pending”

Proposed Pulse Generator

➢ LC based oscillator

- Two complementary switches SW1, SW2
- SW2 helps remove baseline current dissipation → save power
- SW1 helps to obtain desired pulse envelope → good pulse PSD
- Input square pulse train is used to ON/OFF the oscillator operation
Pulse Envelope Analysis

\[ V_{\text{env-rise}} = 2V_{\text{peak-steady}} \left( \frac{t_f - t_0}{(A_{OL} - 1)\omega_0} \right) \]

\[ t_r = t_s - t_f = 4.39 \frac{Q}{(A_{OL} - 1)\omega_0} \]

\[ = 4.39 \frac{1}{(A_{OL} - 1)\times CR_T} \]

\[ V_{\text{env-fall}} = V_{\text{peak}} e^{-t/\tau} \]

\[ t_s \approx \tau \ln 9 = 4.39 CR_T \]

Pulse envelope determines its PSD shape

Measurement Results

**Measured Single Pulse**

Pulse PSD in compliance with FCC Mask

**Measured Output Pulse Train**

> 25dB of sidelobe suppression
Performance Summary

✓ Feature
- Ultra low power
- No static DC current consumption
- Low complexity, low cost
- FCC compliant pulse
- Large amount of sidelobe suppression
- Suitable for multiband operation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measured Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>3.8 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>520 MHz</td>
</tr>
<tr>
<td>Peak power spectral density (PSD)</td>
<td>-41.3 dBm/MHz</td>
</tr>
<tr>
<td>Sidelobe suppression</td>
<td>&gt; 25 dB</td>
</tr>
<tr>
<td>$V_{dd}$</td>
<td>190 mV</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3.5 ns</td>
</tr>
<tr>
<td>$V_{dd}/I_{DD}$</td>
<td>1.5 V / 0 mA</td>
</tr>
<tr>
<td>Dynamic current at PRF of 100, 40, and 0.1 MHz</td>
<td>1120, 450, and 1.13 μA, respectively</td>
</tr>
<tr>
<td>Energy consumption per pulse</td>
<td>~ 16.8 pJ</td>
</tr>
<tr>
<td>Chip size</td>
<td>560 x 550 μm²</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 0.18 μm</td>
</tr>
</tbody>
</table>

Die size 560 μm x 550 μm


Tx IR-UWB Design

✓ Added feature
- OOK modulation
- Band switching capability

Proposed transmitter with OOK modulation

[Diagram of transmitter design]
Tx IR-UWB Measurement Results

OOK data stream and modulated pulse train

3 sub-bands with 500MHz BW

Tx Performance Summary

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measured Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-band center frequencies</td>
<td>3.2, 3.8, and 4.4 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>520 MHz</td>
</tr>
<tr>
<td>Peak power spectral density (PSD)</td>
<td>– 41.3 dBm/MHz</td>
</tr>
<tr>
<td>Maximum sidelobe suppression</td>
<td>&gt; 20 dB</td>
</tr>
<tr>
<td>$V_{pp}$</td>
<td>180 mV</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3.5 ns</td>
</tr>
<tr>
<td>Dynamic current at PRF of 0.1, 40</td>
<td>1.2, 486, and 1215 µA, respectively.</td>
</tr>
<tr>
<td>, and 100 MHz</td>
<td></td>
</tr>
<tr>
<td>Energy consumption per pulse</td>
<td>~ 18 pJ</td>
</tr>
<tr>
<td>$V_{DD}$</td>
<td>1.5 V</td>
</tr>
<tr>
<td>Chip size</td>
<td>580 x 680 µm²</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 0.18-µm</td>
</tr>
</tbody>
</table>
Transmitter Summary

✓ Main Advantages:
- Output pulse PSD compliant with FCC mask.
- No static current dissipation, only dynamic current which is proportional to PRF.
- Pulse center frequency can be changed, switchable for multi-band.
- Support OOK modulation.
- Simple circuit, very compact in size leading to low complexity low cost.


C. Energy Detection IR-UWB Receiver

- Simplicity, low cost and low-power
- Multiplier acts as Squarer for energy collection, no need of synchronization, avoid performance degradation due to timing jitter
- Gating ON/OFF the whole Rx to reduced the baseline power dissipation
- Able to recover the input data, acquisition based on Threshold estimation
- Narrow band interference can be blocked using BPF
- 1.5V supply in 0.18um CMOS, fully integrated with analog solution
IR-UWB LNA

- Wideband LNA is the most power hungry block in Rx
  - LC filter combined with cascode topology
  - lowest NF among wideband LNA design techniques
  - 1.5 Supply
  - Gating ON/OFF to reduce the baseline power consumption

IR-UWB LNA: Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Width [GHz]</td>
<td>3 ~ 8</td>
</tr>
<tr>
<td>Max Gain [dB]</td>
<td>10.5</td>
</tr>
<tr>
<td>NF [dB]</td>
<td>Min: 3.2 @ 4.9 GHz</td>
</tr>
<tr>
<td></td>
<td>Max: 3.9 @ 8 GHz</td>
</tr>
<tr>
<td>IIP3 [dBm]</td>
<td>0</td>
</tr>
<tr>
<td>Input matching (dB)</td>
<td>&lt; -12</td>
</tr>
<tr>
<td>Static current / Supply [mA / V]</td>
<td>3.5 / 1.5</td>
</tr>
</tbody>
</table>

