UWB for Wireless Sensor Networks
Outline

• Technical background
• Why is it good? Applications of UWB
• Standards activities
• Implications for sensor networks
• Resources and Conclusions
What is UltraWideBand?

- Communication that occupies more than 500 MHz of spectrum
- Communication with fractional bandwidth of more than 0.2
- More possibilities than pulses

**Time-domain behavior**

- Narrowband Communication
- Frequency Modulation

**Frequency-domain behavior**

- Ultrawideband Communication
- Impulse Modulation

(FCC Min=500Mhz)
UWB Signals

• Earliest form of radio communication – Hertz, 1870s

• Impulse followed by shaping filter and Chirp signals
  – Best suited for non-coherent pulse transmissions

• Synchronous pulse synthesis
  – Best suited for frequency/time-agile systems and synchronous systems

• OFDM and COFM
  – Best suited for fine PSD tailoring
Basic Impulse Information Modulation

Pulse length ~ 200ps; Energy concentrated in 2-6GHz band;
Voltage swing ~100mV; Power ~ 10uW

- **Pulse Position Modulation (PPM)**

- **Pulse Amplitude Modulation (PAM)**

- **On-Off Keying (OOK)**

- **Bi-Phase Modulation (BPSK)**
UWB Spectrum

- FCC ruling permits UWB spectrum overlay

- FCC ruling issued 2/14/2002 after ~4 years of study & public debate
- FCC believes current ruling is conservative
- Worldwide regulations differ – Japan, EU, Asia…
Theoretical capability & application spaces

Free Space UWB Channel

- Channel Capacity: $C$
- Cutoff Rate: $\tilde{R}_o$

Very High Data Rate Applications

Low Data Rate and/or Location Tracking Applications

Channel Capacity or Cutoff Rate [Mb/s]

Link Distance [m]

- $f_c = 6.85$ GHz
- $F_{PRF} = 20$ Mp/s
- $D_f G_f = 75$ nW/MHz
- $B = 7500$ MHz
- $B = 1500$ MHz
- $G_R = 1$
- Rx-NF = 3 dB
- $P_M = 10^{-1}$
- $P_M = 10^{-8}$

IBM Zurich Research Laboratory

Applications

- Theoretical capability & application spaces
Theoretical Data Rates over Range

UWB shows significant throughput potential at short range.

UWB shows significant throughput potential at short range.
Performance Analysis with encoding rules
So why is UWB so interesting?

- **7.5 Ghz of “free spectrum” in the U.S.**
  - FCC recently legalized UWB for commercial use
  - Spectrum allocation overlays existing users, but its allowed power level is very low to minimize interference

- **Very high data rates possible**
  - 500 Mbps can be achieved at distances of 10 feet under current regulations

- **Simple CMOS transmitters at very low power**
  - Suitable for battery-operated devices
  - Low power is CMOS friendly
  - “Moore’s Law Radio” --Data rate scales with the shorter pulse widths made possible with ever faster CMOS circuits

- **Low cost**
  - Nearly “all digital” radio?
  - Integration of more components on a chip (antennas?)
Advantages

- **Range/bitrate scalability**
  - Extremely good W/Mbit communication

- **Localization**
  - Sub-centimeter resolution using pulse leading edge detection
  - passes through building blocks, walls, etc. (LOS not required)

- **Robustness to interference and multipath**
  - Path delay $>>$ pulse width => possible to resolve different signal paths
  - Use a RAKE receiver to turn multipath into a consistent advantage
  - Consistent range

- **Radio as a sensor (radar)**
  - Localization and multipath robustness are a consequence of this
  - Channel characterization reveals absorptive/reflective sources and their positions

- **Difficult to intercept in traditional ways**
  - Low interference (that’s why we allow it, after all)
  - Very low spectral energy density

- **Size**
  - 4.5 mm$^2$ in 90 nm process for high data rate designs
  - integration of more components onto a single chip
Ultra Wideband Characteristics

• Extremely low transmission energy (less than 1mW)
• Very high bandwidth within short range (200Mbps within 10m)
• Extremely difficult to intercept
  – Short pulse excitation generates wideband spectra – low energy densities
  – Low energy density also minimizes interference to other services
• Multipath immunity
• Commonality of signal generation and processing architectures
• Radar
  – Inherent high precision – sub-centimeter ranging
  – Wideband excitation for detection of complex, low RCS targets
• Geolocation/Positioning
  – Sub-centimeter resolution using pulse leading edge detection
  – passes through building blocks, walls, etc. (LOS not required)
• Low Cost
  – Nearly “all-digital” architecture
  – ideal for microminiaturization into a chipset
• Frequency diversity with minimal hardware modifications
UWB Advantages

