Radiolocation in Cellular Networks

by Prof. Gregory D. Durgin

Section I: RSS System Trials

Georgia Tech College of Engineering

The Propagation Group

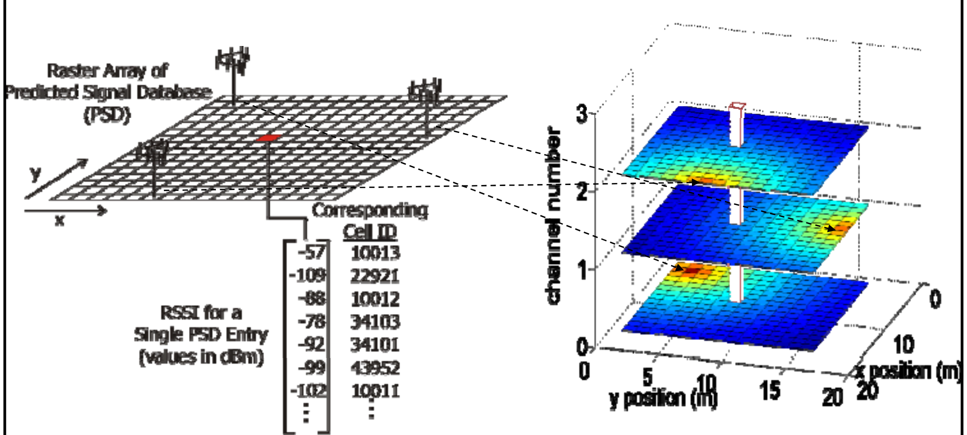
Outline of Section II

- 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

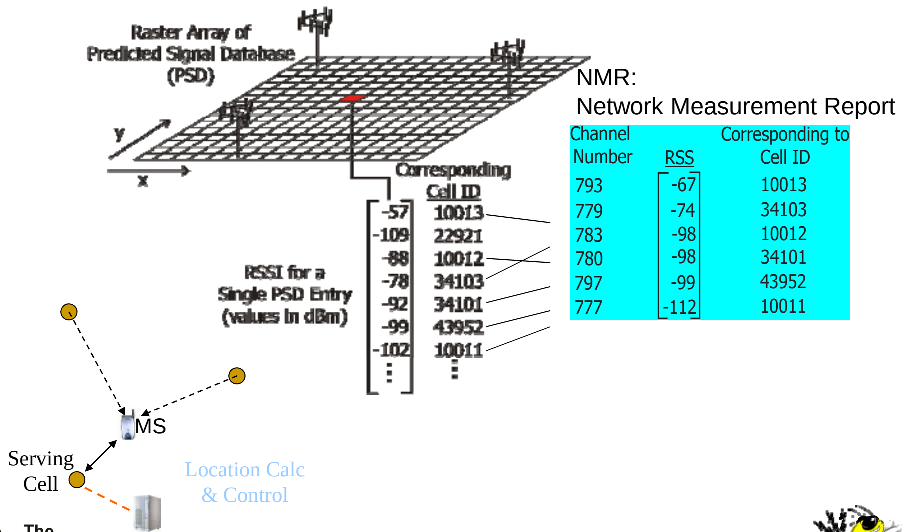
Why RSS Signature Location?

- 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



Cramer-Rao Lower Bound

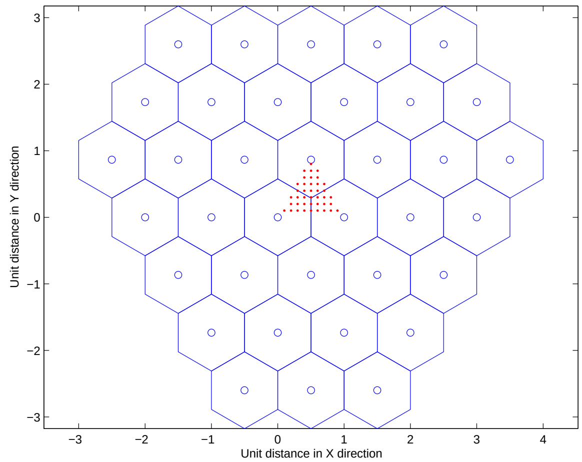
- The CRLB provides a lower bound on the covariance matrix of the unbiased estimator

