Radiolocation in Cellular Networks

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Abstract – This tutorial presents an overview of how cellular phones can be found within a cellular network for both E911 dispatching and location-based services. We show how real radio location systems work with examples of measurement campaigns in live systems. After reviewing all location techniques, significant attention is paid to emerging received signal strength “finger-printing” techniques that have been deployed across the US and beyond. The tutorial concludes with several case studies in applications and radio forensics – using cellular location to fight crime.

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Acknowledgements

- Georgia Tech Foundation
- Polaris Wireless Inc.
- Cingular (now AT&T)
- Comarco Wireless
- NSF CAREER Grant ECS-0546955
- Aerospace Corp.

Credits

- Greg Durgin: Professor tenure 2009
- Jian "Jet" Zhu: models, analysis, measurements PhD 2006
- Ryan Pirkl: measurements PhD 2009
- Josh Griffin: measurements PhD 2009
- Albert Lu: measurements Lab Engineer 2006-2008
- Chris Durkin: models, measurements MS 2005
- Anil Rohatgi: measurements & web demo MS 2006
- Prof. Paul Steffes: cellular consultant colleague
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  - Marty Feuerstein
  - Steve Spain
  - Tarun Bhattacharya
  - Soma Pitchaih
  - Manlio Allegra
  - Prof. Paul Steffes: cellular consultant colleague
Radiolocation in Cellular Networks

by Prof. Gregory D. Durgin

Section I: Basics of Cellular Location; Assisted GPS

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Special Thanks to the Polaris Wireless Team...
- Marty Fountain
- Steve Spagn
- Tarun Sheth
- Uma Prakash
- Mentor Alege

Special Thanks to the Georgia Tech Foundation...
This Tutorial is Geared Towards…

- Engineers interested in how location works on a cellular network
- Researchers who are looking for interested research topics in new location areas
- Technologists interested in the possibilities of real-time location systems and their applications
- People who want to have a good time

Outline of Section I

- Recommended Reading
- History of Cellular Location
- Taxonomy of Location Techniques
- Trade-offs for Different Techniques
- Review of GPS Principles
- Assisted Global Positioning System

E911 Position Location Mandate

- 1996 FCC mandate for all US carriers
  - Original Target: <50m 67%, <100m 95% (3D)
  - Handset Target: <100m 67%, <300m 95% (2D)
  - Network Target: <50m 67%, <150m 95% (2D)
- Numerous delays, failures
- Today’s systems use a conglomerate of
  - Time-difference-of-arrival
  - Assisted GPS
  - Received Signal Strength Matching
Cell Global Identity (CGI)

- CGI uses serving cell identification
- In most areas, CGI error is > 1 km
- Easy and cheap to implement

Cellular Global Identity (CGI)

Serving cell provides location estimate for the cell phone

Angle-of-Arrival

AOA: Angle of Arrival - Location solution based on apparent signal arrival angle

Pros
- Only 2 base stations needed
- Legacy handsets covered

Cons
- LOS condition essential
- Low location accuracy
- Additional equipment cost
- Long deployment period

Facts
- Moderate open area accuracy
- Atlanta area deployment cost: Several million dollars
Time-Difference Of Arrival (TDOA)

- Time-of-Arrival triangulation
- Requires at least 3 audible base stations for 2D location

Time-of-Arrival

TOA: Time of Arrival - Location solution based on apparent signal arrival time

**Pros**
- Legacy handsets covered
- Precisely synchronized clocks
- LOS condition essential
- Poor in rural area
- Additional equipment for GSM, TDMA

**Cons**
- Legacy handsets covered
- Precisely synchronized clocks
- LOS condition essential
- Poor in rural area
- Additional equipment for GSM, TDMA

**Facts**
- Moderate open area accuracy
- Atlanta area deployment cost: Several million dollars
- Brother technologies
  - TDOA
  - E-OTD

Global Positioning System (GPS)

- Requires separate RF chain in every handset
- Requires LOS to at least 3 satellites
- Must be adapted to the cellular network
**Assisted Global Positioning System**

A-GPS: Assisted Global Positioning System
- Location solution based on apparent TOA from GPS space vehicles

- **Pros**
  - High outdoor accuracy

- **Cons**
  - LOS condition essential
  - Legacy handset not covered

- **Facts**
  - Atlanta area deployment cost:
    - Several million dollars to be absorbed by consumer

---

**Received Signal Strength**

RSS: Received Signal Strength Fingerprint
- Minimum of 1 site measurements attributes of received signal

