Mission-Critical Networking and Situation-Awareness

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Introduction / Terminology

- Mission-Critical Operations
  - Military
  - Emergency Response
  - Search and Rescue
    - Urban
    - Mine Incidents

- Situation-Awareness
  - Wireless Sensor Networks
    - Sensing the Environment
    - Physiological Monitoring of Workers
  - Indoor Localization and Tracking
Presentation Outline

- Real-Time Deployment of Multihop Relays ("Breadcrumbs") for Communication Range Extension
- An Overview of Indoor Localization Research at NIST
Real-Time Deployment of Multihop Relays ("Breadcrumbs") for Communication Range Extension
Motivation & Objectives

Motivation
- Public safety operations require reliable, rapidly-deployed communications
- Frequent wireless dead spots encountered inside large buildings, in underground tunnels, and other difficult radio environments

Objectives
- Maintain network connectivity for reliable communications
- Minimize impact on user’s mission
Approach

- Extend signal coverage through a multihop network that relays data/voice between first responders and Incident Command (IC)
- “Breadcrumb” relays (●) are automatically deployed at appropriate points along path, creating a multihop network
- Link layer and routing protocols provide reliable two-way communications, transfer of user vital signs, etc.
Technical Challenges

- Automating the deployment process...When/where to deploy relays?

- Reliable end-to-end transmission
  - Link-quality-sensitive route metric
  - Link and network layer retransmission

- Adapting to changes in link quality and topology
  - Timely route updates
  - Power control
Questions & Overview

Questions to Address

- How to measure the quality of a wireless link reliably and efficiently? (in order to determine when to deploy a new relay)
- What criteria should be used to trigger deployment?
- Is real-time on-the-fly deployment feasible? (Will it result in well-connected networks capable of reliable communications?)

What Follows

- Approach to real-time deployment
- Overview of 900 MHz and 2.4 GHz prototypes
- Test results of 2.4 GHz prototype
- Next steps
Packet Reception Rate vs. Average Received Signal Strength at 900 MHz

Packet Reception Rate vs. Average Signal-to-Noise Ratio at 2.4 GHz

- Collected over a fixed topology on single floor of an office building
- Clear threshold ⇒ RSS/SNR as indicator of link reliability
Mobile Link Measurements

- Measured by a mobile rx moving at fixed velocity down an office corridor
- \( \Rightarrow \) Approaches needed to cope with multipath fading
Overview of Deployment Algorithm

1. Mobile node probes channel every $\Delta$ sec.
2. Measures SNR of each Probe ACK (bidirectional)
3. If average SNR of each responding relay is less than a threshold, trigger deployment of new relay.

![Diagram of deployment algorithm](image)
900 MHz Experimental Platform

- Crossbow MICA2 Mote (MPR400CB)
  - ChipCon CC1000 transceiver at 916 MHz
  - 8-bit ATMega128L 7.37 MHz processor
  - 128 kB program memory, 4 kB SRAM
  - Powered by 2 AA batteries
  - 5 dBm max. RF power

- Multi-Sensor Module (MTS310)
  - Light, Temperature
  - Acoustic, Sounder
  - 2-Axis Accelerometer
  - 2-Axis Magnetometer
900 MHz Prototype System

Applications
- Continuous monitoring of Mobile Node’s sensors
- Two-way text messaging between Base and Mobile
- Display approximate location of Mobile Node
  - using RFID location tags

Technical Features
- Rapid link measurement w/ adaptive probing
- Real-time deployment w/ local placement assistance
- Modified DSDV routing with link quality metric
- Power control
2.4 GHz Prototype Breadcrumb

Gumstix motherboard
- 400 MHz Linux computer
- 16 MB Flash
- 64 MB SDRAM
- 8 cm × 2 cm

Wifistix expansion board
- IEEE 802.11b/g
- Open source driver
- 8 cm × 2 cm

Lithium polymer battery & charger
Deployment Monitor

- Next breadcrumb to be deployed continuously probes and measures link quality to its neighbors.