$$\mathrm{Cov}(\hat{z}) \geq \mathrm{Cov}_{cr}(z)$$

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

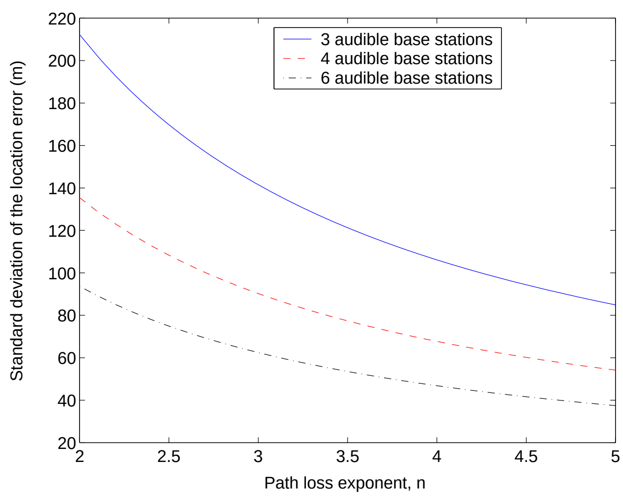
Number of NMRs: 30

Standard deviation of measurement error: 3.5

Number of audible base station: 4

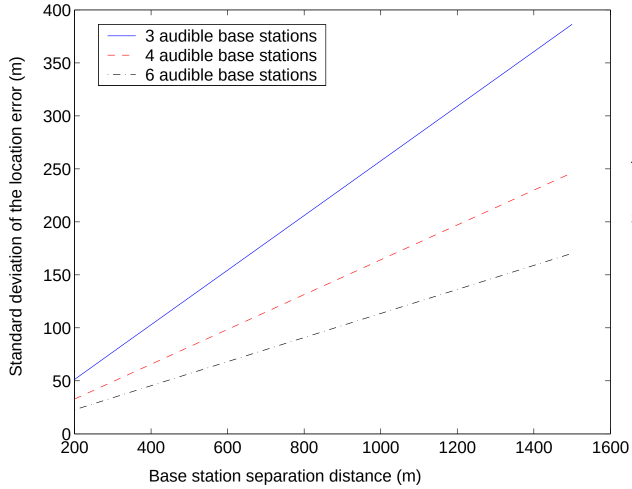
Output: 82.0 m

Numerical Result: Path Loss-Related



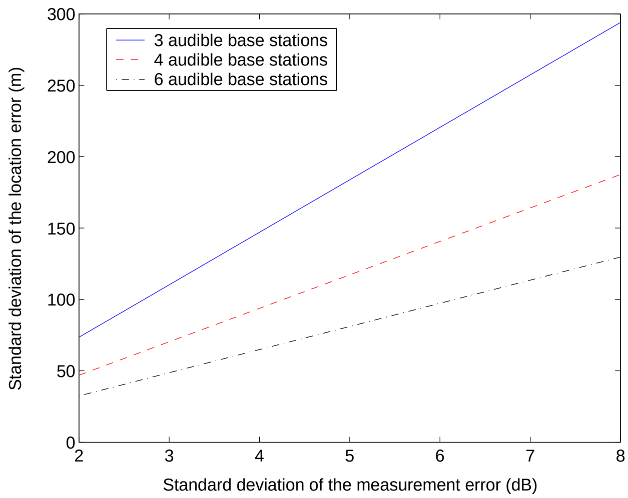
larger path loss exponent because higher path loss increases the uniqueness of the RSS signature.

Performance: Base Station Separation Distance



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

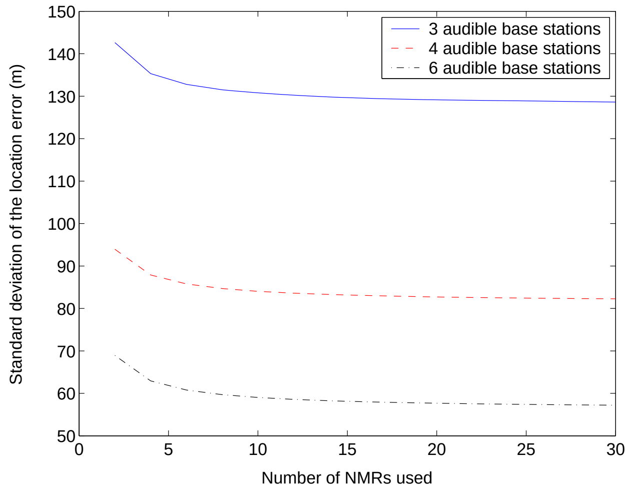
Numerical Result: Measurement Error-related



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.