- **Capacity**
  - possibility of achieving high throughput
- **Low power & Low cost**
  - Can directly modulate a baseband pulse
  - Can be made nearly all digital
  - High capacity with lower Tx power levels
- **Fading robustness**
  - Wideband nature of the signal reduces time varying amplitude fluctuations (?)
  - Relatively immune to multipath cancellation effects
    » Path delay ~ 1ns > pulse duration
    » But don’t we build RAKE just to rebuild the multipath thing ?
    » What about ISI ?
- **Position location capability**
  - Developed first as radar technology (!)
- **Flexibility**
  - Can dynamically trade-off throughput for distance
UWB Applications

• Stream DVD content to HDTVs simultaneously.

• Wirelessly synchronize appliance clocks.

• Connect high-data rate peripherals.

• Move huge files between digital cameras, camcorders, and computers.

• Military applications (radars, penetrate walls, etc.)
UWB Application 1: WPAN

• Desktop and Laptop PCs
  – High res. printers, scanners, storage devices, etc
  – Connectivity to mobile and CE devices

• Mobile Devices
  – Multimedia files, MP3, games, video
  – Personal connectivity

• CE Devices
  – Cameras, DVD, PVR, HDTV
  – Personal connectivity

One PHY for Personal Computing, Consumer Electronic and Mobile, Wireless Personal Area Connectivity
UWB Application 2

- Positioning, Geolocation, Localization
  High Multipath Environments
  Obscured Environments

- Communications
  High Multipath Environments
  Short Range High Data Rate
  Low Probability of Intercept/Interference

- Radar/Sensor: MIR (motion detector, range-finder, etc.)
  Military and Commercial: Asset Protection
  Anti-Terrorist/Law Enforcement
  Rescue Applications
Related Standards

- IEEE 802.15 : Wireless Personal Area Network (WPAN)
- IEEE 802.15.1 : Bluetooth, 1Mbps
- IEEE 802.15.3 : WPAN/high rate, 50Mbps
- IEEE 802.15.3a: WPAN/Higher rate, 200Mbps, UWB
- IEEE 802.15.4 : WPAN/low-rate, low-power, mW level, 200kbps
PHY: Single-Band and Multi-Band

- Single-Band Implementation
  - One pulse occupies the whole BW.

- Multi-Band Implementation
  - The 7.5GHz are divided into multiple bands.
  - Information is independently encoded in the different bands.
  - The lower limit of 500MHz must be maintained.
Single-Band and Multi-Band
Single-Band and Multi-Band

Multi-band signals transmitted at different discrete times. The sequence repeats at each symbol. Center frequencies are shown in the vertical axis.
Why prefer Multi-Band?

- Adaptive band selection → Avoids interference.

- Low complexity → Smaller transceiver cost.

- Low circuit frequency → Power conservation.

Sacrifice one band for co-existence
Direct Sequence Ultra Wideband

- The DS-UWB system uses the DSSS technique, which successfully emerged as the PHY layer of choice in 3G cellular networks. This technique employs BPSK and QPSK modulation and a MAC that combines FDM, TDM, and CDM.

- In the DS-UWB system, as shown in Fig., the 3.1--10.6 GHz band is divided into a low band from 3.1 to 4.9GHz and an optional high band from 6.2 to 9.7 GHz. The bandwidth of the high band is twice the bandwidth of the low band, resulting in shorter time-domain pulses in the high band. The 4.9--6.1 GHz band is purposely neglected to avoid interference with IEEE 802.11a devices operating in the 5 GHz U-NII bands.
Multiband Orthogonal Frequency-Division Multiplexing

- MB-OFDM, the technology developed by the Multiband OFDM Alliance (MBOA), uses the OFDM technique, which emerged as the technology of choice for IEEE 802.11 WLAN standards operating in the U-NII 2.4 and 5 GHz unlicensed bands, and in the UWB 3.1--10.6 GHz unlicensed bands.

- Following this approach, the spectrum is divided into 15 bands each of width 528 MHz. In each band, a 128-point OFDM system using QPSK modulation is implemented to limit the required precision of mathematical operations and make digital implementation at ultrahigh sampling rates feasible.