- **Pros**
  - Indoor accuracy
  - Low deployment cost
  - Fast deployment speed
  - Legacy handsets covered

- **Cons**
  - Poor coverage in rural area
    (Better than TOA and AOA solution though)

- **Facts**
  - Moderate indoor and outdoor accuracy
  - Atlanta area deployment cost:
    - Several thousand dollars

---

**RSS Position Location for E911**

Received Signal Strength (RSS) Measurements by a cellular handset...
### Comparison of Techniques

<table>
<thead>
<tr>
<th></th>
<th>TOA</th>
<th>AOA</th>
<th>A-GPS</th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Accuracy</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Moderate</td>
</tr>
<tr>
<td>Outdoor Accuracy</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Rural Accuracy</td>
<td>Poor</td>
<td>Poor</td>
<td>Great</td>
<td>Poor</td>
</tr>
<tr>
<td>Deployment Cost</td>
<td>Very High</td>
<td>Very High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Deployment Speed</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Slow</td>
<td>Fast</td>
</tr>
<tr>
<td>Operation Cost</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Legacy Handset</td>
<td>Covered</td>
<td>Covered</td>
<td>Not Covered</td>
<td>Covered</td>
</tr>
</tbody>
</table>

### Basics of A-GPS

- Cellular implementation of a GPS receiver
- Often implemented as a single chip solution in a handset
- Operates similarly to a portable GPS unit, with some important simplifications

### GPS Satellites

- 24 satellites
  - 6 constellations with 4 satellites each
  - “spares” in orbit, too
- Each orbit inclined 55 degrees, at 60 degree longitudinal orientation
- All-earth coverage
  - Minimum 4 satellites
  - Maximum 9+ satellites
Pseudo-Noise Generator

![Diagram of Pseudo-Noise Generator]

Pseudo-Noise Sequence

![Graph of Pseudo-Noise Sequence]

GPS Satellites Transmission

- Uses a Gold Sequence
  - Two 10-bit shift registers XORed together
  - Easy to generate and correlate in early hardware
  - Does not require an extensive table in memory
- Different delays between two sequences result in different codes
  - Uniquely identifies each satellite
  - About 64 “useful” delay offsets (other delay offsets result in partial correlation in some Gold codes)
  - Correlation with a PN provides relative time-of-arrival estimate
**GPS Transmission**

- The GPS satellites also spread a low-rate (50 bps) data waveform that helps...
  - Correct for satellite orbit variations (ephemeris)
  - Synchronize the clock
  - Provide satellite “health and history” (almanac)
- Spread spectrum allows reception in the presence of some interference

---

**Example Calculation**

**Mission:**
To determine the location in Atlanta, GA of a GPS Receiver based on positioning data from only three GPS satellites.

GIVEN GPS Positioning Data:

<table>
<thead>
<tr>
<th>Sat 1</th>
<th>Sat 2</th>
<th>Sat 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat</td>
<td>43.329°</td>
<td>44.321°</td>
</tr>
<tr>
<td>Lon</td>
<td>84.427°</td>
<td>84.385°</td>
</tr>
<tr>
<td>TDo</td>
<td>0.000000000</td>
<td>0.000397056</td>
</tr>
</tbody>
</table>

---

**Example Calculation**

Initially we calculate the rectangular coordinates of the three GPS satellites (in meters):

- **Sat 1**
- **Sat 2**
- **Sat 3**

Even we know that the receiver location is in Atlanta, GA within 300 m from map data, we can determine the distance from the center of Earth to the GPS Receiver (this is 6378100 m).
How Easy is it to Jam GPS?

Sample Problem:
A typical, open-sky GPS receiver picks up 8 approximately equal-powered satellite signals when operated near Hartsfeld-Jackson International Airport. These signals (the GPS C/A codes) are 50 bit/sec identification and timing data that are spread at 1.023 Mcps to an RF bandwidth of 2 MHz. You are hired by the department of homeland security to evaluate the ability to jam GPS receivers near the airport. If a malevolent agent has a 7 dBi-gain Yagi antenna connected to a jammer/transmitter and aims this device at a plane beginning a landing approach from 5 kilometers away, how much jamming power is required to make the C/A code have a C/I < 6 dB after despreading?

