Ultra-Wideband (UWB) Wireless Communications

Robert Qiu
Associate Professor
Tennessee Technological University
rqiu@IEEE.ORG

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Outline

- Introduction
- UWB Principles
- IEEE 802.15.3a/IEEE 802.15.4a
  - Receiver Design Challenges
  - OFDM and Pulse-based UWB
- Physics-Based Optimum Receiver Structures
  - Communication Theory and Physics (Gabor 1953)
- Conclusion
Wireless Networking Systems Lab

- Established Aug. 1 2003
- UWB/3G/4G physical layer and cellular network levels
- Radio Propagation and Channel Modeling
- Receiver analysis and design
- Hardware prototyping
- Working with industrial and DOD R&D organizations.
- 10+ years R&D experiences in wireless communications
Mobile Devices Market Segmentation

- Modules - Embedded Apps
- Telematics / Telemetry

Add-On Devices

Data Devices w/ Integral Wireless

Business / Smart Phones

Basic Phones

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Nokia 3330

PDQ

Ericsson R380

Blackberry

Palm

Greater Multi-Media Capability
Larger Displays / Touch-Screens and Keyboards

Multi Wireless Modes & Generally Higher Data Rates

HandSpring Visor, Spring Board Modules

Ericsson R380 Smart Phone

Palm

Palm

Nokia 3330

PDQ

Ericsson R380

Blackberry

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Greater Multi-Media Capability
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Multi Wireless Modes & Generally Higher Data Rates

HandSpring Visor, Spring Board Modules
3G & UWB Combining Air Interface

Complementing Technologies

Wide Area Network

Local Area Network

Personal Area Network

WLAN

UWB

3G

WCDMA

EDGE

CDMA2000

Not to Scale
1 Wide Area cell = ~10 000 WLAN cells

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The UWB Home Wireless Network

Broadband services: Cable, xDSL, Satellite, Terrestrial

IEEE 802.15.3a
UWB Communications & Sensor Networks

Applications
- Remote surveillance, threat detection
- Video to the foxhole/battlefield
- High-resolution location services

Key Technologies
- Ultra-wide band systems
- Mobile, adhoc networks
- Data fusion / synthesis

Open Research Issues
- Pulse Propagation
- Optimum Receiver
- Test-bed development / trials

Environments
- Real-time
- Distributed
- Dynamic
- Hostile

IEEE 802.15.4a
DARPA Networking in Extreme Environments (NETEX)

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What Is Ultra-Wideband (UWB)?

- **Definition (In radar, etc)**
  
  \[
  2 \frac{f_u - f_l}{f_u + f_l} \geq 0.25 = 25\%
  \]

  Where:
  
  \( f_u = \) upper 10 dB down point
  \( f_l = \) lower 10 dB down point

- Or greater than **500 MHz (FCC Feb 2002)**

- At FCC Part 15 powers (a few tens of **microwatts** total - across several GHz), cannot be reliably measured below 10 dB down points

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7.5 GHz UWB Spectrum Allocated by FCC 02/2003

Source: IBM Research

- Conventional carrier modulation
- Direct sequence spread spectrum
- Ultra-wideband

Frequency (GHz):
- GSM-900
- IS-54
- IS-95
- AMPS
- GSM-1.8
- DECT
- GSM-1.9
- IMT-2000
- 802.11b
- Bluetooth
- HomeRF
- 802.15.4
- IEEE 802.11a
- ETSI Hiperlan
- ARIB MMAC

Ultra-wideband (10.6 GHz)
Time Modulated Ultra-Wideband—An Example

- Not a sinewave, but millions of pulses per second
- Time coded to make noise-like
  - Channelization
  - Anti-jam
  - Smooths spectrum
- Pulse position modulation

\[ \delta = 125 \text{ ps} \]

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UWB

- FCC allocated 7.5 GHz unlicensed spectrum (2002)
- Requires shift in thinking
- Short “Pulses” are building blocks.
- Fading is not a major issue
- Too many resolvable quasi-static pulses
- Pulse distortion
- Deterministic solutions from Maxwell’s equations
- UWB radio may be good for low data rate (<a few Mb/s) applications (IEEE 802.15.4a)
Experimental Setup

0.5 ns pulse
UWB Pulse Spectrum

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Indoor

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Outdoor

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Flat grass ground
Reflection from buildings
Representative Measurements (USC)

- Blocked LoS
- Hold Recvd Clear LoS
- Hold Recvd Blkd LoS

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Per-Path Pulse distortion

- Channel distortion
  - Pulse delay
  - per-path pulse distortion
- A new phenomenon for UWB.
- Caused by frequency-selectivity of the channel medium.
UWB Receiver Design Challenges

- Energy collection versus complexity (cost)
  - RAKE may be too costly
- Time synchronization
- Inter-symbol interference (ISI)
  - 10 symbols overlapping for indoor (100 Mbps)
  - Symbol-level equalizer
- Non-coherent detector
  - Transmitted reference
  - Energy-detector
Why UWB and why spectrum agility?

