UWB technology for wireless sensors in avionics

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Overview

• Data transmission concepts
• High data rate vs. low data rate
• TES LDR UWB development
• HDR systems – already here
What is Ultra-Wideband?

- A wireless "technology" to quickly transmit very large amount of digital data over an extremely wide frequency spectrum at very low power and over short distances.
Basics of UWB Signaling

Basics

Fractional bandwidth

\[ B_f = \frac{B}{f_c} = \frac{2 \cdot (f_u - f_i)}{(f_u + f_i)} > 20\% \]

or

Absolute bandwidth

\[ B > 0.5GHz \]

Properties

- Wide bandwidth
- Low average power spectral density
- High temporal resolution
- High information transmission capacity
The appeal of UWB

1. UWB Communication
   i. Higher data-rate
   ii. immunity to multi-path fading
   iii. narrowband interferers can be nulled with little performance degradation

\[ C = BW \cdot \log_2(1 + \text{SNR}) \]

- \( C \) represents capacity in bits
- \( BW \) is bandwidth
- \( \text{SNR} \) is signal-to-noise ratio

2. UWB Imaging
   i. Higher range resolution
   ii. Higher azimuth beam forming resolution

Resolution \( \propto \frac{1}{BW} \)
Introduction to UWB-IR (Impulse Radio)

- Works by transmitting a series of very low power pulses
  - Very short pulse duration (<2ns)
  - Uniform or non-uniform of inter-pulse spacing
- Pulse Repetition Frequency (PRF) can range from hundreds of thousands to billions of pulses/second
- Information spread over a wide spectrum w/ low PSD
IEEE 802.15.4a (UWB-IR) technology

- Alternate PHY for IEEE 802.15.4
  - Based on UWB-IR (Impulse Radio) technology
  - Based on the “same” 802.15.4 MAC
    - Smooth porting of existing Zigbee or other standard/proprietary stacks

- Main benefits vs. existing 2.4GHz 802.15.4 PHY:
  - Precise ranging/locationing capability
    - <30 cm accuracy
  - Inherent security (LPI/LPD)
  - Low active power consumption:
    - Duty cycle <3.2%
  - Scalability:
    - Performance/complexity (receiver structure) trade-off
  - Data rate flexibility: 110kbps to 6.8/27.24 Mbps
  - Multipath robustness
Global UWB regulations for LDR systems

• USA (FCC):
  – Approved since Feb 2002 (indoor/outdoor)
  – Unlicensed band 3.1 to 10.6GHz @ -41.2dBm/MHz

• Europe (ECC stepped ruling plan):
  – Step 1 (approved since February 2007):
    • 6 to 8.5 GHz @ -41.2dBm/MHz, indoor and outdoor (no infrastructure)
    • 3.4 to 4.8GHz @ -41.2dBm/MHz with LDC (see next slide)
  – Step 2:
    • 3.1-3.4GHz & 8.5-9GHz: work in progress to open with adequate protection mechanisms
    • Operation in vehicles/railways

• Japan (MIC) – indoor only
  – Approved since August 2006
  – 7.2 to 10.25GHz @ -41.2dBm/MHz
  – 4.2 to 4.8GHz @ -41.2dBm/MHz until Dec 2008
  – 3.4-4.8GHz & 6-7.25GHz (FPU): work in progress to open with adequate protection mechanisms

• South Korea (RRL) and China (SRMC)
  – see next slide
  – Approved in South Korea since March 07 & expected approval date for China: Q407
802.15.4a Band Groups 1 & 2

ECC TG3

3.4-4.8 GHz

Double Duty Cycle limitation
5% over 1 sec,
0.5 % over 1 Hour

Max Ton = 5msec
Mean Toff > 38 msec

DAA Required
(Waived in 4.2-4.8 GHz
until the end of June’10) for SK

EU w/o & w/ tbd mitigation sch
Japan w/o & w/ tbd mitigation sch
South Korea w/o & w/ tbd mitigation sch
China w/o & w/ tbd mitigation sch

DAA Option2 for South Korea in 3.1-4.8 GHz:
Transmission period < 5ms, Stop period >= 1s

Transmission period < 5ms, Stop period >= 1s

for SK
IEEE 802.15.4(a) application positioning

- **Video**
  - WiMedia™
  - Wi-Fi®
  - Bluetooth™

- **Data**
  - 802.11g
  - 802.11a
  - 802.11b
  - Wireless Networking

- **Voice**
  - Wireless Video Applications
  - Wireless Data Applications

- **Monitors**
  - Wireless Sensors

- **Effective throughput**
  - Faster
  - Slower

- **Range**
  - Closer
  - Farther

- **IEEE 802.15.4(a)**
IR-UWB implementation solutions

Digital
- High performance
- Low complexity analog design

Coherent
- Complex digital baseband
- High power consumption
- Short range
- High clock precision requirement

