The
Propagation
Group

Georgia Institute
of Technology

Extended Indoor/Outdoor Location of Cellular Handsets Based on Received Signal Strength at Greenville, SC

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EXECUTIVE SUMMARY

This report documents an intensive, two-month measurement campaign exploring the performance of cellular handset location systems based on received signal strength (RSS). Building upon the success of the original Georgia Tech campus E911 location experiments, the new results in this report demonstrate the feasibility of RSS-based location in a 1920 MHz GSM network where the majority of calls originate *indoors*. Since most cell phone calls nowadays are believed to originate indoors (exactly where most proposed position location solutions fail), the ability to locate in-building E911 calls is a huge public safety problem.

The results from this experiment are quite promising, however. The highest level of accuracy achieved by our location algorithm across the entire network was 51% of all test points having location error less than 100m and 79% having location error less than 300m. Although these numbers are slightly below the respective 67% and 95% safety targets set by the FCC, the Greenville trials represent a worst-case scenario for an RSS location system: a largely rural area with low density of base stations and a majority of indoor callers.

The engineers from Georgia Tech's Propagation Group compiled test measurements that included indoor data from 1 four-story hotel, 2 high-rise office buildings, 1 eight-story residential complex, 1 five-floor parking garage, 15 stand-alone restaurants, 23 small downtown shops, 1 grocery store, 2 department stores, and a variety of retail and shopping center structures. All of this data had to be painstakingly logged into georeferenced maps by hand since the GPS unit failed to acquire an indoor position 90% of the time. In addition to the extensive indoor measurements, the field engineers also collected numerous tracks of outdoor pedestrian test data and outdoor drive-test data. The end result is an extensive indoor/outdoor testbed for position location experiments that covers 63 square-kilometers of urban, suburban, and rural areas and contains nearly 90,000 measurement records.

In arriving at the performance statistics, a number of position location innovations were made and documented along the way. These include

- a new search-area limiting algorithm based on novel pieces of information in a network measurement report (NMR) (Section 6.1.3)
- an improved algorithm for estimating a handset location from a sequence of multiple NMRs (Section 6.1.4)
- new indoor penetration loss statistics for 1920 MHz (Section 4.1)
- demonstration that an RSS location system can still function after a major frequency plan change in the middle of a data collection (Section 5.1)

Overall, the results of this experiment reveal interesting behavior of RSS-based position location that confirm the technology as an accurate, cost-effective way to improve public safety.

Chapter 1

INTRODUCTION

This report documents the results of an extended set of experiments for mobile handset location within a commercial cellular GSM network in Greenville, SC.

A previous measurement campaign on the Georgia Tech campus indicated that RSS-based techniques can approach or even exceed the FCC guidelines of 100m accuracy 67% of the time and 300m accuracy 95% of the time for a network with a majority of indoor users. This performance was demonstrated on a 850MHz TDMA network with average cell size of 600m in diameter. A limitation of this previous measurement campaign was the small size of the testing and simulation area is limited (2000 m by 2500 m), which may hide some of the egregious errors that can happen in a full-sized network.

The Greenville measurement campaign documented in this report was performed within a GSM network, which has an average cell radius of 1800m. Since the cell radius has increased about 4 times compared to the previous location in urban Atlanta, the cell coverage area has increased by a factor of 16. Furthermore, the total test area is a much larger area (7000m by 9000m) to allow for the possibility of egregious errors in the location estimate.

The results in this extended study show that RSS location techniques can approach the FCC E911 requirements for *indoor* handset locations— even in a mix of urban, suburban, and rural areas. The tabulated performance results of the location engine are discussed in detail in Section 6.1.4 using a relative RSS method with a new search-area limiting algorithm, a sequence of 10 network measurement reports, and RF maps calibrated with both outdoor and indoor measurements. The error distance in this case is 100m or less 51% of the time and 300m or less 79% of the time. The location algorithm must be improved to meet FCC E911 requirement for a stand-alone system, but the result shows excellent potential for cellular networks with large amounts of *indoor* callers.

The Greenville test zone contains a mix of urban, suburban, and rural areas. The measurement campaign lasted for 3 weeks (Dec 13,2004 -Dec 31, 2004). The major sources of error for this analysis include the following: 1) old Geographic Information System (GIS) data, 2) Global Positioning System (GPS) errors in data logging, and 3) compensation for a major frequency plan change that occured in mid-campaign.

Chapter 2

MEASUREMENT PLAN

All measurements were taken in Greenville, SC, which is the area surrounded by the box in Figure 2.1. This 7000 m by 9000 m region was selected as the experimental test area. In this large area, 9 small test areas (test spots), and over 50 buildings were measured. Nearly 90,000 active call network measurement reports (NMRs) were recorded from the Ericsson TEMs handset.

The distance between base stations in Greenville was approximately 1700-2000 meters. 24 microcells and no macro cells exist in the testing area. Another 24 microcells exist in the surrounding area. The building construction style varies from steel and concrete with brick surfaces to wood frame and pre-fabicated/ mobile home units. Terrain in the Greenville area is relatively flat with small hills, but becomes mountainous outside the suburban area.