- Deployment monitor on mobile display:

- When that breadcrumb is deployed, next breadcrumb is set to probe.
2.4 GHz Prototype System Features

Applications
- Two-way voice between Base and Mobile Node
- Continuous monitoring of Mobile Node’s sensors
- Display approximate location of Mobile Node
  - using RFID location tags
- Video

Technical Features
- Rapid link measurement
- Real-time deployment w/ local placement assistance
- IEEE 802.11 PHY/MAC
- OLSR routing w/ ETX metric
- IP support
Test in NIST AML

- March 24 & 26, 2008
- Buildings 217, 218, and 219
Deployment Example

- 8 breadcrumbs deployed
- IEEE 802.11 2-Mbps data rate
- OLSR
  - HELLO period 0.5 s
- During deployment:
  - 28 kbps full-duplex VoIP call between IC and FR
  - Ping every second
- After deployment:
  - 10 MB file transfer
  - Audio recording
During Deployment

11% Packet Loss Rate
During Deployment: Packet Losses

11% Packet Loss Rate
During Deployment: Round-Trip Time

![Graph showing round-trip time vs. number of hops]

- Average round-trip time (blue circles)
- Median round-trip time (red crosses)

Number of hops on the x-axis, average/median round-trip time (ms) on the y-axis.
File Transfer

- 9-hop route
- 10 MB file
- Transmission time: 8 min 3 s
  - Average throughput: 166 kbps
  - Peak throughput: 232 kbps
- Simultaneous ping:
  - Average RTT: 173 ms
  - Packet loss rate: 36%
Audio

- Reading of Gettysburg Address
- Linphone VoIP connection with 16 kHz Speex codec at 28 kbps

Simultaneous Ping Results

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Min/Avg/Max RTTs (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>29/41/55</td>
</tr>
<tr>
<td>200</td>
<td>35/54/100</td>
</tr>
<tr>
<td>220</td>
<td>40/58/94</td>
</tr>
</tbody>
</table>

Bldg 217
Stairwell 3

IC

5

6

Bldg 218-SB

219-SB

Bldg
Ongoing and Future Work

- Systematic study of link quality measurement techniques
- Routing protocol improvements
  - Smoother route transitions
  - Incorporate new link quality metrics
- Feasibility of image/video over deployed multihop network
- Integration of Inertial Navigation Unit
  - To provide estimate of user’s location between RFID tags
- Network simulation of cognitive radio breadcrumbs


An Overview of Indoor Localization Research at NIST
Program Scope

- Performance evaluation of various ranging, direction estimation, and localization techniques through simulations and prototyping
- Evaluation of COTS localization products
- Participation in IEEE & NFPA standardization activities
- Basic research and development of new localization techniques
NIST Location System

- Developed in 2003.
- Works based on Received Signal Strength (RSS) measurements and IEEE 802.11b technology.
- Locates mobile nodes within 2 meters in 80% of queries.
- Software available for download at: www.antd.nist.gov/wctg/NISTlocation/locationdemo.htm
Extension to Use of Spatial Spectrum

Given a directional antenna, spatial spectrum is basically a two-dimensional graph of the received power versus azimuth of main lobe. Each point on this graph indicates the received signal strength when the main lobe of the antenna is directed toward the corresponding azimuth.

Conjecture: Spatial Spectrum, as measured by a receiver, is unique per layout and transmitter location.
## Performance Results

<table>
<thead>
<tr>
<th></th>
<th>Radio Map Res: 1x1</th>
<th>Radio Map Res: 2x2</th>
<th>Radio Map Res: 3x3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AP=1</td>
<td>AP=2</td>
<td>AP=3</td>
</tr>
<tr>
<td><strong>SS – L1</strong></td>
<td>0.83</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td><strong>SS – L2</strong></td>
<td>1.03</td>
<td>0.86</td>
<td>1.06</td>
</tr>
<tr>
<td><strong>SS – EMD</strong></td>
<td>1.05</td>
<td>1.04</td>
<td>1.02</td>
</tr>
<tr>
<td><strong>SS – PPD</strong></td>
<td>1.90</td>
<td>1.50</td>
<td>1.45</td>
</tr>
<tr>
<td><strong>SS – HD</strong></td>
<td>2.30</td>
<td>1.59</td>
<td>1.55</td>
</tr>
<tr>
<td><strong>SS – KL</strong></td>
<td>2.64</td>
<td>1.35</td>
<td>1.34</td>
</tr>
<tr>
<td><strong>RSS – L2</strong></td>
<td>15.78</td>
<td>4.37</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Average position error in meters (array size: 8, step-size: 5 deg)
Localization Using Relative Signal Strength

Relative ordering of the received signal strengths from several sensors located inside a building can be used to identify the location of a mobile. This approach potentially provides better performance with imperfect layout information or noisy signal strength measurements.
Simulation Testbed of an RF-Based Indoor Localization Systems Using a Ray-Tracing Tool