HDR
- Longer range
- Lower power consumption

Non-coherent
- Very low complexity digital baseband
- Very low power consumption
- Low clock precision requirement

LDR
- Quite long range
- Lower performance
- Challenging analog design
- High complexity digital baseband
- High power consumption
- High clock precision requirement
Simplified UWB transceiver architecture

- Buffer
- Pulse Generator
- Clock Generator
- FPGA Baseband
- ADC
- Receiver
- Tx buffer
- RS encoder
- SECDED encoder
- SHR Insert
- PPM
- Processor MAC APPL
- Rx buffer
- SECDED decoder
- RS decoder
- AGC
- Packet detection
- Synchronization
- Phase 1
- Phase 2
Xilinx Virtex IV Pro platform was selected as general platform for PHY, MAC and application development and demonstration. VirtexII Pro devices combine programmable logic and a PowerPC into a single platform.
UWB-IR RFE test chip & demonstrator

- Feasibility concept: RFE in SiGe 0.25um (2.25-2.75V) & baseband on a FPGA
  - Frequency band of operation: 3-5GHz (US, EU, Japan, SK)
  - Based but not fully-compliant with 802.15.4a UWB-IR
    - Compliant pulse burst & RRC pulse, convolutional/RS en/decoder
- Non-coherent Receiver
  - Energy detection scheme but not-cost and not-performance optimized
- Demonstrator system inc lite version of 802.15.4 MAC
  - Inc rigid & flexible monopole/dipole/directional UWB antennas
UWB IC test boards developed during WISE
Pulse generator

Generates a pair of pulses in duration of main clock half-period. Suitable for On-off keying or Pulse-Position Modulation. The signal can be used for up-conversion for use in other frequency bands (e.g. 60 GHz). Requires out of chip filtering to fit in regulation mask.

Master-slave D-type flip-flop (MS-DFF) with substractor
- Pseudo “Manchester-encoded” data input up to 500 Mbps
- Rise and fall edges of encoded data input generate pulses
- Pulse duration & position dependent on clock frequency/phase offset
  • 1GHz to 10GHz reference clock input
– Energy detection based non-coherent receiver
– Gain chain control distributed before and after mixer that acts as square law device in order to optimize the dynamic range
– Energy detection performed by bank of 8 Integrators that follow square-law device
– Embedded digital logic performs OOK demodulation. PPM demodulation can be performed using external circuitry
– By controlling the system clock phase better resolution in time can be achieved what is important for ranging applications
Non-coherent receiver implementation

- Receiver chain operating between 3-5 GHz
- Simple implementation based on pulse energy collection:
  - Mixer (square law):
    - Input signal (3-5GHz) & output signal (0-1 GHz)
- Dynamic range: 62dB
  - LNA: 16dB, FGA: 1 to 17dB, VGA: -10 to 36dB (3dB steps)
UWB Demonstrator system

- Sensor
- App CPU & upper MAC
- HW MAC
- BBP
  - SHR Gen
  - BPM mod
  - Data burst Gen
  - Int0
  - Synchronization
  - Int1
  - AGC
- Comparator
- AFE
  - Pulse generator
  - LPF
  - PLL
  - ADC
  - PGA
  - LPF
  - PGA
  - LNA

- Xilinx ML405 board (230x150 mm)
- Daughter AFE board (100x75 mm)
- UWB antennas (44x41 mm)

- Sensor module (72x45 mm)
- RS232
PHY parameters

- Platform development for data communication in sensor networks using UWB technology
- PHY implementation
- Digital part:
  - IEEE 802.15.4a alike
    <Preamble><SFD><PhyHeader><Data>
  - Data rate: 110kbit/s, 850kbit/s
  - Packet size up to 127 bytes
- RF part:
  - Band 3-5 GHz, Central frequency 4.5 GHz
  - Bandwidth 500 MHz
  - Total transmit power (max) -10dBm
  - Receiver sensitivity (PER 1%) –70dBm
Transmitter Output

- One packet at Tx output with preamble, SFD, and data part (timebase of lower part 50ns/div).
Digital BB PHY Implementation

- Xilinx FPGA Device: Virtex 4, XC4VFX20
- Slices: 8544
- Speed Grade: -10
- Synthesis Tool: XST of ISE 9.2 / Synplify Pro

<table>
<thead>
<tr>
<th>Part</th>
<th>LUT</th>
<th>FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY without FEC (RS, SECDED)</td>
<td>2914</td>
<td>1294</td>
</tr>
<tr>
<td>FEC</td>
<td>1671</td>
<td>1162</td>
</tr>
<tr>
<td>% of total 17088 LUT/FF</td>
<td>27%</td>
<td>15%</td>
</tr>
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LDR outlook