- The MAC is time--frequency multiple access (TFMA), which combines the time- and frequency diversity benefits of FHSS and DSSS into one MAC technique.
802.15.3a – high data rate WPAN standard

• **Direct sequence (DS-UWB)**
  – Championed by Motorola/XtremeSpectrum
  – Classic UWB, simple pulses,
  – 2 frequency bands: 3.1-4.85GHz, 6.2-9.7GHz
  – CDMA has been proposed at the encoding layer
  – Spectrum dependent on the shaping filter – possible differing devices worldwide

• **Multiband Orthogonal Frequency Division Multiplexing (OFDM)**
  – Intel/TI/many others
  – Similar in nature to 802.11a/g
  – 14 528MHz bands (simplest devices need to support 3 lowest bands, 3.1GHz – 4.7 GHz)
  – Spectrum shaping flexibility for international use
### IEEE 802.15.3a Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate</td>
<td>110 and 200 Mb/s</td>
</tr>
<tr>
<td>Range</td>
<td>30 and 12 ft</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>100 and 250 mW</td>
</tr>
<tr>
<td>Bit error rate</td>
<td>1e-5</td>
</tr>
<tr>
<td>Co-located piconets</td>
<td>4</td>
</tr>
<tr>
<td>Interference capability</td>
<td>Robust to IEEE systems</td>
</tr>
<tr>
<td>Co-existence capability</td>
<td>Reduced interference to IEEE systems</td>
</tr>
</tbody>
</table>
UWB & radar

Constant Stream (1 MHz) of Transmit Pulses

Transmit Signal

Return Signal

Target

Scope, A/D, etc.

MPR Timing

MPR Tx

IF Amplifier

Sample and Hold

Transmit Time

Receive Time

0 μs
0 μs + 10ps
1 μs
1 μs + 20ps
2 μs
2 μs + 30ps

Result Represents Target Return

Advantaca, MIR for motes!
UWB Radar
UWB Altimeter & Obstacle Avoidance Radar

Design Characteristics
- UWB altimeter & obstacle avoidance system
- Spectrally shaped waveform design
- L-band altimeter
  - 1.0W peak, 400 MHz instantaneous BW
  - 1.3-1.7 GHz, 27% fractional BW
  - 25 μW average power @ 10kpps
  - ~5000 feet range, < 1 foot resolution
- C-band collision/obstacle avoidance sensor
  - 0.25W peak, 500 MHz instantaneous BW
  - 5.4-5.9 GHz, 8.9% fractional BW
  - 5 μW average power @ 10kpps
  - High sensitivity – 1/4” diam. wire @ 300’
UWB Radar

UWB Collision Avoidance Backup Sensor

Design Characteristics
- C-band UWB backup sensor
  - 0.25W peak, 500 MHz instantaneous BW
  - 5.25-5.85 GHz, 10.8% fractional BW
  - 5 μW average power
- High-speed, dual tunnel detector
- Range
  - 1 - 50 feet against human target
  - 1 - 200 feet against pickup truck
- Clutter resistant
- Extremely low false alarm rate – range gate cutoff

“Smart” license plate
- C-band collision avoidance radar
- L-band tag (vehicle-to-vehicle & vehicle-to-roadside)

Multispectral Solutions, Inc.
UWB Radar
UWB Intrusion Detection

Design Characteristics

- L-band Through-the-wall sensor
  - 1.0W peak, 400 MHz instantaneous BW
  - 1.3-1.7 GHz, 27% fractional BW
  - 25 μW average power @ 10kpps
  - 0-200 feet (through wall)

- L-band Intrusion Sensor
  - 4.0W peak, 400 MHz instantaneous BW
  - 1.3-1.7 GHz, 27% fractional BW
  - 100 μW average power @ 10kpps
  - 1000 feet against human target
MBOA: vision for wire replacement

- Big players backing MBOA
- Inclusion in many consumer electronic devices as wire replacement
  - Cameras, MP3 players, etc.
  - Chipsets & motherboard support
- Split from IEEE process
  - Will become an industry standard
  - Perhaps post-facto IEEE ratification
802.15.4a – alternate PHY for 802.15.4

• Addresses the following
  – Globally deployable
  – Compatible / interoperable with 802.15.4
  – Longer range
  – Higher reliability
  – Ranging/localization support
  – Lower latency & support for mobility
  – Low cost

• Current UWB systems not quite suitable
  – 90 nm CMOS is expensive, 200 mW is a lot of power

• Still in early stages
  – Proposals due Jan. 2005!
  – DS-UWB a major contender (Motorola)
  – Chirp Spread Spectrum another cool tech (Nanotron)
  – Many axes for diversity: Basic tech (2.4 v. UWB), ranging (UWB v. CSS v. Phase-based ranging), pulse shapes, channel arbitration (CSMA v. CDMA)
## Comparison of 2.4G and “UWB band”