Given a specific building layout and a transmitter location, a ray-tracing tool predicts the multipath profile of the channel at any given point. A simulation testbed as shown below is used to evaluate the performance of different ranging/AOA algorithms that are used in a localization process.
Multiple Test scenarios have been chosen to represent various canonical propagation conditions that normally occur in indoor environments.
Overall Performance

CDF for DOA Estimation

- WISE MUSIC (ULA)
- WISE MUSIC + Spatial Smoothing (ULA)
- WISE MUSIC (UCA)
- WISE Maximum Likelihood (UCA)
- WISE Beamforming (UCA)
- EDX MUSIC (ULA)
- EDX MUSIC + Spatial Smoothing (ULA)
- EDX MUSIC (UCA)
- EDX Maximum Likelihood (UCA)
- EDX Beamforming (UCA)
Error w.r.t. the Strongest Ray
Range Error (m)

Nominal Parameters:

BW = \{0.05, 0.1, 0.2, 0.5, 1\} GHz
Fc= \{0.6, 2.4, 5\} GHz
Noise = \{No, Moderate, High\}
Antenna height = \{0.2, 1.8\} m
Can TOA-Based Localization Meet First Responders’ Expectations?

**Test Parameters:**

- **BW**: \{0.05, 0.1, 0.2, 0.5, 1\} GHz
- **Fc**: \{0.6, 2.4, 5\} GHz
- **Noise**: \{No, Moderate, High\}
- **Antenna height**: \{0.2, 1.8\} m

![Graph showing range error vs. TX-RX distance]
Evaluation of COTS Products

• Evaluated three UWB ranging/localization systems:
  – Multispectral Solutions, Inc. (MSSI) Pal650 System
  – MSSI ranger designed and developed for CERDEC
  – Time Domain, Inc. PulseON P210 Radio System

• Evaluations were done in four NIST buildings using many deployment scenarios.
Overview of UWB Ranging

- UWB cited as most promising technology for precision location systems (cm error)
- A standardization effort is completed through the IEEE 802.15.4a Task Group incorporating ranging into their UWB radio
- Several companies (MSSI, Time Domain, Aether Wire & Location) have delivered products with precision location and ranging capabilities for indoors
- The scope of our work is to push UWB ranging to the limit and conduct an extensive measurement campaign to characterize its performance
  - 1 W power emission
  - 6 GHz bandwidth
  - 150 dB dynamic range
- Open questions: How does UWB ranging perform . . .
  . . . as a function of wall material?
  . . . at long ranges up to 45 meters?
  . . . as a function of bandwidth?
  . . . as a function of center frequency?
UWB Ranging Measurement System

- **Time-domain measurements:**
  - Tx emits a UWB pulse
  - Rx measures received pulses which together form the channel impulse response
  - Thresholding determines first arrival of the direct path

- **Frequency-domain measurements:**
  - Tx emits a series of synchronized tones
  - Rx measures the amplitude and phase shift of each which together form the channel frequency response impulse response recovered through the IDFT

Gives flexibility to vary bandwidth and center frequency of UWB pulse
Measurement Campaign

- Testing in four buildings with uniform interior walls allows gauging performance according to construction material.
- 50 experiments conducted in each building on our NIST campus.

### Building layout of NIST North Building:
- Solid points indicate the varying positions of the TX
- Hollow points indicate the varying positions of the RX
- In the test with the longest range, the signal must traverse 12 walls in the direct path

<table>
<thead>
<tr>
<th>Building</th>
<th>Wall material</th>
<th>LOS range (10)</th>
<th>NLOS range (40)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST North</td>
<td>Sheet rock/aluminum studs</td>
<td>1.2–24.3 m</td>
<td>1.7–40.7 m max wall no.: 12</td>
</tr>
<tr>
<td></td>
<td>Plaster/wooden studs</td>
<td>2.0–15.7 m</td>
<td>4.7–33.0 m max wall no.: 7</td>
</tr>
<tr>
<td></td>
<td>Cinder block</td>
<td>3.4–45.0 m</td>
<td>5.9–40.8 m max wall no.: 9</td>
</tr>
<tr>
<td>Plant</td>
<td>Steel</td>
<td>2.9–43.7 m</td>
<td>4.9–44.0 m max wall no.: 8</td>
</tr>
</tbody>
</table>
Results: Line-of-Sight