2.1 Setup Overview

Our measurement was performed with an Ericsson's TEMS measurement unit. The scanner data was collected by running the measurement handset in scanner mode and using an external whip antenna, which has higher gain than the handset antenna. This antenna was placed on top of the moving car during collections. The scanner data is used to calibrate the Predicted Signal Database (PSD). Handset active call data

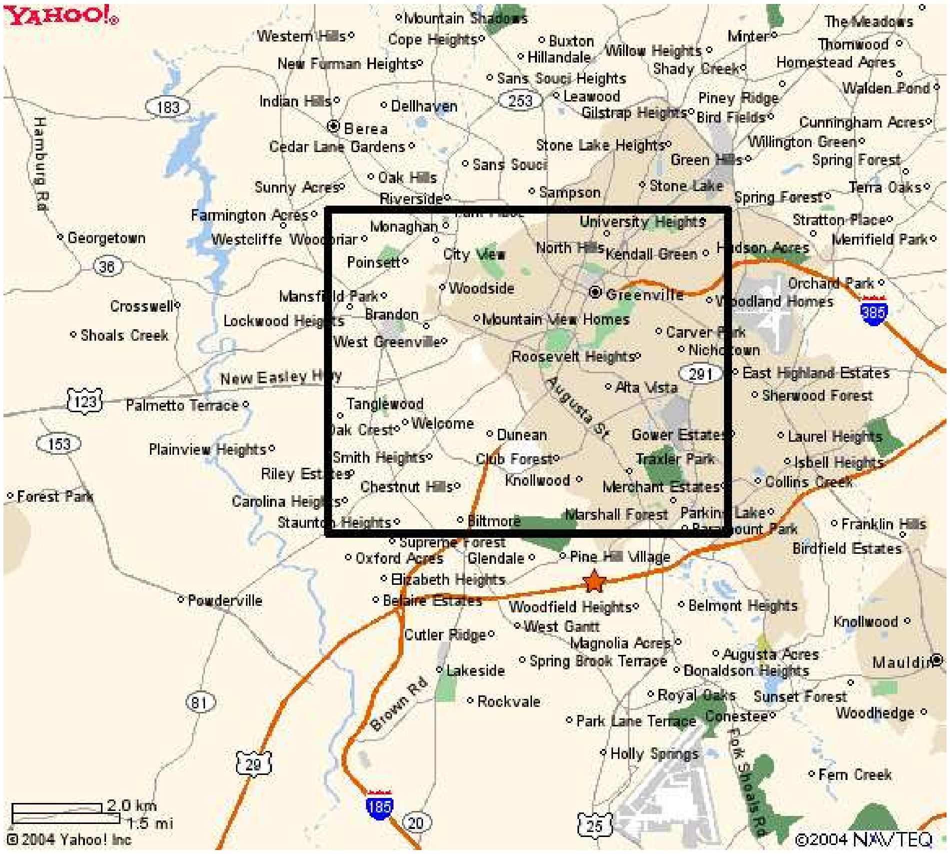

Figure 2.1 The 7000 m by 9000 m test area in Greenville, SC

was collected by the same TEMS unit but with the handset antenna—a short whip connected to the phone.

To measure as much area as possible, drive-test measurements, outdoor walking measurements, and indoor walking measurements were taken. The drive-test measurements were used to construct a calibrated RF map database. These measurements provide a fast way to measure across a large outdoor area. The walking measurements collected active call network measurement reports and filled in the holes where the drive-testing could not access.

2.2 Equipment and Calibration

2.2.1 Ericssion TEMS Unit

The Ericssion TEMS is a portable device for RF scanning and active call measurement. The hardware components of the system include one ERICSSON TEMS handset, a Garmin GPS V, and a laptop with 2 serial ports. The total weight of this system is about 7 lbs. The scanning function of this TEMS unit was used to collect data for PSD calibration. We programmed the 30 channels (Absolute Radio Frequency Channel Number 512-526 and 786-800) to correspond with the base stations around the test area in Greenville, SC. The Ericssion TEMS unit also provides the function to record the active call data that includes network measurement reports (NMRs). This active call function is used to collect NMRs for testing the performance of the RSS location engine.

2.2.2 Calibration Procedure

A standard free-space calibration procedure was employed on each day of RF measurement to monitor the integrity and consistency of the test system. The calibration consisted of spatially-averaged power measurements taken in an outdoor area without large obstacles in the nearby area. The calibration data was taken at the start and the end of each day. The spatially-averaged power measurements were compared to verify the consistency of the RF equipment and to monitor any cellular network change at the calibration area.

For the period Dec 13, 2004 to Dec 17, 2004, the calibration was performed in front of the parking lot of the Budget Inn at 10 Mills Avenue Greenville, SC 29605. For the day of Dec 23, 2004, the calibration was performed in the parking lot of the shopping mall at 3401 W Blue Ridge Drive Greenville, SC 29611. For the peroid Dec

29, 2004 to Dec 31, 2004 the calibration was performed in front of the parking lot of the Valu-Lodge Inn at 107 Duvall Drive Greenville, SC 29607.