Jamming GPS

With jamming power, \( P_j \), included, the SNR formula becomes:

\[
\text{SNR} = \frac{M \cdot P_0}{N_0 + (Q-1)P_0 + P_j} = \frac{M \cdot P_0}{\text{SNR}} \cdot N_0 = (Q-1)P_0 \approx 2.484 \times 10^{-11} \text{W}
\]

Assuming a jamming frequency of \( f_j = 1.575 \text{ MHz} \), then the link budget formula could be used to obtain the required jamming power,

\[
P_j = P_0 \left( \frac{4\pi R_B}{G_B G_M} \right)^2 \left( 1 + \frac{2.484 \times 10^{-11}}{1.10^9} \right) \approx 53.9 \text{ mW}
\]

Accuracy in GPS Systems

- \( N_{\text{sat}} \) – number of satellites used in estimate
- \( T_b \) – bit duration (20 ms)
- \( T_c \) – chip duration (1 \( \mu \)s)
- \( T_{\text{int}} \) – integration period (for super-resolution)
- \( (C/N)_{\text{despread}} \) – carrier-to-interference ratio after despreading (linear)

\[
\sigma_r = c T_c \sqrt{ \frac{N_{\text{sat}} T_b}{T_{\text{int}} (C/N)_{\text{despread}}}} \quad c = 3.0 \times 10^8 \text{ m/s}
\]
Dilution of Precision (DOP)

- Previous formula assumes near-ideal arrangement of GPS satellites received
- If decoded satellites are clustered in one area of the sky, significant DOP results
- Different types of DOP
  - GDOP – geometrical dilution of precision
  - PDOP – position dilution of precision
  - HDOP – horizontal dilution of precision
  - VDOP – vertical dilution of precision

Sources of Error in GPS

- 2.4m – Receiver noise
- 4.3m – Ephemeris error (orbit discrepancies)
- 3.5m – Clock errors
- 6.4m – Ionospheric delay
- 2.0m – Tropospheric delay
- 3.0m – Multipath (optimistic)
- 32.0m – Selective Availability (discontinued)
- Total error of 9.5m without selective availability

Augmented GPS Concepts

- Which errors are avoidable?
  - 2.4m – Receiver noise
  - 4.3m – Ephemeris error (orbit discrepancies)
  - 3.5m – Satellite clock errors
  - 6.2m – Ionospheric delay
  - 2.0m – Tropospheric delay
  - 3.0m – Multipath
- Make a fixed location measurement in a local area to check for these errors
- Broadcast this corrective information
The “A” in Assisted GPS for Cellular

- Handset receives synchronization cues
- Base station has information about local atmospheric delay
- Handset only calculates pseudo-ranges, sends to base station for the final calculations
- Principle issue is yield, not accuracy

Applications for Cellular Networks

- E911 Emergency Location
- Find a friend
- Site-specific advertising and vendor location
- Real-time traffic modeling
- Site-specific driving directions
- Smart network optimization (by carrier)

For Further Reading…

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

Cramer-Rao Lower Bound

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

\[ \text{Cov}(\hat{\theta}) \geq \text{Cov}_y(\theta) \]

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

- 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.

Numerical Result: NMRs Used

Using more NMRs increases location accuracy.

The location accuracy improves dramatically when the number of NMRs used increases from 1 to 10.

Phase I: Georgia Tech Campus Study
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

Level 0 Predicted Signal Database

Modified Hata Model:
\[ P_s = P_t + G_s + G_r + 10 \log_10 \left( \frac{d}{d_0} \right) - 20 \log_10 \left( \frac{f}{f_0} \right) + 30 \]
Indoor Location

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

RSSI-based system perhaps the only way to discriminate indoor/outdoor users.

Predicted Signal Database Modeling

Octant model of orientation loss
**Level 2 Predicted Signal Database**

Level 2: Calibration with outdoor measurements and indoor modeling

**Level 3 Predicted Signal Database**

Level 3: Calibration with exhaustive outdoor and indoor measurements

**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>Accuracy</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>Best</td>
</tr>
<tr>
<td>Generating Speed</td>
<td>Fast</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Very Slow</td>
</tr>
<tr>
<td>Generating Cost</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
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

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

Repeatability Measurements

- Head-handset shadowing
  - Measure tracks of data in the same area, but with different orientations
  - Average variation has \( \sigma = 2 \) dB
- Small-scale fading within a “bin”
  - Measure tracks of data through a bin
  - Note: pure Rayleigh fading predicts \( \sigma = 5 \) dB
  - Average variation of \( \sigma = 2 \) 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 perfect knowledge of the antenna/RF chain bias between the user handset and the scanner used to calibrated the PSD