Continuous LNA S-parameter, NF performance
ON/OFF Transient

- Clock is applied at the CG Transistor to reduce settling time (5ns)
- ON/OFF UWB LNA reserves wideband characteristic
- Voltage gain is around 12 dB

Gated Active Squarer

- Gilbert Cell based multiplier
- Higher Gain
- Gated current source with No static power dissipation
- Using square law

\[ V_{out} = kV_{in}^2 + DC - DC \]
\[ = kV_{in}^2 \]
Gated Active Squarer

- Average energy consumption per pulse (at 40MHz PRF) is 4.9pJ

Analog Integrator

- Integration is proportional to the amount of discharge on C_{1,2}
- C_{1,2} are fully charged at first
- Base band Input signal after squarer turns on M_{1,2} to create the path for discharging
- Higher input, larger discharging current
- S_{1,2} for reset for each integration
- S_{3} to remove the static DC dissipation
- Hold buffer is just amplifier

[From K. Vladimir]

Measurement Results

Measured output pulse trains of the Tx and Rx with the 100MHzOOK data pulse train at the input


Comparator Block

- Dynamic latched comparator
- No static power dissipation
- Resolution: few 10mV
- Extra Cap to remove the overshoot of clock

- Average power dissipation ~6.3pJ/pulse
Complete Energy Detection Receiver

- Pulse train from Tx act as input signal of the receiver to test the Rx operation

Transitory Timing Diagram

- Clock
- Input Data
- Pulse train
- Integrator output
- Output Data
Measurement Results: Transient

Data

Tx Output

Rx Output

160mV

Measurement Results: NF and S11

- Measured receiver front-end NF
- Measured receiver input matching S11

- Average NF is around 13.5dB over the 3-5GHz band
- S11 <-10 dB in 3-5 GHz range
Power Dissipation

- Static DC current: 450μA
- Average power dissipation: ~73pJ/pulse
- At low PRF, leakage and static DC currents dominate energy efficiency

Performance Summary

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measurement Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation frequency range</td>
<td>3-5 GHz</td>
</tr>
<tr>
<td>Subband bandwidth / Center Freq</td>
<td>528 MHz / 3.8 GHz</td>
</tr>
<tr>
<td>Min detectable input</td>
<td>-60 dBm (Sim)</td>
</tr>
<tr>
<td>S11</td>
<td>&lt; -10 dB in 3-5 GHz band</td>
</tr>
<tr>
<td>NF</td>
<td>~ 13.5 dB</td>
</tr>
<tr>
<td>Dynamic power dissipation</td>
<td>~73 pJ/pulse</td>
</tr>
<tr>
<td>Static DC current consumption</td>
<td>450 μA</td>
</tr>
<tr>
<td>$V_{DD}$</td>
<td>1.5 V</td>
</tr>
<tr>
<td>Core chip size</td>
<td>1.3 mm$^2$</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 0.18-μm</td>
</tr>
</tbody>
</table>

Chip photo of the Tx/Rx, 1.1 x 1.5 mm$^2$
Conclusions

✓ A new pulse generation technique is proposed
  - Energy efficient, ultra low power, low complexity
  - Fully satisfy FCC spectral mask
  - Multiband operation

✓ Energy Detection Receiver Architecture is best suited for low data rate (LDR) IR-UWB system
  - Low complexity, low power
  - No need accurate timing for synchronization
  - Relax accuracy requirement of pulse center frequency

✓ Building blocks
  - Highly integrated using CMOS
  - Energy efficient design by removing static current dissipation

Feasible energy efficient, low cost IR-UWB transceiver

RF Design Consideration

✓ Design and simulation
  - PVT and frequency shift are significant
  - Bond and pad models should be included
  - Separate analog and digital GND and VDD
  - Design with wide frequency tuning range
  - Confirmed with post-simulation is a must

✓ Layout and PCB
  - Small devices and short signal path: reduce parasitic
  - Guard ring for different blocks: RF and digital
  - The less numbers of Pads, the higher chance of chip working
3. IR-UWB for Radar

Transceiver architecture of the UWB pulse radar.

Operation

Fig. 1. System clock timing.

Fig. 2. System with input and output transient simulation.

4. Future Plan

- Research direction on IR-UWB
  - Improve the performance like the sensitivity: more gain stages
  - Include the Antenna for design and test
  - Other approach for Tx (digital synthesized pulser) and Rx (other than non-coherent ED)
  - Design with other alternative approach, such as differential transmitted correlation receiver (DTR)

Differential Transmitted Reference (DTR)

- Reduced freq, mismatch, relax ADC
- Provide good correlation template
- Avoid multipath signals

Fig. 1: DTR UWB Receiver with an envelop detection scheme

- Improve SNR and BER
- More accurate correlation, remove false alarm

- At the Cost of more complex and high power dissipation

Fig. 2: Fully Digital DTR UWB Receiver with an envelop detection scheme
Thank you !