Short-Range Ultra-Wideband Systems

R. A. Scholtz
Principal Investigator

A MURI Team Effort between
University of Southern California
University of California, Berkeley
University of Massachusetts, Amherst
Features of a Rationale

FCC Compliance ➠ Low Power Applications
  ➠ Short-Range and/or Low Data Rate Applications

For a Given Center Frequency:
  “Ultra-Wide Bandwidth” ➠ Very Large Bandwidth
  ➠ Fine Time Resolution
  ➠ Ranging is a Killer Application

For a Given Bandwidth:
  “Ultra-Wide Bandwidth” ➠ Very Low Center Frequency
  ➠ Good Propagation through Materials

These are comparative/relative statements.
More Consequences of UWB Constraints

Fine Time Resolution \( \Rightarrow \) \( T_{unc}/T_{res} \) Large \( \Rightarrow \) Long Acquisition Times

“Ultra-Wide Bandwidth” \( \Rightarrow \) Channel Distortions \( \Rightarrow \) Matched Filter Design Problems
\( \Rightarrow \) Receiver Design for Efficient Energy Capture

Very Large Bandwidth \( \Rightarrow \) Large Frequency Diversity \( \Rightarrow \) Multipath Mitigation

FCC Compliance \( \Rightarrow \) Power Optimization Requirements
\( \Rightarrow \) Design for Spectral Flatness/Shaping
High-Level Questions

Are answers for UWB questions simply bandwidth-scaled from narrowband designs, or is there a paradigm shift in approach/viewpoint?

Is UWB radio the best choice for a given application?

Is asynchronous UWB radio an effective use of the RF spectrum?
Overview of the Proposal
The Research Team

University of Southern California
Bob Scholtz, Keith Chugg, Won Namgoong
(propagation, systems, circuits)
UltRa Lab

University of California, Berkeley
Bob Brodersen, David Tse
(circuits, information theory)
Berkeley Wireless Research Center

University of Massachusetts, Amherst
Dave Pozar, Dan Schaubert, Dennis Goeckel
(antennas, systems)
Antennas Laboratory

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Goals

- **Channel Characterization:** UWB propagation and interference models for short-range propagation scenarios

- **Antenna Design:** Basic limits on radiation and reception of UWB signals; time-domain characterization; practical antennas for integrated UWB tagging systems.

- **System Design:** Issues uniquely affected by large bandwidth, fine time resolution, large frequency diversity, e.g., rapid sync acquisition, designs and architectures for efficient recovery of signal energy, low power-density modulation, ranging in dense and resolvable multipath.

- **Implementation:** UWB architectures and topologies for single-chip implementation in CMOS; simultaneous optimization of antennas, algorithms, and circuits for performance and power consumption.

- **Test Beds:** Hardware and simulation test beds for UWB systems and components; cooperate with government agencies in testing efforts.
Focus

• The study of UWB systems that require both position location and communication as operational requirements.

• To ground research in reality, environments in which we can perform measurements and experiments will be pursued.

• Parameters for design related to RF tags, e.g., IFF systems, shipping and logistic systems, status monitoring, battlefield asset tracking, traffic monitoring, medical tagging.
Impact on Universities and Education

Five meetings so far

- New Relationships between Team Members
- New Relationships with Industry
- Improved Infrastructure and Capabilities of Labs
- Training of Graduate Students in UWB Technology
- Annual Workshops on UWB Technology
- Student Exchange

Fall 2002 workshop jointly sponsored with Intel
Where We Want To Be In Two More Years

Understand the issues, answer questions posed in proposal
(basic research and cross-fertilization)

Characterize, optimize, construct, and test critical/novel parts of a UWB radio
(fabrication feasibility)

Have the ability to do reasonable sanity checks on a design:
- Develop good performance prediction techniques
- Produce believable link budgets
- Produce reasonable battery power budgets
(system feasibility)

MURI Team
- Scholtz
- Brodersen
- Namgoong

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For more information, copies of papers, etc., visit the UltRa Lab’s web site at

http://ultra.usc.edu/New_Site/

The MURI team has a page at this web site.
FCC Regulations
FCC Expected to Deal Blow to Ultra-Wideband

Telecom: Faster wireless may face constraints. Some worry the technology could cause airwave interference.

By JUBE SHIVER Jr.
TIMES STAFF WRITER

WASHINGTON—In a setback to computer and consumer product makers, federal regulators today are expected to tightly constrain a breakthrough wireless technology that backers had hoped would usher in a new era of wireless networking and tracking.