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

<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</td>
<td>20%</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>&lt;300m</td>
<td>60%</td>
<td>90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Level 3 Indoor/Outdoor Meas.</th>
</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</td>
<td>54%</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>&lt;300m</td>
<td>94%</td>
<td>94%</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

<table>
<thead>
<tr>
<th>PSD level</th>
<th>Level 1 Indoor Meas.</th>
<th>Level 2 Indoor Model</th>
<th>Level 3 Indoor/Outdoor Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor/Outdoor</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
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<tr>
<td>Discrimination Rate</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Location Error Statistics</td>
<td>&lt;100 m</td>
<td>56%</td>
<td>65%</td>
</tr>
<tr>
<td>Error Statistics</td>
<td>&lt;300 m</td>
<td>96%</td>
<td>96%</td>
</tr>
</tbody>
</table>

RSS Indoor/Outdoor Discrimination
Algorithm: Location With Averaging

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

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

Comparison of Different Algorithms

<table>
<thead>
<tr>
<th></th>
<th>Abs</th>
<th>Relative</th>
<th>Hybrid</th>
<th>Hybrid with Averaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrimination Rate</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Best</td>
</tr>
<tr>
<td>Location Error</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Best</td>
</tr>
<tr>
<td>Statistics</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>Location Fix</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>Generation Time</td>
<td>Not good</td>
<td>Not good</td>
<td>Close</td>
<td>Satisfied</td>
</tr>
<tr>
<td>E911 Mandate</td>
<td>Not good</td>
<td>Not good</td>
<td>Close</td>
<td>Satisfied</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

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**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

Table 4.1 Discrimination rate by signal level of RSSs, distribution

<table>
<thead>
<tr>
<th></th>
<th>Indoor</th>
<th>Outdoor</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrim</td>
<td>28.71%</td>
<td>21.45%</td>
<td>27.33%</td>
</tr>
<tr>
<td>Overall</td>
<td>25.73%</td>
<td>29.92%</td>
<td>28.96%</td>
</tr>
</tbody>
</table>

GPS effectiveness

Table 4.2 Gps accuracy statistics based on Mobiware Indoor and outdoor measurements

<table>
<thead>
<tr>
<th></th>
<th>GPS valid</th>
<th>GPS not valid</th>
<th>Disturbance Occur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Outdoor</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

Table 4.3 Gps accuracy statistics. Barney's omnipresent vehicle scan

<table>
<thead>
<tr>
<th></th>
<th>GPS valid</th>
<th>GPS not valid</th>
<th>Disturbance Occur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Outdoor</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</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 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor/McC.</td>
<td>200 m</td>
<td>98%</td>
</tr>
<tr>
<td>Outside/McC.</td>
<td>500 m</td>
<td>79%</td>
</tr>
<tr>
<td>Percentage</td>
<td>80%</td>
<td>85%</td>
</tr>
<tr>
<td>Standard dev.</td>
<td>200 m</td>
<td>300 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

Figure 5b: Pseudo-transmitter case in an ultra-dense urban environment.

Example Indoor Prediction Mask

Location Results in Manhattan (Fall 2005)

<table>
<thead>
<tr>
<th>Error Statistics</th>
<th>Level 1 PSD</th>
<th>Level 2 PSD</th>
<th>Level 1 PSD</th>
<th>Level 2 PSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50m</td>
<td>25.3%</td>
<td>36.8%</td>
<td>67.4%</td>
<td>69.0%</td>
</tr>
<tr>
<td>&lt;100m</td>
<td>75.9%</td>
<td>77.0%</td>
<td>83.3%</td>
<td>85.1%</td>
</tr>
<tr>
<td>&lt;200m</td>
<td>92.0%</td>
<td>95.4%</td>
<td>92.0%</td>
<td>94.3%</td>
</tr>
<tr>
<td>&lt;500m</td>
<td>98.9%</td>
<td>100%</td>
<td>99.9%</td>
<td>100%</td>
</tr>
<tr>
<td>&gt;500m</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Level 1 PSD: RF database calibrated with outdoor measurement

Level 2 PSD: Calibration with outdoor measurement and indoor modeling
Radiolocation in Cellular Networks

by Prof. Gregory D. Durgin

Section III: Propagation/CSI

Acknowledgements
- Georgia Tech Foundation
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- Cingular (now AT&T)
- Comarco Wireless
- NSF CAREER Grant ECS-0546955
- Aerospace Corp.

