Radiolocation in Cellular Networks

by Prof. Gregory D. Durgin

Section I: RSS System Trials

Outline of Section II

- Trials on Georgia Tech Campus
  - Indoor/outdoor data collection
  - Urban campus performance
- Trials in Greenville, SC
  - Wide area urban/suburban performance
  - Multi-story buildings
  - Enhanced Algorithms
- Trials in Manhattan, NY
  - Urban environment
  - Indoor penetration modeling
Why RSS Signature Location?
- Moderate indoor and outdoor accuracy
- Low deployment cost
- Fast deployment speed
- Legacy handsets covered
- Covers multiple cellular technologies
- Additional capability: indoor/outdoor discrimination
- Fits in different sizes of network
- Expandable to other communication technologies such as WLAN2

How an RSS Signature Engine Works
How an RSS Signature Engine Works

NMR: Network Measurement Report

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>RSS</th>
<th>Cell ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>793</td>
<td>-67</td>
<td>10013</td>
</tr>
<tr>
<td>779</td>
<td>-74</td>
<td>34103</td>
</tr>
<tr>
<td>783</td>
<td>-98</td>
<td>10012</td>
</tr>
<tr>
<td>780</td>
<td>-98</td>
<td>34101</td>
</tr>
<tr>
<td>797</td>
<td>-99</td>
<td>43952</td>
</tr>
<tr>
<td>777</td>
<td>-112</td>
<td>10011</td>
</tr>
</tbody>
</table>

Cramer-Rao Lower Bound

- The CRLB provides a lower bound on the covariance matrix of the unbiased estimator

\[
\text{Cov}(\hat{z}) \geq \text{Cov}_{cr}(z)
\]

where \( z = \begin{bmatrix} x \\ y \end{bmatrix} \)

- Path loss exponent
- Geometry of base station
- Measurement correlation
- Number of NMRs used
- Number of audible base station
- Measurement Error
CRLB- Simulation Environment

Baseline:
Path loss exponent: 3.3
Average base station separating distance: 500 (m)
Measurement correlation from same base station: 0.5
Number of NMRs: 30
Standard deviation of measurement error: 3.5
Number of audible base station: 4
Output: 82.0 m

Numerical Result: Path Loss-Related

larger path loss exponent because higher path loss increases the uniqueness of the RSS signature.
Performance: Base Station Separation Distance

- The location error increases linearly with the base station separation distance.

Numerical Result: Measurement Error-related

- A higher standard deviation of measurement error leads to a more inaccurate location estimation.
- The standard deviation of the measurement error has to be lower than 6.5 dB so that the standard deviation of the location error is lower than 100 m when six base station signals are reported in an NMR.
Phase I: Georgia Tech Campus Study

Using more NMRs increase location accuracy. The location accuracy improves dramatically when the number of NMRs used increases from 1 to 10.
Three Keys to Accurate RSS Location

- **Accuracy of Predicted Signal Database**
  - Most difficult aspect of the problem
  - Requires propagation modeling

- **Repeatability of Measurement at Handset**

- **Location Algorithm**
  - Many different variations possible
  - Attempt to achieve CRLB limit

Preparing a Predicted Signal Database

Information used in preparing RF maps:

- Base station longitude
- Base station latitude
- Sector antenna orientation
- Sector antenna height
- Frequency channel
- Transmit power
## Comparison of Different PSDs

<table>
<thead>
<tr>
<th></th>
<th>Level 0</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>Best</td>
</tr>
<tr>
<td><strong>Generating Speed</strong></td>
<td>Fast</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Very Slow</td>
</tr>
<tr>
<td><strong>Generating Cost</strong></td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
</tr>
</tbody>
</table>

Level 0: Pure Prediction
Level 1: Calibration with outdoor measurement
Level 2: Calibration with outdoor measurement and indoor modeling
Level 3: Calibration with exhaustive outdoor and indoor measurements