Proponents had boasted that the TimeDomain Corp., a Huntsville, Ala., company that has been developing the technology.

In addition, the FCC staff is expected to oppose most commercial and consumer applications of ultra-wideband tracking technology out of fear it might fall into the wrong hands.

“We think a conservative approach is appropriate at the outset,” a top administration official said. “We can make adjustments later.”

Although military and public safety personnel will be able to use ultra-wideband’s radar capabilities to see through walls and other obstructions, the FCC staff wants to limit commercial applications to

FCC Approves New Wireless System

Federal regulators approved the use of a new wireless technology that could help rescue workers find people buried in rubble or locate stresses in the side of a bridge, overcoming fears it would interfere with important navigation aids.

The Federal Communications Commission voted unanimously to approve limited use of ultra-wideband technology for handheld wireless communications, ground-penetrating radar and vehicle collision avoidance systems.

The FCC approved the marketing and operation of products using UWB technology but limited it to the range above the 3.1-gigahertz frequency and, in some cases, restricted use to law enforcement, scientific researchers and certain industries such as construction.

Reuters
FCC UWB Device Classifications

Authorizes five classes of devices – different limits for each:

- **Imaging Systems**
  1. Ground penetrating radars, wall imaging, medical imaging
  2. Thru-wall Imaging & Surveillance Systems

- **Communication and Measurement Systems**
  3. Indoor Systems
  4. Outdoor Hand-held Systems

- **Vehicular Radar Systems**
  5. Collision avoidance, improved airbag activation, suspension systems, etc.
FCC First Report and Order Authorizes Five Types of Devices

<table>
<thead>
<tr>
<th>Class / Application</th>
<th>Frequency Band for Operation at Part 15 Limits</th>
<th>User Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications and Measurement Systems</td>
<td>3.1 to 10.6 GHz (different “out-of-band” emission limits for indoor and outdoor devices)</td>
<td>No</td>
</tr>
<tr>
<td>Imaging: Ground Penetrating Radar, Wall, Medical Imaging</td>
<td>&lt;960 MHz or 3.1 to 10.6 GHz</td>
<td>Yes</td>
</tr>
<tr>
<td>Imaging: Through-wall</td>
<td>&lt;960 MHz or 1.99 to 10.6 GHz</td>
<td>Yes</td>
</tr>
<tr>
<td>Imaging: Surveillance</td>
<td>1.99 to 10.6 GHz</td>
<td>Yes</td>
</tr>
<tr>
<td>Vehicular</td>
<td>24 to 29 GHz</td>
<td>No</td>
</tr>
</tbody>
</table>
UWB Emission Limits for GPRs, Wall Imaging, & Medical Imaging Systems

Operation is limited to law enforcement, fire and rescue organizations, scientific research institutions, commercial mining companies, and construction companies.

Source: www.fcc.gov

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UWB Emission Limits for Thru-wall Imaging & Surveillance Systems

Operation is limited to law enforcement, fire and rescue organizations. Surveillance systems may also be operated by public utilities and industrial entities.

Source: www.fcc.gov
UWB Emission Limit for Indoor Systems

Source: www.fcc.gov

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UWB Emission Limit for Outdoor Hand-held Systems

Source: www.fcc.gov
Basic Power Computations

FCC bound: 500 microvolts/meter/(MHz)^{1/2} @ 3 meters
  = -41.25 dBm/MHz EIRP

FCC band: 3.1 GHz to 10.6 GHz = 7500 MHz
  - 41.25 + 38.75 = -2.5 dBm EIRP (bound)

\[ R_b \left( \frac{E_b}{N_{tot}} \right) = \left( P_t G_t \right) \left( \frac{1}{L_{prop}} \right) \left( \frac{4\pi R^2}{G_r \lambda^2/4\pi} \right) \eta_{rec} / (N_o + I) \]
## UWB Band: Power Comparison

<table>
<thead>
<tr>
<th></th>
<th>500 MHz</th>
<th>5GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center Frequency</strong></td>
<td>500 MHz</td>
<td>5GHz</td>
</tr>
<tr>
<td><strong>Relative bandwidth</strong></td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td><strong>Relative EIRP/MHz</strong></td>
<td>1</td>
<td>6.25</td>
</tr>
<tr>
<td><strong>Relative power gain</strong></td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Net power advantage</strong></td>
<td>2 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Unknowns:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interference</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Propagation Advantage</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td><strong>Time Resolution</strong></td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Assumptions:** same fractional bandwidth, identical (scaled) antennas
Sanity Check: Link Budgets
Sanity Check: Comparative Communication Link Budgets (1)