Numerical Result: NMRs Used



Using more NMRs increase 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**

Comparison of Different PSDs

	Level 0	Level 1	Level 2	Level 3
Accuracy	Low	Moderate	High	Best
Generating Speed	Fast	Moderate	Moderate	Very Slow
Generating Cost	Low	Moderate	Moderate	High

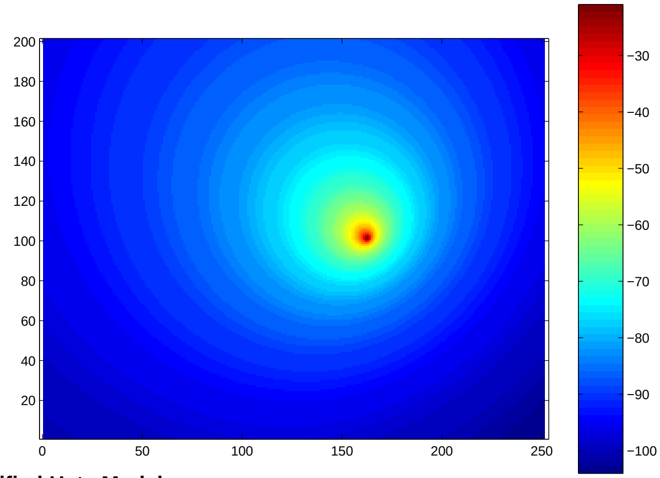
Level 0: Pure Prediction

Level 1: Calibration with outdoor measurement

Level 2: Calibration with outdoor measurement and indoor modeling

Level 3: Calibration with exhaustive outdoor and indoor measurements

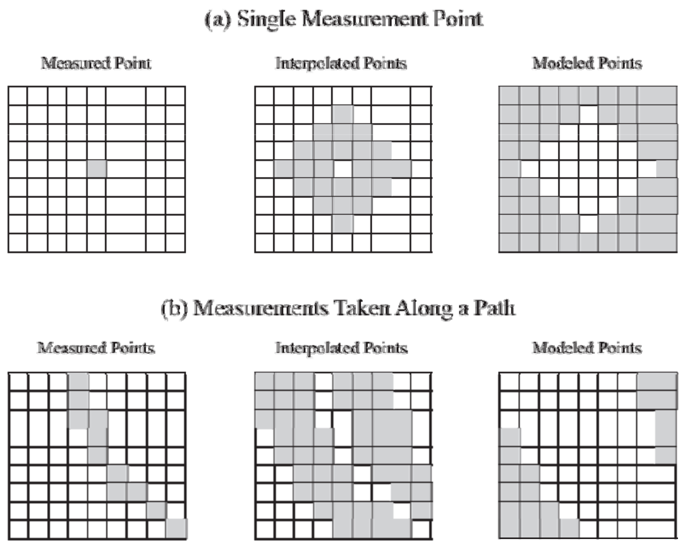
Level 0 Predicted Signal Database



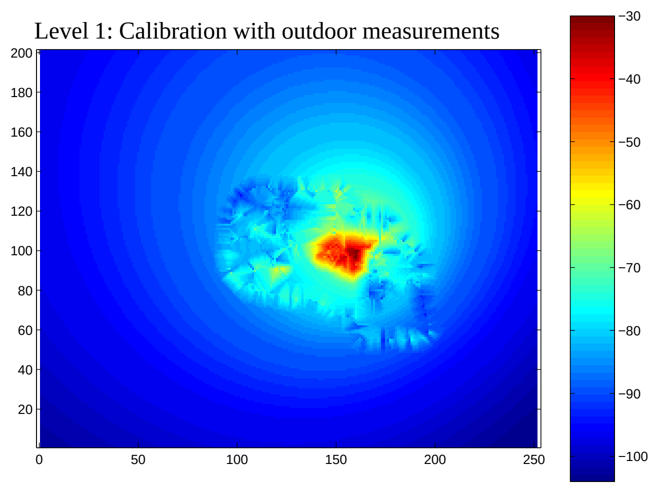
Modified Hata Model:

$$P_R = P_T + G_R + G_T \cos(\theta - \theta_t) - 10n \log_{10}\left(\frac{d}{1\text{ m}}\right) - 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + C_{\text{dB}}$$

