Time Difference of Arrival
Localization Testbed: Development, Calibration, and Automation

GRCon 2017

Intelligent Digital Communications
Georgia Tech VIP Team
Overview

- Introduction
  - IDC Team
  - Stadium Testbed
- RFSN Control Center (RFSNCC)
  - Why?
  - How?
- Lab Setup and ToA Calibration
  - Why?
  - Experiment Setup
  - Results
Introduction

Hayden Flinner
IDC Team Purpose

- IDC is using software defined radio to enhance spectrum utilization
  - Radio frequency (RF) spectrum is a valuable, limited resource
  - Analyzing how devices interact over RF spectrum allows us to find ways to improve communication in an optimal manner
Localization

- Using SDR to develop localization algorithms for Extreme Emitter Density environments (10k-100k people/km2)

- Recorded terabytes of time synchronous RF IQ data, during football games, at the GT football stadium to assist in algorithm development
TDoA Localization

- Assuming time-synced nodes:
  1. Record ToAs
  2. Take differences
  3. Apply $\Delta d = c\Delta t$
Stadium Testbed

Hayden Flinner
RF Sensor Node (RFSN)

Network Relay
B200
Power Relay
Intel NUC
Stadium Testbed

RFSN3

RFSN1

RFSN2

D1

D2

D3

Emitter

RFSN3

9
2 Mobile Nodes
RFSN Control Center (RFSNCC)
Why RFSNCC?

1. Currently 3 fixed nodes - Goal 10+

2. Logging into each machine and running long series of time-synced record commands is not scalable
   a. Excessive man-hours
   b. Error-prone

3. Maintaining RF IQ dataset and associated metadata is tedious
Initial Plan

Upload Schedule

Website

RFSN1

RFSN2

…
### Current Site

### CSV Scheduling

**CSV Formatting Reference**

<table>
<thead>
<tr>
<th>Choose File</th>
<th>No file chosen</th>
</tr>
</thead>
</table>

**Submit**

### Schedule Recording Form

<table>
<thead>
<tr>
<th>Session Name</th>
<th>Starting Path (/path/)</th>
<th>Log Name (test.log)</th>
<th>Start Early (sec)</th>
<th>Sample Rate (samples/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring17Test</td>
<td>/spring17/test/</td>
<td>log.txt</td>
<td>60</td>
<td>25e6</td>
</tr>
</tbody>
</table>

- **RFSN Node 1**
- **RFSN Node 2**
- **RFSN Node 3**

**Time Offset (min)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Length (sec)</th>
<th>Gain (db)</th>
<th>Frequency (hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/21/2017</td>
<td>03:00 AM</td>
<td>5</td>
<td>55</td>
<td>2.4E+9</td>
</tr>
<tr>
<td>04/21/2017</td>
<td>03:05 AM</td>
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<td>04/21/2017</td>
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<td>04/21/2017</td>
<td>03:15 AM</td>
<td>5</td>
<td>55</td>
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<td>04/21/2017</td>
<td>03:20 AM</td>
<td>5</td>
<td>55</td>
<td>2.4E+9</td>
</tr>
</tbody>
</table>

[Add] [Submit Form]
## Current Site

### RFSNS

<table>
<thead>
<tr>
<th>RFSN</th>
<th>Power</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFSN Node 1</td>
<td>RFSN Node 1: ON/OFF</td>
<td>Click to see Status</td>
</tr>
<tr>
<td>RFSN Node 2</td>
<td>RFSN Node 2: ON/OFF</td>
<td>Click to see Status</td>
</tr>
<tr>
<td>RFSN Node 3</td>
<td>RFSN Node 3: ON/OFF</td>
<td>Click to see Status</td>
</tr>
</tbody>
</table>
Lab Setup and ToA Calibration
Why a Lab Testbed?

- Wired nodes provide controlled test environment.
- Easier to vary cable lengths to test emitter/receiver positions than to run around stadium.
Lab Testbed
Why Calibration Experiment?

- Verify that ToAs being recorded are plausible
- Remove delay inherent to USRPs for more accurate location measurements
Cramer-Rao Lower Bound (CRLB)

- CRLB for the standard deviation of the TDoA is theoretic limit on how accurate results can be

\[
\sigma^2(\hat{t}_2 - \hat{t}_1) \geq \frac{1}{4\pi^2 (SNR_{linear})\beta_{rms}^2} (s^2)
\]

\[
\beta_{rms} = \frac{\beta}{\sqrt{12}} \quad \beta \text{ is the BW}
\]

\[
\hat{t}_n \text{ is the unknown ToA at sensor } i
\]

\[
SNR_{linear} = 10^{\frac{SNR_{dB}}{10}}
\]

\[
SNR_{dB} = 10\log_{10}\left(\frac{\sum|X_i|^2}{\sigma_{noise}^2}\right)
\]
Cramer-Rao Lower Bound (CRLB)

Relationship between CRLB and bandwidth
Q: Does our testbed give us sane results?

<table>
<thead>
<tr>
<th>TDoA</th>
<th>Btw 1 &amp; 2</th>
<th>Btw 1 &amp; 3</th>
<th>Btw 2 &amp; 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (ns)</td>
<td>18.228</td>
<td>26.440</td>
<td>8.213</td>
</tr>
<tr>
<td>Variance (ns^2)</td>
<td>4.004E-5</td>
<td>3.478E-5</td>
<td>1.644E-5</td>
</tr>
<tr>
<td>Std Dev (ns)</td>
<td>6.327E-3</td>
<td>5.898E-3</td>
<td>4.054E-3</td>
</tr>
<tr>
<td>MSE (ns^2)</td>
<td>7.241E-5</td>
<td>3.506E-5</td>
<td>5.508E-5</td>
</tr>
<tr>
<td>SNR (dB)</td>
<td>79.904</td>
<td>80.279</td>
<td>80.279</td>
</tr>
</tbody>
</table>

- TX sampling rate: 16 Msps
- RX sampling rate: 16 Msps with 32 MHz master clock.
A: Yes! Std. Devs. above CRLB!