<table>
<thead>
<tr>
<th></th>
<th>2.4</th>
<th>UWB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot of potential interferers</td>
<td>• Lot of potential interferers</td>
<td>• Currently cleaner</td>
</tr>
<tr>
<td>BW=80MHz, max error 1.5m</td>
<td>• BW=80MHz, max error 1.5m</td>
<td>• BW&gt;500MHz, max error &lt;0.3m</td>
</tr>
<tr>
<td>One channel</td>
<td>• One channel</td>
<td>• Several channels</td>
</tr>
<tr>
<td>High power allowed</td>
<td>• High power allowed</td>
<td>• Low power allowed</td>
</tr>
<tr>
<td>Worldwide regulation</td>
<td>• Worldwide regulation</td>
<td>• US only (currently)</td>
</tr>
<tr>
<td>Outdoor, no use restriction</td>
<td>• Outdoor, no use restriction</td>
<td>• Outdoor, handheld only + more</td>
</tr>
<tr>
<td>Easier implementation</td>
<td>• Easier implementation</td>
<td>• Tougher implementation</td>
</tr>
</tbody>
</table>

- We may have both… We may define one PHY in two bands (see 15.4 as an example)
- The 2.4 band will be different than the other only by some parameters (e.g. pulse shape if one uses impulse radio)
A QUANTITATIVE COMPARISON OF TECHNOLOGIES

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>DATA RATE (Mb/s)</th>
<th>OUTPUT POWER (mW)</th>
<th>RANGE (meters)</th>
<th>FREQUENCY BAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrowband ISM</td>
<td>&lt;0.1</td>
<td>10-20</td>
<td>30</td>
<td>433 MHz</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>1-2</td>
<td>100</td>
<td>100</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>IrDA</td>
<td>4</td>
<td>100 mW/sr</td>
<td>1-2</td>
<td>Infrared</td>
</tr>
<tr>
<td>HDR UWB (Hotspot)</td>
<td>100-500</td>
<td>1</td>
<td>10</td>
<td>3.1-10.6 GHz</td>
</tr>
<tr>
<td>IEEE 802.11a</td>
<td>54</td>
<td>40-800</td>
<td>20</td>
<td>5 GHz</td>
</tr>
<tr>
<td>IEEE.802.11b (WiFi)</td>
<td>11</td>
<td>200</td>
<td>100</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>IEEE 802.11g</td>
<td>54</td>
<td>65</td>
<td>50</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>LDR/MDR UWB</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;10</td>
<td>3.1-10.6 GHz</td>
</tr>
</tbody>
</table>

Source: IEEE Spectrum 9.03
# A Relative and Approximate Comparison of System Complexity and Cost

![Comparison Diagram](image)

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>ROBUSTNESS</th>
<th>COEXISTENCE</th>
<th>LOCALIZATION</th>
<th>COMPLEXITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISM</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>IrDA</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>HDR UWB (Hotspot)</td>
<td>Medium-High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>IEEE 802.11a</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>IEEE 802.11b (WiFi)</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>LDR/MDR UWB</td>
<td>Medium-High</td>
<td>High</td>
<td>Medium-High</td>
<td>Medium-Low</td>
</tr>
</tbody>
</table>
Antennas

- Generally omnidirectional
- Mass producible
- Challenges
  - Size
  - Gain
  - Efficiency
- Smallest currently described antenna: 16x13.6x3mm
- For size may need to go to higher frequencies (24 and 60 GHz)
  - Range suffers

ETRI, 30x30mm, 3.1-8.3 GHz, omni

Hitachi, 30x30mm, 3.1-6.5 GHz
Power characteristics

- High data rate designs (MBOA)

<table>
<thead>
<tr>
<th>Block</th>
<th>90 nm</th>
<th>130 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX AFE (110Mb/s)</td>
<td>76 mW</td>
<td>91 mW</td>
</tr>
<tr>
<td>TX Total (110 Mb/s)</td>
<td>93 mW</td>
<td>117 mW</td>
</tr>
<tr>
<td>RX AFE (110Mb/s)</td>
<td>101 mW</td>
<td>121 mW</td>
</tr>
<tr>
<td>RX Total (110 Mb/s)</td>
<td>155 mW</td>
<td>205 mW</td>
</tr>
<tr>
<td>RX Total (200 Mb/s)</td>
<td>169 mW</td>
<td>227 mW</td>
</tr>
<tr>
<td>Deep Sleep</td>
<td>15 µW</td>
<td>18 µW</td>
</tr>
</tbody>
</table>