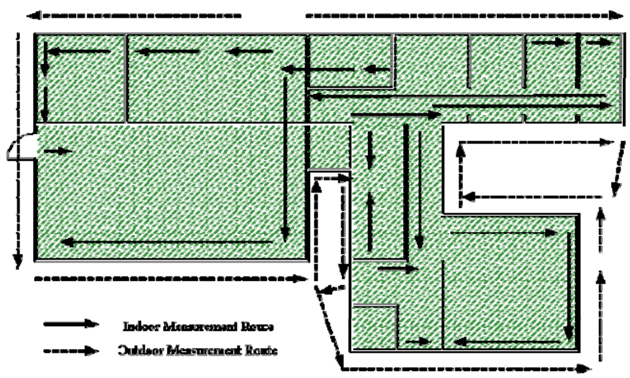
Level 1 Predicted Signal Database



Level 1 Predicted Signal Database



Building Measurement Sample



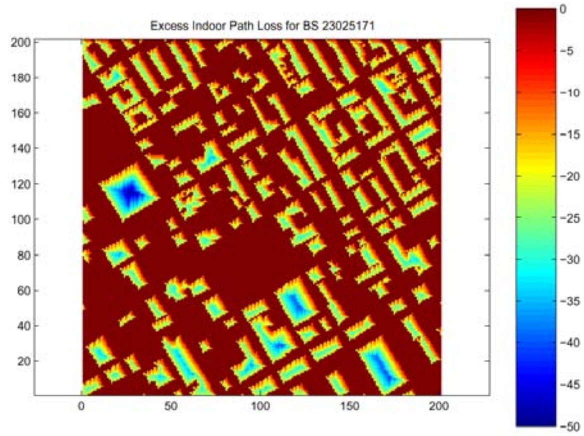
Measurement Route Record at Architecture Building

Measurement Photos

Indoor Location

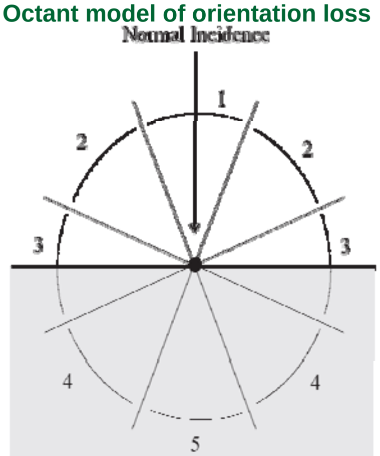
Stat: 67% of all European cell-phone calls are indoors.