SD of TDoA data plotted against its CRLB at 16 MHz sampling bandwidth
Calibration: Testbed Setup

- Nodes 2, 3, 4, and 5 were passed delayed signal sequence.
- Nodes 1 and 6 received non-delayed signal sequence.

TX: 25 Msps -- RX: 25 Msps, 50 MHz master clock.
Calibration: Running Experiment

- LMR-240 cables of known lengths were attached 110 seconds into each recording session.
- For each node, average ToAs seen during first 100 seconds was subtracted from ToA vector during each recording session.
- Used magnitude interpolation around the cross-correlation peak value to compute ToA estimate.

TX: 25 Msp -- RX: 25 Msp, 50 MHz master clock.
Time Difference of Arrival over 12 ft LMR240 cable

- Expected delay through 12 ft LMR240 cable is: 12 ft / 0.8262 ft/ns = **14.5243 ns**

### Results

<table>
<thead>
<tr>
<th>TDoA -&gt;</th>
<th>Btw 1 &amp; 2</th>
<th>Btw 1 &amp; 3</th>
<th>Btw 1 &amp; 4</th>
<th>Btw 1 &amp; 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (ns)</td>
<td>13.0750</td>
<td>13.7267</td>
<td>13.1034</td>
<td>0.0242</td>
</tr>
<tr>
<td>Variance (ns²)</td>
<td>1.8990E-1</td>
<td>9.5577E-3</td>
<td>6.6974E-3</td>
<td>3.0686E-4</td>
</tr>
<tr>
<td>Std Dev (ns)</td>
<td>0.4358</td>
<td>0.0978</td>
<td>0.0818</td>
<td>0.0175</td>
</tr>
<tr>
<td>MSE (ns²)</td>
<td>2.2976E-0</td>
<td>6.4481E-1</td>
<td>2.0323E-0</td>
<td>8.9917E-4</td>
</tr>
</tbody>
</table>

Results are of average TDoA vector from four runs.
Time Difference of Arrival over 50 ft LMR240 cable

<table>
<thead>
<tr>
<th>TDoA -&gt;</th>
<th>Btw 1 &amp; 2</th>
<th>Btw 1 &amp; 3</th>
<th>Btw 1 &amp; 4</th>
<th>Btw 1 &amp; 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (ns)</td>
<td>61.0461</td>
<td>59.4250</td>
<td>60.1079</td>
<td>0.0035</td>
</tr>
<tr>
<td>Variance (ns²)</td>
<td>1.9459E-4</td>
<td>6.0374E-4</td>
<td>3.7281E-5</td>
<td>4.1453E-6</td>
</tr>
<tr>
<td>Std Dev (ns)</td>
<td>0.0139</td>
<td>0.0246</td>
<td>0.0061</td>
<td>0.0020</td>
</tr>
<tr>
<td>MSE (ns²)</td>
<td>3.0133E-1</td>
<td>1.1676E-0</td>
<td>1.5527E-1</td>
<td>1.6303E-5</td>
</tr>
</tbody>
</table>

Results are of average TDoA vector from four runs.

- Expected delay through 12 ft LMR240 cable is: $\frac{50 \text{ ft}}{0.8262 \text{ ft/ns}} = \text{60.5181 ns}$
Time Difference of Arrival over 100 ft LMR240 cable

<table>
<thead>
<tr>
<th>TDoA -&gt;</th>
<th>Btw 1 &amp; 2</th>
<th>Btw 1 &amp; 3</th>
<th>Btw 1 &amp; 4</th>
<th>Btw 1 &amp; 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (ns)</td>
<td>121.7498</td>
<td>123.1022</td>
<td>122.7003</td>
<td>0.4180</td>
</tr>
<tr>
<td>Variance (ns^2)</td>
<td>5.6723E-4</td>
<td>1.0220E-3</td>
<td>1.3408E-4</td>
<td>9.6546E-5</td>
</tr>
<tr>
<td>Std Dev (ns)</td>
<td>0.0238</td>
<td>0.0320</td>
<td>0.0116</td>
<td>0.0098</td>
</tr>
<tr>
<td>MSE (ns^2)</td>
<td>0.5706</td>
<td>4.4814</td>
<td>2.9312</td>
<td>0.1772</td>
</tr>
</tbody>
</table>

Results are of average TDoA vector from four runs

- Expected delay through 100 ft LMR240 cable: $\frac{100 \text{ ft}}{0.8262 \text{ ft/ns}} = 121.0361 \text{ ns}$
Time Difference of Arrival over 200 ft LMR240 cable

- Expected delay through 200 ft LMR240 cable: \(200 \text{ ft} / 0.8262 \text{ ft/ns} = 242.0722 \text{ ns}\)
Wrapping Up

● Experiments show our timing variance on 4 different cable lengths (with 4 trials apiece) match expectations

● RFSNCC allows us to schedule and collect data easily

● Already collected relatively large (40TB) dataset from stadium
Contact


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ToA Calculation

- Simple parabolic interpolation

Figure 12.1: Illustration of parabolic peak interpolation using the three samples nearest the peak.