---

**Level 0 Predicted Signal Database**

**Modified Hata Model:**

\[
P_R = P_T + G_R + G_T \cos(\theta - \theta_b) - 10n \log_{10} \left( \frac{d}{1 \text{ cm}} \right) - 20 \log_{10} \left( \frac{4\pi}{\lambda} \right) + C_{dB}
\]
Level 1 Predicted Signal Database

(a) Single Measurement Point

Level 1: Calibration with outdoor measurements

(b) Measurements Taken Along a Path
Building Measurement Sample

Measurement Route Record at Architecture Building

Measurement Photos
Indoor Location

Stat: 67% of all European cell-phone calls are indoors.

RSSI-based system perhaps the only way to discriminate indoor/outdoor users.
Level 2 Predicted Signal Database

Level 2: Calibration with outdoor measurements and indoor modeling

Collecting Handset Test Data

- Manually log indoor data
  - Connect cellular scanners to palmtop computer
  - Record data on indoor maps
  - Active call data

- Separate acquisitions
  - Scanner data for predicted signal database
  - Active call data to build a test database
Level 3 Predicted Signal Database

Level 3: Calibration with exhaustive outdoor and indoor measurements

Three Keys to Accurate RSS Location

- **Accuracy of Predicted Signal Database**
  - Most difficult aspect of the problem
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- **Repeatability of Measurement at Handset**

- **Location Algorithm**
  - Many different variations possible
  - Attempt to achieve CRLB limit
Repeatability Measurements

- Head-handset shadowing
  - Measure tracks of data in the same area, but with different orientations
  - Average variation has \( \sigma = 2 \text{ dB} \)

- Small-scale fading within a “bin”
  - Measure tracks of data through a bin
  - Note: pure Rayleigh fading predicts \( \sigma = 5 \text{ dB} \)
  - Average variation of \( \sigma = 2 \text{ dB} \)
  - Handsets perform some temporal averaging in their measurements

Three Keys to Accurate RSS Location

- Accuracy of Predicted Signal Database
  - Most difficult aspect of the problem
  - Requires propagation modeling

- Repeatability of Measurement at Handset

- Location Algorithm
  - Many different variations possible
  - Attempt to achieve CRLB limit
### Algorithm: Absolute RSS Location

**Assumption in Absolute RSS Location:**
- Assume prefect knowledge of the antenna/RF chain bias between the user handset and the scanner used to calibrated the PSD

\[
N_{RSS1} = N_{RSS} - \text{Bias}
\]

\[
M = \sqrt{\sum_{i=1}^{N} (N_{RSS_{x,y,i}} - N_{RSS})^2}
\]

<table>
<thead>
<tr>
<th>PSD level</th>
<th>Level 1 Outdoor Meas.</th>
<th>Level 2 Indoor Model</th>
<th>Level 3 Indoor/Outdoor Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor/Outdoor Discrimination Rate</td>
<td>32%</td>
<td>78%</td>
<td>86%</td>
</tr>
<tr>
<td>Location Error Statistics</td>
<td>&lt;100m: 20%</td>
<td>45%</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td>&lt;300m: 60%</td>
<td>90%</td>
<td>95%</td>
</tr>
</tbody>
</table>

### Algorithm: Relative RSS Location

**Relative RSS Location:**
- Mean is removed from Both NMR and each roaster point in PSD

\[
P_{NMR_{x,y}} = P_{NMR} - \frac{1}{N} \sum_{i=1}^{N} N_{RSS_i} = P_{RSS} - \frac{1}{N} \sum_{i=1}^{N} N_{RSS} \quad M(x,y) = \sqrt{\sum_{i=1}^{N} (P_{NMR_{x,y,i}} - P_{RSS})^2}
\]

<table>
<thead>
<tr>
<th>PSD level</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Indoor/Outdoor Discrimination Rate</td>
<td>43%</td>
<td>43%</td>
<td>51%</td>
</tr>
<tr>
<td>Location Error Statistics</td>
<td>&lt;100m: 54%</td>
<td>54%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>&lt;300m: 94%</td>
<td>94%</td>
<td>95%</td>
</tr>
</tbody>
</table>
Algorithm: Hybrid RSS Location

Fact:
– Indoor/Outdoor discrimination information is embedded in absolute RSS
– Fingerprint method is more accurate by using relative RSS information

Assumption for Hybrid RSS Location:
– All commercial hand sets have roughly similar attenuation in RF chain.