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



Predicted Signal Database Modeling

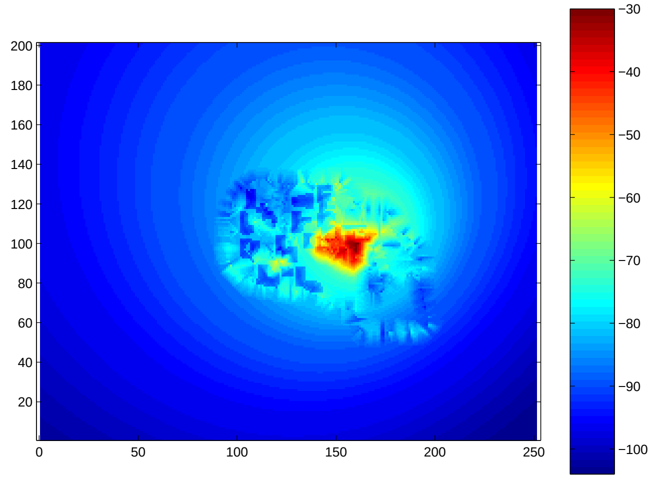
Octant model of orientation loss



Octant	1	2	3	4	5
Loss (dB)	7.5	8.3	8.9	9.3	9.2

Level 2 Predicted Signal Database

Level 2: Calibration with outdoor measurements and indoor modeling

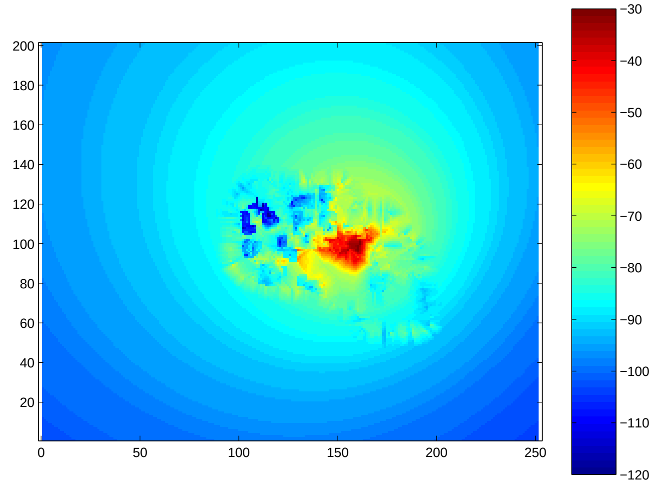


Collecting Handset Test Data

- 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
  - 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 σ = 2 dB
- Small-scale fading within a “bin”
  - Measure tracks of data through a bin
  - Note: pure Rayleigh fading predicts σ = 5 dB
  - Average variation of σ = 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 prefect knowledge of the antenna/RF chain bias between the user handset and the scanner used to calibrated the PSD

$$Nrssc_i = Nrss_i - \text{Bias} \qquad M = \sqrt{\sum_{i=1}^{N}(Prss_{x,y,i} - Nrssc_i)^2}$$

PSD level		Level 1 Outdoor Meas.	Level 2 Indoor Model	Level 3 Indoor/Outdoor Meas.
Indoor/Outdoor Discrimination Rate		32%	78%	86%
Location Error Statistics	<100m	20%	45%	67%
	<300m	60%	90%	95%

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Algorithm: Relative RSS Location

Relative RSS Location:

– Mean is removed from Both NMR and each roaster point in PSD

$$Prssr_{x,y,i} = Prss_{x,y,i} - \frac{1}{N}\sum_{j=1}^{N} Prss_{x,y,j} \qquad Nrssr_i = Nrss_i - \frac{1}{N}\sum_{j=1}^{N} Nrss_j \qquad M(x,y) = \sqrt{\sum_{i=1}^{N}(Prssr_{x,y,i} - Nrssr_i)^2}$$

PSD level		Level 1 Outdoor Meas.	Level 2 Indoor Model	Level 3 Indoor/Outdoor Meas.
Indoor/Outdoor Discrimination Rate		43%	43%	51%
Location Error Statistics	<100 m	54%	54%	60%
	<300 m	94%	94%	95%

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Algorithm: Hybrid RSS Location

Fact:

– **Indoor/Outdoor discrimination information is embedded in absolute RSS**

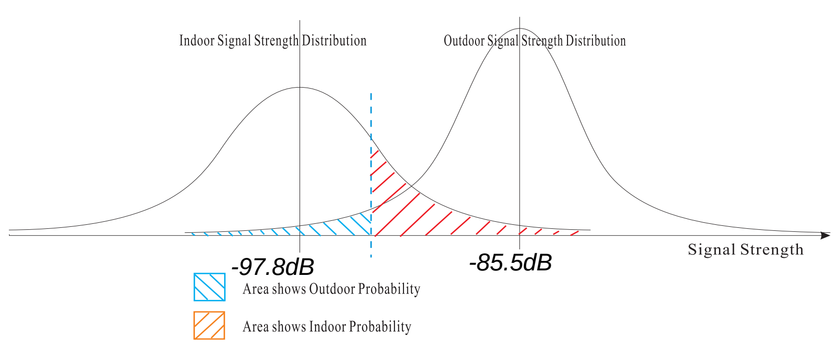
– **Fingerprint method is more accurate by using relative RSS information**

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.

RSS Indoor/Outdoor Discrimination



$$p(x) = \frac{1}{\sigma_i \sqrt{2\pi}} e^{-(x-\mu_i)^2/(2\sigma_i^2)}$$

$$P_i(x) = \frac{1}{\sigma_i \sqrt{2\pi}} \int_x^{-\infty} e^{-(x-\mu_i)^2/(2\sigma_i^2)} dx' = \frac{1}{2}[1 - \mathrm{erf}(\frac{x-\mu_i}{\sigma_i \sqrt{2}})]$$

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-(t)^2} dt'$$

Algorithm: Hybrid RSS Location

$$M_H(x,y) = M(x,y)/P_i(\sum_{i=1}^{N} Nrssr_i) \qquad M_H(x,y) = M(x,y)/P_o(\sum_{i=1}^{N} Nrssr_i)$$