\textit{NIST North, }f_c= 5 \text{ GHz}

- There is no apparent correlation between range error and ground-truth range
- The average range error decreases with increasing bandwidth
- The average range error decreases at a diminishing rate
- The average range error at \(B = 6\) GHz is 6 cm throughout all four buildings
Results: Non line-of-sight

*Child Care*, $f_c = 5\ GHz$

- The range error increases with increasing ground-truth range
- The signal propagates through walls at a speed slower than light, and so introduces error in the range estimate
- The average range error decreases with increasing bandwidth, but at a diminishing rate
- The average range error at 6 GHz is:
  - 24 cm in *NIST North*
  - 38 cm in *Child Care*
  - 84 cm in *Sound*
  - 350 cm in *Plant*
Results: Non line-of sight

*Sound*, \( B = 1\) GHz

- The effects of center frequency are more pronounced in cinder block than other materials tested
- The average range error increases 30 cm from \( f_c = 3\) GHz to \( f_c = 7\) GHz (25%)
- Similar increase in average range error at \( B = 2\) GHz and \( B = 4\) GHz in cinderblock
- Increases of about 5 cm in sheet rock and 10 cm in plaster
Conclusions

• In LOS conditions, the UWB ranging system has 6 cm average error in all four buildings.

• In NLOS conditions, the UWB ranging system has:
  – 1% average error in sheet rock
  – 2% average error in plaster
  – 4% average error in cinder block
  – 10% average error in metal up to 15 m

• The range error is significantly reduced in translating to position error through triangulation.
How to Compute Location?

- A backbone network with at least three RXs is required to compute two-dimensional location.
- The RXs triangulate the three ranges to the TX to a single point as the intersection of the three circles.
- Requires pre-installation of the RXs outside the building and long range to reach the TX inside.

If a RX could also determine the angle of the TX, then no backbone network would be required!

- The RX could pinpoint the location of the TX relative to the RX as the intersection between a circle and a directed line.
- A firefighter could then find the locations of trapped victims equipped with TX beacons.
Extended temporal channel sounder to a spatial-temporal channel sounder by mounting the receiver antenna on a two-dimensional positioning table.

The circular array pattern was realized virtually by tracing the element positions sequentially.
Spatial-Temporal Channel Impulse Response

- The frequency sweeps taken at each element of the virtual array can be processed together to generate the spatial-temporal channel impulse response $h(t, \theta)$.
- Now the first arrival indexed in time and angle can be extracted from the response, giving both the range and direction of the TX with respect to the RX.
Results: LOS, NIST North, 
\[ B = 6 \text{ GHz}, f_c = 5 \text{ GHz} \]

- No apparent correlation between errors and ground-truth range
- Errors decrease with increasing bandwidth, but at diminishing rate
- Throughout all four buildings, average angle error of 1.1°
  - range error of 20 cm
  - location error of 31 cm
Results: NLOS, NIST North, \(B = 6 \text{ GHz}, f_c = 5 \text{ GHz}\)

- Errors increase with increasing ground-truth range
- More and more walls between the TX and RX with increasing ground-truth range:
  - Range error: the signal propagates through walls at a speed slower than light, so the estimated range is always greater than the actual range
  - Angle error: the walls deflect the signal off its original angle from the transmitter
- Average location error in \(NIST\ North\) is 150 cm, \(Child\ Care\) is 159 cm, \(Sound\) is 656 cm, \(Plant\) is 995 cm
Results: NLOS, Sound,  
B = 2 GHz

- The signal penetrates the walls better at lower frequencies, so the average range error is smaller.
- The angular resolution is higher at larger frequencies, so the average angle error is smaller.
- The two phenomena compensate for each other, so the average location error is the same at lower and higher frequencies.

\[ f_c = 3 \text{ GHz} \quad \text{and} \quad f_c = 7 \text{ GHz} \]
## Results: Compiled Results