- Power efficient per bit, but...
  - Receive ~ 2x transmit
  - Unclear startup times
  - Receiver: unclear scaling with data rate
    » Linear extrapolation – 60-130 mW data rate independent power consumption
  - Passive wakeup schemes not applicable
    » Cf. low probability of detection
Existing Products/Eval kits

- Wisair UB501 RF/UB 531 BB (MB-OFDM, April 2004)
- Freescale (Motorola)/XtremeSpectrum XS110
  - FCC certified
- PulsON 200 - UWB Evaluation Kit
- AEtherWire localizer (do they still exist??)
- A slew of MIR applications
  - Collision avoidance, fluid level detection
- Intel/TI are not shipping anything yet
CSEM LDR UWB WPAN/WLAN TECHNOLOGY

IST FP5 URSafe project
General Atomics Multi-Band Transceiver Prototype
Commercial UWB

Æther Wire & Location (USA) (http://www.aetherwire.com)
• Low power, miniature, distributed position location (“Localizers”) and communication devices.
• DARPA Projects (Defense Advanced Research Projects Agency)
Intel (USA) (http://www.intel.com/technology/itj/q22001/articles/art_4.htm)
• UWB for communicating between devices, instead of networking PCs (wireless USB);
Pulse-Link (USA) (Fantasma Networks IP) (http://www.pulselink.net/default.htm)
• Very active on patents and IP;
• Development of UWB platform for wireless video, short and long (km) range communication, positioning.
Time Domain (USA) (Pulse-ON technology) (http://www.time-domain.com)
• Wireless Communications (Home WLAN), Precision Location and Tracking and High Definition Portable Radar
• Already a 5-chip chipset: PulseONÆÊ chipset (IBM foundry)
MultiSpectral Solutions, Inc (MSSI) (USA) (http://www.multispectral.com)
• High-speed communications networks and data links, collision and obstacle avoidance radars, precision geolocation systems for personnel location and mapping, intelligent transportation systems.
XtremeSpectrum (USA) (http://www.xtremespectrum.com)
• First product announced for middle 2002
McEwan Technologies (USA) (http://www.mcewantechnologies.com)
• McEwan Technologies licenses its wideband and ultra-wideband (UWB) radar sensor technology to industry. Thomas McEwan is the inventor of the MIR Rangefinder UWB radar developed at the Lawrence Livermore National Laboratories (LLNL).
Wisair (Israel) (http://www.wisair.com)
Bibliography

• Young Man Kim. Ultra Wide Band (UWB) Technology and Applications. Ohio State University NEST group.
• Robert Fontana. Recent Applications of Ultra Wideband Radar and Communications Systems. Multispectral Solutions
• Roberto Aiello et. al. Understanding UWB – Principles and Implications for Low power Communications. March 2003, doc. IEEE 802.15-03/157r1
• Anuj Batra et al. Multi-band OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a. IEEE 802.15-03/268r3
• Reed Fisher et al. DS-UWB Physical Layer Submission to 802.15 Task Group 3a. IEEE P802.15-04/0137r3
• Benoit Denis. UWB Localization Techniques. IEEE 802.15-04/418r1
• Jeffrey Reed et al. Introduction to UWB: Impulse Radio for Radar and Wireless Communications. www.mprg.org
Other sources

- UltraWideBand Technology for Short or Medium Range Wireless Communications; Jeff Feorster, Evan Green, Srinivasa Somayazulu, David Leeper Intel Architecture Labs; http://www.intel.com/technology/itj/q22001/articles/art_4.htm
- Ultra-wideband Technology for Short-Range, High-Rate Wireless Communications; Jeff Foerster, Intel Labs; http://www.ieee.or.com/Archive/uwb.pdf
- Introduction to UWB: Impulse Radio for Radar and Wireless Communications; Dr. Jeffrey Reed, Dr. R. Michael Buehrer, David McKinstry; http://www.mprg.org/people/buehrer/ultra/UWB%20tutorial.pdf
- Ultra Wideband (UWB) Frequently Asked Questions (FAQ); http://www.multispectral.com/UWBFAQ.html
- Ranging in a Dense Multipath Environment Using an UWB Radio Link Joon-Yong Lee and Robert A. Scholtz (University of Southern California), IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 20, NO. 9, DECEMBER 2002.
- Experimental Results from an Ultra Wideband Precision Geolocation System, Robert Fontana, Multispectral Inc., Ultra-Wideband, Short-Pulse Electromagnetics, 1/1/2000
Bandwidth: key to ranging

(Approximate) Range Resolution vs. Bandwidth (AWGN Channel)
(Based on Square Root Raised Cosine Filtering)

125 MHz for 1m resolution
Heisenberg at work