RSSA: Received Signal Strength Aggregate, The average of the strongest several channels, could be used to discriminate indoor/outdoor caller.
### Algorithm: Hybrid RSS Location

Algorithm: Hybrid RSS Location

\[ M_d(x, y) = \frac{M(x, y)}{\sum_{i=1}^{N} N_{rss_i}} \]

<table>
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<tr>
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<th>Level 2 Indoor Model</th>
<th>Level 3 Indoor/Outdoor Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor/Outdoor Discrimination Rate</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Location Error Statistics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;100 m</td>
<td>56%</td>
<td>56%</td>
<td>65%</td>
</tr>
<tr>
<td>&lt;300 m</td>
<td>96%</td>
<td>96%</td>
<td>96%</td>
</tr>
</tbody>
</table>

### Algorithm: Location With Averaging

10 NMRs were linearly averaged to form an averaged NMR to increase the Repeatability of Measurement at Handset

Algorithm: Location With Averaging

<table>
<thead>
<tr>
<th>PSD level</th>
<th>Level 1 Outdoor Meas.</th>
<th>Level 2 Indoor Model</th>
<th>Level 3 Indoor/Outdoor Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor/Outdoor Discrimination Rate</td>
<td>92%</td>
<td>92%</td>
<td>91%</td>
</tr>
<tr>
<td>Location Error Statistics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;100 m</td>
<td>61%</td>
<td>64%</td>
<td>78%</td>
</tr>
<tr>
<td>&lt;300 m</td>
<td>97%</td>
<td>98%</td>
<td>98%</td>
</tr>
</tbody>
</table>
**Phase I: Conclusions**

- RSS location techniques meet the FCC's requirements for E911 accuracy.
- The techniques remain accurate for *indoor* handsets.
- RSS location engine has ability to discriminate between indoor and outdoor handsets.
- Research provide performance up-limit for Indoor modeling.
Phase II: Large Area GSM Experiments

- Different commercial network trials in varied environments
  - Urban, suburban, rural environments in Triton’s GSM network at Greenville, SC
  - Larger testing area allow the existing of egregious location error
  - The effect of high-rise building

- Accurate propagation modeling
  - Based on more knowledge: building structure, building materials, surrounding environment, multi-path effects, base station location and elevation.
  - Reduce the time and cost of extensive drive-testing

- More complicated RSS fingerprint location algorithm
  - DSP filtering technology: matching vs. tracking
  - Iterative calculation

Extended Experiment in Greenville, SC

The 7000 m by 9000 m test area in Greenville, SC
Base stations in Greenville

Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 786 on Dec 14, 2004. The thick path is a single drive-test route through the test area.

RSS Indoor/Outdoor Discrimination

The received signal strength in dB-received over the 0 neighbor DCCHs (dBm) is shown for indoor and outdoor conditions.
RSS Indoor/Outdoor Discrimination

Table 4.1 Discrimination rate by using handset RSSA distribution.