PSD level		Level 1 Outdoor Meas.	Level 2 Indoor Model	Level 3 Indoor/Outdoor Meas.
Indoor/Outdoor Discrimination Rate		90%	90%	90%
Location Error Statistics	<100 m	56%	56%	65%
	<300 m	96%	96%	96%

Algorithm: Location With Averaging

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

PSD level		Level 1 Outdoor Meas.	Level 2 Indoor Model	Level 3 Indoor/Outdoor Meas.
Indoor/Outdoor Discrimination Rate		92%	92%	91%
Location Error Statistics	<100 m	61%	64%	78%
	<300 m	97%	98%	98%

Comparison of Different Algorithms

	Abs	Relative	Hybrid	Hybrid with Averaging
Discrimination Rate	Low	Low	High	Best
Location Error Statistics	High	Moderate	Low	Best
Location Fix Generation Time	Fast	Fast	Fast	Slow
E911 Mandate	Not good	Not good	Close	Satisfied

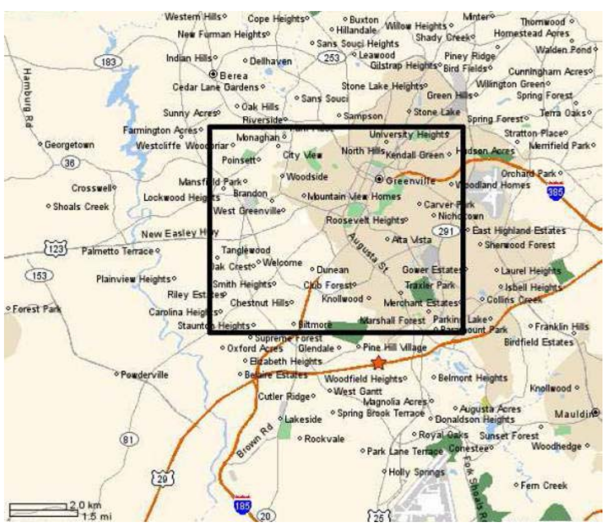
Phase I: Conclusions

- 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

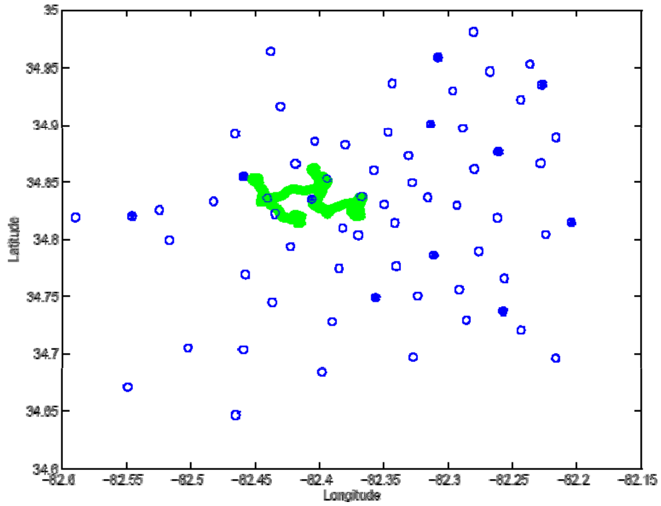
- **Different commercial network trials in varied environments**
  - Urban, suburban, rural environments in Triton's GSM network at Greenville, SC
  - Larger testing area allow the existing of egregious location error
  - The effect of high-rise building
- **Accurate propagation modeling**
  - Based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



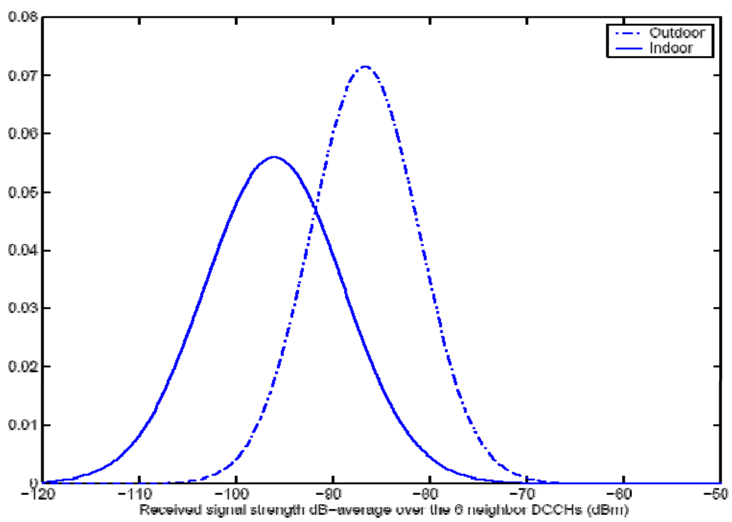
The 7000 m by 9000 m test area in Greenville, SC

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 s a single drive-test route through the test area.