- **Why UWB for IEEE 802.15.3a?**
  - UWB technology is uniquely suited for high-rate, short range access
    - Theoretical advantages for approaching high rates by scaling bandwidth
    - Newly allocated unlicensed spectrum (7.5 GHz) that does not take away from other narrowband systems (licensed or unlicensed)
    - CMOS implementations now possible at these higher frequencies ➔ All CMOS architecture

- **Why spectrum agility for a UWB solution?**
  - Just because the FCC allows UWB to transmit on top of other services does not mean we should!
    - Government regulations should be broader than industry requirements
  - Spectrum usage and interference environment changes by country location, within a local usage area, and over time
    - Enable adaptive detection and avoidance strategies for better coexistence and possible non-contiguous spectrum allocations for flexible regulations in future
  - Allow for simple backward compatibility and future scalability
Flexible Spectrum Use

- Center frequencies chosen for ease of implementation
- 440 MHz band separation for improved flexibility
- ~538 MHz wide bands to best utilize spectrum

(based on regulation and geographical location)
Communications and Physics (Gabor 1953)

- The electromagnetic signals used in wireless communication are subject to the general laws of radiation and propagation.
- Communication theory developed mainly mathematical lines, taking for granted the physical significance of the quantities which figure in its formalism.
- Communication is the transmission of physical effects.
- Hence communication theory should be considered as a branch of physics.
Physics-Based Channel Model and Optimum Receiver Structures

- **Goal:** Connect the time-domain electromagnetics and communication (information) theory.
- **Mission:** Develop the optimum detection theory of physical signals governed by Maxwell’s Equations.
- **Tasks:**
  - Channel model models based on experiments and theory (analytical and computer simulations)
  - Optimum detection theory and information theory
  - Sub-optimum receivers
  - Hardware system (transceiver) prototyping
Per-Path Pulse Distortion Based UWB Channel

\[
(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}) E(t, t'; r, r') = -\delta(t - t') \delta(r - r')
\]

\[
(\nabla^2 + k^2) E(k, r, r') = \delta(r - r')
\]

\[
\alpha_n = -\frac{1}{2} \quad \text{for a single edge diffraction}
\]

Multiple diffraction must be included!
Concept of UWB Pulse Distortion due to Diffraction

\[ h(\tau) = \sum_{n=1}^{N_{GO}} A_n \delta(\tau - \tau_n) + \sum_{n=1}^{N_{2GO}} B_n R_n(\tau) \otimes \delta(\tau - \tau_n) + \sum_{n=1}^{N_{GTD}} C_n g_n(\tau) \otimes \delta(\tau - \tau_n) + \sum_{n=1}^{N_{GO+GTD}} D_n [R_n(\tau) \otimes g_n(\tau)] \delta(\tau - \tau_n) \]

UWB pulse distortion is a physical phenomenon !!!

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Physics-Based Multipath Channel Model

Turin’s Model
Since 1956

\[ h(\tau) = \sum_{n=1}^{N} A_n e^{j\phi_n} \delta(\tau - \tau_n) \]

\[ h_n(\tau) = \text{per path impulse response} \]

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Diffraction-Based Pulse Shape Distortion

Diffracted Signal $d(t)$ and Template Signal $v(t)$

alpha = -1: 0.25: 0 (bottom to top)

- alpha=0 $$\Rightarrow$$ Incident Waveform

Red dashed $$\Rightarrow$$ Template Pulse $v(t)$
Per-Path Impulse Response
(CharACTERIZING THE PULSE WAVEFORM)

\[ h_n(\tau) = \begin{cases} 
\xi(\tau_\alpha - \tau) \sum_{n=0}^{\infty} \frac{C_n}{n!} (\tau_\alpha - \tau)^n, & \tau < \tau_\alpha \\
\eta(\tau_\alpha - \tau) \sum_{n=0}^{\infty} \frac{D_n}{n!} (\tau_\alpha - \tau)^n, & \tau > \tau_\alpha
\end{cases} \]

\[ H_n(\omega) = \sum_{n=0}^{\infty} \left\{ \frac{D_n}{n!} \frac{1}{(j\omega)^n} \int_0^{\infty} \eta\left(\frac{t}{j\omega}\right) t^n e^{-t} dt - \frac{C_n}{n!} \frac{1}{(-j\omega)^n} \int_0^{\infty} \xi\left(\frac{t}{-j\omega}\right) t^n e^{-t} dt \right\} \]

Example:

\[ \xi(\tau) = 1/\sqrt{\tau} \quad \eta(\tau) = 1/\sqrt{\tau} \]

Pulse diffracted by a PEC Edge
Comparison of Exact Solution with Asymptotic GTD/UTD Solutions

Direct=0.35  Reflected = 0.65  Diffracted= 0.92735

Cross-Correlation

UTD  Keller  Felsen Exact

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UWB Pulse Shape Transform Caused by Diffraction

\[ H_n(j\omega) = (j\omega)^{\alpha_n} \]
Physics-Based Optimum Receiver Structures

Received signals $r(t) \rightarrow$ Matched Filter $y^*(-t) \rightarrow$ Sampler $t = nT_s \rightarrow$ MLSE (Viterbi)

Mathematical equations:

- $r(t) = \sum_{n=-\infty}^{\infty} a_n y(t - nT_s) + n(t)$
- $y(t) = x(t) \otimes h(t)$
- $h(t) = \sum_{n=1}^{N} A_n h_n(t) \otimes \delta(t - \tau_n)$
- $x(t) = \text{transmitted pulse shape}$

Inter-symbol Interference or Multiuser Detection

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Summary

- UWB is one of the most promising technologies
  - 7.5 GHz unlicensed spectrum from 3.1-10.6 GHz
  - Volume products will be shipped in 3-4 years

- UWB is good for both short-range (10-30m) and long-range (100-1000m)

- Per path pulse distortion in a UWB channel is one of the major potential problems in system design
  - Experimental measurements verified
Thank You!

Robert Qiu  rqiу@IEEE.ORG