• PHY layer implementation of the non-coherent UWB
• Hardware implementation of analogue front-end circuitry
• Digital PHY has been implemented verified on VHDL and circuit level, with accompanying measurements on ML405 development platform.
• Test application for PHY evaluation
• The same digital platform is going to be used in MAC and application implementation and will enable the system integration.
• Further work will also address improvement of PHY layer performance by implementing interference rejection-mitigation processing.
LDR UWB performance for the market

- IEEE-802.15.4a full conformance
- Transceiver + HMAC + AES encryption engine on the same die:
  - CMOS090 preferably
- Mandatory PRF only: 15.6M & 3.90MHz & all associated data rates
- Normal & wideband signal support (0.5GHz/1.3GHz):
  - Larger absolute bandwidth & higher SNR (localization accuracy) + longer range
  - Larger relative bandwidth for better penetration
- No pulse spectral shaping or optional TD pulse combo
- -91 dBm sensitivity for 100kb/s:
  - Likely to be a coherent receiver
- Adjustable resolution window (down to sub 3ns) for sub-meter ranging capability
- Die size:
  - <9.5mm2 for the whole Trx/HMAC/AES function
- Power consumption
  - <18mA @3V (average) for both Tx/Rx, STB < 2uA
- Preamble repetition: 64 & 1024 at a minimum (4096 as a nice to have if non-coherent approach gets selected), 8-symbol SFD only
- No private ranging and no preamble time-multiplexing
Partial band implementation (in this case 2 GHz bandwidth) eases implementation and allows smaller antennas and smaller system size.

- Usage of simple detection techniques relaxes demanded Eb/No

- Channel capacity of 1 Mbit/s is provided at distance of 10m even for severe channel conditions (n=3.5)

- Channel capacity of 1 Kbit/s is provided at distance of 80m even for severe channel conditions (n=3.5)

Figure shows channel capacity in function of link distance for several propagation channels.
In terms of positioning, UWB-HDR could be seen as “3rd generation Bluetooth.”
Main technology benefits for UWB-HDR

• Extremely high speed but short range technology
  – Ideal for high speed data transfer (file synchronization between 2 devices with short transmission time) as well as bandwidth-intensive & time-sensitive applications (High definition audio/video streaming)

<table>
<thead>
<tr>
<th>Transmission Rate</th>
<th>Transfer time for a 512 MByte file (*)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 Mbps</td>
<td>46s</td>
<td>8-10m</td>
</tr>
<tr>
<td>200 mbps</td>
<td>25s</td>
<td>5-6m</td>
</tr>
<tr>
<td>480 Mbps</td>
<td>11s</td>
<td>2-3m</td>
</tr>
</tbody>
</table>

• Unlicensed technology with global footprint:
  – Approved in the US (indoor & outdoor use), Japan (indoor use only at the present time), Europe (indoor use), South Korea (indoor/outdoor)
  – Pending: China (aligned w/ European rules )

(*) Assuming a 20% overhead
Main technology benefits for UWB-HDR

• Potentially longer battery life (mJ/MByte)
  – Perfectly suited for mobile devices

<table>
<thead>
<tr>
<th>Standard</th>
<th>Max Transmission rate (Mbps)</th>
<th>IC power (mW)</th>
<th>mJ/MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>11</td>
<td>200</td>
<td>145</td>
</tr>
<tr>
<td>802.11g</td>
<td>54</td>
<td>250</td>
<td>37</td>
</tr>
<tr>
<td>BT 2.0</td>
<td>3</td>
<td>60</td>
<td>160</td>
</tr>
<tr>
<td>UWB-HDR (WiMedia)</td>
<td>480</td>
<td>600</td>
<td>10</td>
</tr>
</tbody>
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• Relatively low complexity & small form factor (25x55 mm)
• Robustness:
  – Strong immunity to interference and multipath fading
Other technology benefits for UWB-HDR

• Coexistence with other communication devices
  – Low emitted transmit power (noise-like signal) compounded with some “Detect&Avoid” mitigation technique will cause little or no interference to other radio systems operating in the same environment

• Ranging/location awareness capability
  – Could potentially locate another UWB-HR device with a 30 cm range accuracy (for WiMedia compliant devices)
Conclusion

• UWB systems provide large variety of solutions for communication and sensing applications without need for operation licenses
• In scope of the WISE project a LDR UWB demonstrator system has been developed
• During the WISE project the standardization and regulation processes in Europe have been closed
• Current status of the LDR development is still not mature enough for commercial applications
• High data rate UWB systems already exist on the market as excellent solution for high speed data transfer over short distances