RSS Indoor/Outdoor Discrimination



RSS Indoor/Outdoor Discrimination

Table 4.1 Discrimination rate by using handset RSSA distribution.

		Decision		Sub-Total
		Indoor	Outdoor	
Actual	Indoor	26,576 (35.9%)	12,690 (17.1%)	39,266 (53.0%)
	Outdoor	5,140 (6.9%)	29,719 (40.1%)	34,859 (47.0%)
Correct Rate		76%		

GPS effectiveness

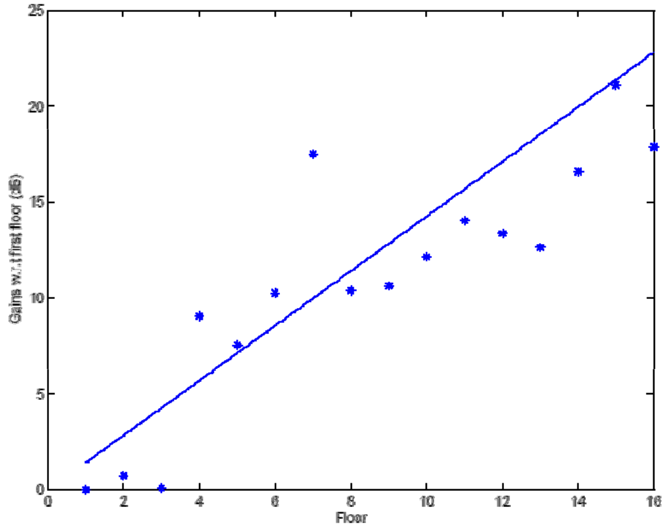
Table 4.2 Garmin V GPS effectiveness statistics based on 60,624 indoor and outdoor measurement records.

	GPS valid	GPS not valid	Sub-total
Indoor	4,069 (6.71%)	35,197 (58.06%)	39,266 (64.77%)
Outdoor	19,394 (31.99%)	1,964 (3.24%)	21,358 (35.23%)
Sub-total	23,490 (38.70%)	37,161 (61.30%)	60,624 (100%)

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

	GPS valid	GPS not valid	Measurement Count
Indoor	10.36% (4,069)	89.64% (35,197)	39,266(100%)
Outdoor	90.8% (19,394)	9.2% (1,964)	21,358(100%)

RSS in a High-rise Building



RSS Location Performance in Greenville

PSD level		Level 1 Outdoor Meas.	Level 3 Indoor/Outdoor Meas.
Error statistics	<100m	30%	51%
	<300m	71%	79%
Percentage statistics	66.7%	270 m	180 m
	95%	580 m	530 m

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

Figure 52: Sample outdoor driving test route in Manhattan, NY

Indoor Propagation Model

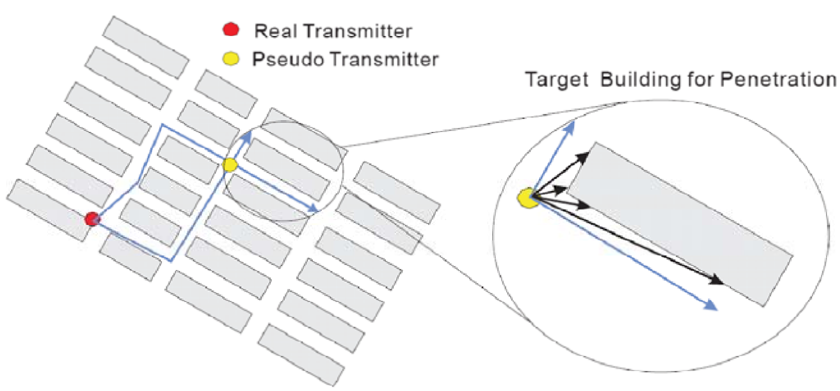
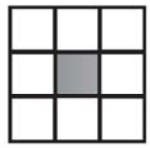
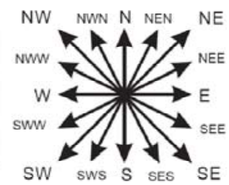


Figure 53: Pseudo-transmitter case in an ultra-dense urban environment.