Outline of Section III
- Path Loss Models
- Data Mining Propagation Elements
  - Antenna Patterns
  - Roads
  - Terrain Diffraction
  - Clutter Effects
- Crime-Fighting with Cellular
- Case Study: 2000 Dekalb Co. Murder Investigation
Tuning a Seidel-Rappaport Model

- This linear system is over-constrained.
- May be solved using MMSE Normal Equations:

\[ \mathbf{A}^T \mathbf{A} = \mathbf{A}^T \left[ y - 20 \log_{10}(d) \right] \]

where

\[ y = \begin{bmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \vdots \\ \mathbf{p}_N \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix}, \quad \mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_N \end{bmatrix}. \]

and

\[ \mathbf{A} = \begin{bmatrix} a_1 & b_1 & \cdots & z_1 \\ a_2 & b_2 & \cdots & z_2 \\ \vdots & \vdots & \ddots & \vdots \\ a_N & b_N & \cdots & z_N \end{bmatrix}. \]

Generalized Seidel-Rappaport Model

- Model distance-related loss as free space.
- Add attenuation factors for each object blocking the line-of-sight.
- Benefits
  - Intuitive
  - Fast computation
  - Linear optimization
- Pitfalls
  - Not deterministic
  - Requires some measurements for tuning.
For Cellular Location Systems, We Have
- Distance between base station and handset
- Bearing angle with respect to BS antenna
- Base station antenna height & downtilt
- Geographical Information Services
  - Terrain maps
  - Clutter maps
  - Road vectors
  - Building footprints (urban areas)

Distance-Related Losses
- Use a path-loss exponent model for loss
- Key differences
  - Other losses present
  - Typically lower than exponent-only models

\[
-10 \left( \frac{3.00}{2.60} \right) \log_{10}(d) + 2.17
\]

Example from 900 MHz Macrocells

Distance and Antennas Only

2 x 2.5 km Received Signal Strength Map
**Antenna Patterns**

- MMSE fit to a 4th-order harmonic expansion
- Most important is the first harmonic cos θ
- θ is angle between center sector and handset bearing angle
- *This model consistently outperforms the range-measure base station antenna patterns*

Table 1: Basic analysis of all data, sorted by frequency and base station type.

<table>
<thead>
<tr>
<th>Cell Type</th>
<th># Sites</th>
<th>Offset (dB)</th>
<th>cos θ</th>
<th>cos 2θ</th>
<th>cos 3θ</th>
<th>cos 4θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro 900</td>
<td>558</td>
<td>2.56</td>
<td>24.3</td>
<td>-6.5</td>
<td>-0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Macro 1900</td>
<td>2275</td>
<td>2.79</td>
<td>9.3</td>
<td>-9.7</td>
<td>0.0</td>
<td>-0.3</td>
</tr>
<tr>
<td>Micro 900</td>
<td>222</td>
<td>2.94</td>
<td>20.8</td>
<td>-4.7</td>
<td>-0.7</td>
<td>-0.8</td>
</tr>
<tr>
<td>Micro 1900</td>
<td>71</td>
<td>1.73</td>
<td>55.6</td>
<td>-4.3</td>
<td>-1.6</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

**Spatial Measurement Distribution**

*Figure 2.1: Three cases of measurement distributions in space.*

**Road Orientation Losses**

- Roads cut “channels” through environment
- Peak gain whenever BS bearing angle aligns with road
- Road orientation data is ubiquitously available
- Often requires conversion to raster format
**Geometry of the Diffracting Half-Plane**

- Incident Plane Wave
- PEC Screen
- Point of Observation

---

**Exact Solution for Diffracting PEC Edge**

- Total Field Solution for PEC Reflection
- Total Field Solution for PEC Transmission

---

**Geometrical Optics – Conducting Edge**

- Geometrical Optics Field, $E_{geo} (\text{dB})$
- Phase of the Geometrical Optics Field, $\phi_{geo}$
Sommerfeld Solution (Perp Pol)

Sommerfeld Minus GO (Perp Pol)

Sommerfeld Solution (Par Pol)
**Knife Edge Formula Minus GO**

Diffracted Field, $\mathcal{E}_d (\phi= 60^\circ)$

Phase of the Diffracted Field, $\mathcal{E}_d$

**Terrain Diffraction Example**

Wedge Geometry

Equivalent Screen Geometry

**Example: FM Propagation Over Terrain**

WREK transmits a 91.1 MHz FM radio signal with effective isotropic radiated power of EIRP = 54.0 dBW (about 250 kW). To reach one coverage area, the station must rely on double diffraction over the top of two terrain peaks of equal altitude that can be modeled as 90-degree wedges. How much received power would each GTD coefficient predict?