- EIRP: same
- Data Rate: same
- Frequency: NB carrier at UWB center frequency
- Antenna pattern: dipole
- Antenna losses: same
- Propagation: free space
- External interference: none
- Reception: Matched filter/correlator in both
- Receiver noise temperature: same
- Modulation: same binary antipodal

⇒ Approximately equal bit error rates

UWB advantage in range/time resolution
Sanity Check: Comparative Communication Link Budgets (2)

- EIRP: same
- Data Rate: optimized
- Frequency: NB carrier at UWB center frequency
- Antenna pattern: dipole
- Antenna losses: same
- Propagation: free space
- External interference: none
- Reception: Matched filter/correlator in both
- Receiver noise temperature: same
- Modulation: optimized

UWB advantage: Higher data rate and/or lower bit error rate

UWB advantage: Range/Time resolution
Sanity Check: Comparative Communication Link Budgets (3)

EIRP: same
Data Rate: same
Frequency: NB carrier at UWB center frequency
Antenna pattern: dipole
Antenna losses: same
Propagation: free space
External interference: other CDMA users
Receiver: Matched filter/correlator in both
Receiver noise temperature: same
Modulation: optimized CDMA

➡️ UWB advantage in number of users
UWB advantage in Range/Time resolution
## Sanity Check: Comparative Communication Link Budgets (4)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NB+</th>
<th>UWB+</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP: FCC regulation</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Data Rate: same</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency: NB carrier at UWB center frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna pattern: dipole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna losses: mismatch problems</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Propagation: terrestrial indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fading Margin</td>
<td>🔄 UWB+ (propagation)</td>
<td></td>
</tr>
<tr>
<td>Receiver Mismatch</td>
<td>🔄 NB+ (receiver design)</td>
<td></td>
</tr>
<tr>
<td>External interference: other radio systems</td>
<td>🔄 NB+</td>
<td></td>
</tr>
<tr>
<td>Interference mitigation: SS PG and excision</td>
<td>🔄 UWB+</td>
<td></td>
</tr>
<tr>
<td>Receiver noise temperature: same</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation: optimized spread spectrum</td>
<td></td>
<td>🔄 UWB advantage in Range/Time resolution</td>
</tr>
</tbody>
</table>

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Research Motivators

- UWB antennas and impedance matching
- UWB propagation modeling and measurements
- Interference excision over ultra-wide bandwidths
  - Handling on-chip interference
  - Efficient receiver processing
- Computationally efficient ranging algorithms
  - UWB link and network synchronization
- Realistic position location schemes for UWB emitters
- UWB node teaming for long-distance transmission
Precision Location

Pairwise Ranging
or
Hyperbolic Navigation

Surveyed
Rover

Precision Time and
Time-Interval Group

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Retrodirective Timing Issues
The UWB Equivalent of Phase Conjugation

No position location knowledge required

Distant Transceiver

wavefront

Precision Time and Time-Interval Group

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Timing Issues

- What is the effect of multipath and blockages on position location and retrodirective array processing using UWB signals?

- What is the effect of multipath and blockages on precision time and time-interval systems?

- What is the effect of UWB time duplexing on PTTI systems?

- How can we characterize the timing noise on voltage-controlled clocks?
Propagation-Related Efforts

- Propagation Data Base on Web - Intel supported
  - Polarization measurement efforts
- Upgrading equipment to the 3.1-10.6 GHz band
  - Folded dipole antenna study
- Development of response envelope models

Propagation models needed by NETEX program
IEEE 802.15 UWB standard effort
Representative Measurements I

Transmitted Signal

Outdoor Rcvd Clear LoS

Office Rcvd Clear LoS

- 200 ns

- 20 ns

- 1 ns
Representative Measurements II

<table>
<thead>
<tr>
<th>Office Rcvd Blkd LoS</th>
<th>Hold Rcvd Clear LoS</th>
<th>Hold Rcvd Blkd LoS</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>200 ns</td>
<td>200 ns</td>
</tr>
<tr>
<td>1 ns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Energy Response Functions

\[ E_1(t+dt) = E_1(t) - a_1 E_1(t) dt - x_{10} E_1(t) dt - x_{12} E_1(t) dt + x_{21} E_2(t) dt \]

\[ E_2(t+dt) = E_2(t) - a_2 E_2(t) dt - x_{20} E_2(t) dt - x_{21} E_2(t) dt + x_{12} E_1(t) dt \]