<table>
<thead>
<tr>
<th></th>
<th>Decision</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indoor</td>
<td>Outdoor</td>
<td>Sub-Total</td>
<td></td>
</tr>
<tr>
<td>Actual</td>
<td>Indoor</td>
<td>26,576</td>
<td>12,090</td>
<td>39,266</td>
<td>(53.0%)</td>
</tr>
<tr>
<td></td>
<td>Outdoor</td>
<td>5,140</td>
<td>29,719</td>
<td>34,859</td>
<td>(47.0%)</td>
</tr>
<tr>
<td>Correct</td>
<td>Rate</td>
<td>70%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GPS effectiveness

Table 4.2 Garmin V GPS effectiveness statistics based on 69,624 indoor and outdoor measurement records.

<table>
<thead>
<tr>
<th></th>
<th>GPS valid</th>
<th>GPS not valid</th>
<th>Sub-total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>4,069 (8.71%)</td>
<td>35,197 (58.90%)</td>
<td>39,266 (64.77%)</td>
</tr>
<tr>
<td>Outdoor</td>
<td>19,894 (31.99%)</td>
<td>1,994 (3.24%)</td>
<td>21,388 (35.23%)</td>
</tr>
<tr>
<td>Sub-total</td>
<td>23,960 (38.76%)</td>
<td>37,191 (61.34%)</td>
<td>60,624 (100%)</td>
</tr>
</tbody>
</table>

Table 4.3 Garmin V GPS effective statistics. Percentages are compared with indoor or outdoor separately.

<table>
<thead>
<tr>
<th></th>
<th>GPS valid</th>
<th>GPS not valid</th>
<th>Measurement Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>10.36% (4,069)</td>
<td>89.64% (35,197)</td>
<td>39,266(100%)</td>
</tr>
<tr>
<td>Outdoor</td>
<td>99.6% (19,894)</td>
<td>2.2% (1,994)</td>
<td>21,388(100%)</td>
</tr>
</tbody>
</table>
RSS in a High-rise Building

RSS Location Performance in Greenville

<table>
<thead>
<tr>
<th>PSD level</th>
<th>Level 1</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error statistics</td>
<td>&lt;100m 30%</td>
<td>&lt;300m 71%</td>
</tr>
<tr>
<td>Percentage statistics</td>
<td>66.7% 270 m</td>
<td>95% 580 m</td>
</tr>
</tbody>
</table>

Location error statistics for the relative RSS-method with limited search area and distance matrix aggregate. (10 NMRs, 6 sectors)
Phase III: Manhattan, NY

- The “ultimate urban environment”
- Indoor modeling is critical
- A-GPS struggles in this kind of environment

Indoor Propagation Model

![Diagram](image)

Figure 53. Pseudo-transmitter case in an ultra-dense urban environment.
## Example Indoor Prediction Mask

![Example Indoor Prediction Mask](image)

### Location Results in Manhattan (Fall 2005)

Level 1 PSD: RF database calibrated with outdoor measurement

Level 2 PSD: Calibration with outdoor measurement and indoor modeling

<table>
<thead>
<tr>
<th>PSDD Level</th>
<th>Indoor Test Points</th>
<th>Outdoor Test Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error Statistics</td>
<td>Level 1 PSD</td>
<td>Level 2 PSD</td>
</tr>
<tr>
<td>&lt;50m</td>
<td>25.3%</td>
<td>36.8%</td>
</tr>
<tr>
<td>&lt;100m</td>
<td>75.9%</td>
<td>77.0%</td>
</tr>
<tr>
<td>&lt;150m</td>
<td>92.0%</td>
<td>95.4%</td>
</tr>
<tr>
<td>&lt;300m</td>
<td>98.9%</td>
<td>100%</td>
</tr>
<tr>
<td>&lt;500m</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Technical Reports...


J. Zhu and G.D. Durgin, “Indoor-Outdoor Location of Cellular Handsets Based on Received Signal Strength.” IEEE Electronics Letters. vol 41, no 1. 6 January 2005.


For Further Reading...


J. Zhu and G.D. Durgin, “Indoor-Outdoor Location of Cellular Handsets Based on Received Signal Strength.” IEEE Electronics Letters. vol 41, no 1. 6 January 2005.


Other References