<table>
<thead>
<tr>
<th>building</th>
<th>$B = 6$ GHz, $f_c = 5$ GHz</th>
<th>$B = 2$ GHz, $f_c = 3$ GHz</th>
<th>$B = 2$ GHz, $f_c = 7$ GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\phi_e$</td>
<td>$d_e$</td>
<td>$x_e$</td>
</tr>
<tr>
<td>NIST North</td>
<td>0.6, 1</td>
<td>9, 14</td>
<td>19, 26</td>
</tr>
<tr>
<td>Child Care</td>
<td>1.5, 1</td>
<td>20, 35</td>
<td>38, 36</td>
</tr>
<tr>
<td>Sound</td>
<td>0.7, 3.1</td>
<td>2, 118</td>
<td>10, 119</td>
</tr>
<tr>
<td>Plant</td>
<td>1.2, 1.3</td>
<td>18, 43</td>
<td>61, 88</td>
</tr>
<tr>
<td>NIST North</td>
<td>0.8, 0.8</td>
<td>33, 34</td>
<td>64, 53</td>
</tr>
<tr>
<td>Child Care</td>
<td>0.2, 2.2</td>
<td>3, 90</td>
<td>14, 161</td>
</tr>
<tr>
<td>Sound</td>
<td>3.4, 2.9</td>
<td>24, 31</td>
<td>150, 194</td>
</tr>
<tr>
<td>Plant</td>
<td>0.2, 14</td>
<td>1, 119</td>
<td>2, 872</td>
</tr>
<tr>
<td>NIST North</td>
<td>5.5, 4.5</td>
<td>45, 36</td>
<td>159, 153</td>
</tr>
<tr>
<td>Child Care</td>
<td>0.2, 18</td>
<td>4, 150</td>
<td>7, 779</td>
</tr>
<tr>
<td>Sound</td>
<td>15.2, 14.1</td>
<td>128, 205</td>
<td>656, 778</td>
</tr>
<tr>
<td>Plant</td>
<td>23.2, 18.4</td>
<td>419, 357</td>
<td>995, 782</td>
</tr>
</tbody>
</table>

### LEGEND

- $\phi_e$ (deg.), $\sigma_{\phi_e}$ (deg.)
- $\mu_d_e$ (cm), $\sigma_{d_e}$ (cm)
- $\mu_x_e$ (cm), $\sigma_{x_e}$ (cm)
- $PL_0$ (dB)
- $\gamma$
Indoor first responder localization using inertial and magnetic sensors, RFID

Red: start of trajectory, involving two crossovers.

Blue: continuation of trajectory with long loop.
Indoor first responder localization using inertial and magnetic sensors, RFID

Blue: unassisted DRM with magnetic heading sensor and step counting.

Red: DRM track with simple position correction at RFID “waypoints.”
Extra Slides
Deployment Algorithm Tradeoffs

### Deployment Parameters

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$</td>
<td>Probe period</td>
</tr>
<tr>
<td>$N$</td>
<td>Averaging filter length</td>
</tr>
<tr>
<td>$S_{th}$</td>
<td>Threshold RSS</td>
</tr>
</tbody>
</table>

### Post-deployment RSS – $S_{th}$ (dB)

- **Probe period, filter length ($\Delta$, $N$)**
  - $\Delta \times N = 4$ sec

- **Filter length ($N$)**
  - $\Delta = 100$ ms
2.4 GHz Symmetric Link Measurements

Bi-directional Filtered SNR Measurements of a Symmetric Mobile Link

- Fixed STA “A”, mobile STA “B”
- “B” carried down 110 m corridor and back at ~ 1.2 m/s
- Sampling period: 100 ms
- Filter: Uniform moving average of last 20 samples (2 s filter)
- Data rate: 2 Mbps
2.4 GHz Asymmetric Link Measurements

- Fixed STA “A”, mobile STA “B”
- “B” carried down 110 m corridor and back at ~ 1.2 m/s
- Sampling period: 100 ms
- Filter: Uniform moving average of last 20 samples (2 s filter)
- Data rate: 2 Mbps

Bi-directional Filtered SNR Measurements of an Asymmetric Mobile Link
## Similarities with LANdroids

<table>
<thead>
<tr>
<th>LANdroid Capability</th>
<th>NIST Breadcrumb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-Configuration</td>
<td>○</td>
</tr>
<tr>
<td>Self-Optimization</td>
<td>○</td>
</tr>
<tr>
<td>Self-Healing</td>
<td>○</td>
</tr>
<tr>
<td>Tethering</td>
<td>○</td>
</tr>
<tr>
<td>Intelligent Power Management</td>
<td></td>
</tr>
<tr>
<td>Placement-by-Indicator</td>
<td>●</td>
</tr>
<tr>
<td>Geolocation</td>
<td>○</td>
</tr>
</tbody>
</table>

○ Partial support  
● Full support