Example Indoor Prediction Mask

	1	2	3	4	5	6	7	8	9	10	11	12	13				
1	0	0	0	0	-80	-82	-85	0	0	0	0	0	0				
2	0	0	0	0	0	0	-84	-86	0	0	0	0	0				
3	0	0	0	0	0	0	-100	-100	-84	-85	0	0	0				
4	0	0	-113	-116	-113	-106	-103	-106	0	-86	-81	-86	0				
5	0	0	-113	-116	-103	-106	-105	-106	-104	-104	0	-81	-80	-83	0	0	0
6	0	0	-111	-113	-95	-92	-98	-109	-99	-102	-105	-94	-99	-80	-80	-79	0
7	-62	-60	-61	0	-84	-91	-92	-92	-94	-81	-85	-102	-90	0	0	-80	-72
8	0	0	-61	-63	-96	-96	-91	-85	-87	-90	-84	-102	-90	-103	0	0	-76
9	0	0	0	0	-64	-57	-59	0	0	-90	-94	-99	-88	-82	0	-76	0
10	0	0	0	0	0	0	-61	-57	-62	-80	-83	-90	-90	-84	-74	-74	0
11	0	0	0	0	0	0	0	0	-59	-62	0	0	0	0	-72	0	0
12	0	0	0	0	0	0	0	0	0	-56	-57	-52	0	-60	-69	0	0
13	0	0	0	0	0	0	0	0	0	0	0	-51	-54	-56	0	ST	0





Indoor Pattering Block

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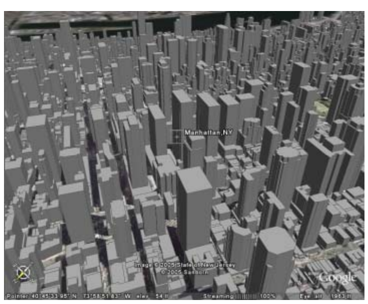
Location Results in Manhattan (Fall 2005)



Level 1 PSD: RF database calibrated with outdoor measurement

Level 2 PSD: Calibration with outdoor measurement and indoor modeling

		Indoor Test Points		Outdoor Test Points	
PSD Level		Level 1 PSD	Level 2 PSD	Level 1 PSD	Level 2 PSD
Error Statistics	<50m	25.3%	36.8%	67.4%	68.0%
	<100m	75.9%	77.0%	83.5%	85.1%
	<150m	92.0%	95.4%	92.5%	95.3%
	<300m	98.9%	100%	99.1%	100%
	<500m	100%	100%	100%	100%

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Technical Reports…

Indoor/Outdoor Location of Cellular Handsets Based on Received Signal Strength (GT)

J. Zhu, G.D. Durgin,
PG-TR-0408018-JZ, 7 June 2004, 87 pages

This report documents an ambitious experiment to turn the campus of Georgia Tech into the world's first indoor/outdoor E911 position location laboratory.

http://www.propagation.gatech.edu/Archive/PG_TR_040608_JZ/PG_TR_040618_JZ.pdf

Extended Indoor/Outdoor Location of Cellular Handsets at Greenville, SC

J. Zhu, G.D. Durgin
PG-TR-050215-JZ, 15 Feb 2005, 97 pages

This report details a set of experiments in Greenville, SC for determining the performance statistics of a received-signal strength location method in a wide-area cellular network.

http://www.propagation.gatech.edu/Archive/PG_TR_050215_JZ/PG-TR-050215-JZ.pdf

Indoor/Outdoor Location of Cellular Handsets Based on Received Signal Strength

J. Zhu
PG-TR-060515-JZ, 15 May 2006, 123 pages

J. Zhu's final dissertation on radiolocation in cellular networks using received signal strength. This research includes results from an indoor/outdoor campaign in Manhattan, NY.

http://www.propagation.gatech.edu/Archive/PG_TR_060515_JZ/PG_TR_060515_JZ.pdf

For Further Reading…

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[4] K. Pahlavan and J. Makea X. Li, “Indoor Geolocation Science and Technology,” *IEEE Communications Magazine*, vol. 40, no. 2, pp. 112–118, Feb 2002.

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