The basic calibration procedure for the RSSI measurement system was as follows:

1. Define Calibration Paths: The calibration path should be selected in an outdoor open area without any large or mobile obstacles. The surroundings of the selected calibration area should be relatively open and have good vision to the sky in all directions. The path of the calibration is a straight line of length 30 m from start point A to end point B, whatever the orientation. The calibration route is large enough to provide a variety of RSSI measurements within a local area, but small enough not to introduce significant large-scale variations in the average RF power.

Figure 2.2 Photograph of TEMS unit setup view

2. System Setup: To begin a day of measurements, the RF measurement system was connected according to the diagram in Figure 2.2 and 2.3. The handset

Figure 2.3 Photograph of TEMS unit connection view

should be held vertically and over the field engineer's head to avoid any head-shoulder shadowing effects. The Garmin V GPS antenna should also be held above the shoulder, set at a vertical orientation, and kept free from obstacles to 80% of the sky. The laptop was held in front of the field engineer's chest in a custom harness.

3. Acquire Data: The equipment is set to measure using the handset. Data is acquired by moving slowly from start point A towards end point B and then returning to point A, This sequence is repeated 3 times. Movement during calibration is slower than 1.3 miles-per-hour to ensure sufficient amounts of data is logged.

4. Post-processing: The data is then immediately downloaded to a computer for analysis. For every dedicated control channel (DCCH) measurement, the RSSI

values taken around each calibration route are linearly-averaged to produce a single average signal strength measurement in dBm free from small-scale fading effects. Four checks for the DCCH records with RSSI values higher than -105 dBm are performed at this point in the procedure:

[a] Long-Term Consistency Check: The average RSSI values are compared with those taken on previous days. If RSSI values differ from previous measurements by +/- 3 dB, a thorough system check is performed.

[b] Short-Term Consistency Check: For an end-of-day calibration, average RSSI values are compared to the start-of-day calibration.

[c] GPS Position Check: GPS operation is verified by comparing the readings to previous GPS measurements.

[d] Record and Save Average RSSI Values: The average values are dated and recorded for future use. In constructing an RSSI database that uses measurements spanning multiple days, it may be necessary to normalize each day's measurement against the calibration measurements.

5. Repeat Procedure: The calibration procedure is repeated using the identical procedure at the end of a measurement day.

6. On-site Check: The following procedure should be performed before taking measurements at any location:

[a] Clock synchronization check: Since the time stamp is the only link between NMRs and the GPS fix program, the synchronization between the TEMS system clock and the laptop system clock should agree with less than 1 second of difference.

[b] Active call check: Run the script to repeat dialing 611 for customer service to get continuous active call network measurement reports.

[c] Record file size check: Once the system begins recording a file, the record file size should keep increasing. Begin data collection after the recording file size is larger than 18kB to ensure that the TEMS software is setup correctly.

By going through the calibration procedure, a network frequency optimization was instantly detected on Dec 17, 2004. DCCHs at testing areas were changed from Absolute Radio Frequency Channel Number (ARFCN) 786-800 to ARFCN 512-526. Section 5.1 discusses how this change was accommodated in the experiment without having to re-collect a week's worth of data.

Chapter 3

DATA COLLECTION

3.1 Building Construction

Building material and design of exterior walls determine the penetration loss experienced by radio waves that enter a building. This penetration loss information is very useful in discriminating between indoor and outdoor calls. In the previous Georgia Tech campus experiment, the penetration loss for typical urban office buildings from a statistical point of view was reported to be 12.3 dB [Zhu04]. The buildings set in this Greenville experiment are quite different from the Georgia Tech campus buildings, which were mainly steel, concrete, and brick. The building materials at Greenville are mainly brick and concrete in the downtown area and partially modular units and wood in other areas.

3.2 Frequency Plan Change

A new complication to the Greenville experiment was the mid-measurement frequency plan change made by the local cellular carrier. Our subsequent compensation for this change demonstrates that real-life network modifications can be considered through data adjustment and software with out have to re-collect existing data.

The DCCH channels were changed during the measurement campaign on Dec

17, 2005. This frequency plan change was applied to the entire network. DCCHs originally at ARFCN 786-800 range were moved to ARFCN 512-526 by the carrier, a 55MHz change in carrier frequency in the 1920 MHz band. This network optimization change was limited to the DCCH frequency plan only. No tower transmit powers were reassigned. One drive test was performed before the frequency plan change on Dec 16, 2004 and another drive test was performed after the frequency change on Feb 01, 2005.

3.2.1 Drive Test Measurement

Drive test measurements were used to calibrate the PSD. The procedure is similar to the drive test measurements conducted by wireless service providers to optimize their network. The TEMS unit was placed in a vehicle with an external scanner whip antenna mounted on the vehicle rooftop. A GPS antenna was also placed on the rooftop of the vehicle. RSS information from ARFCN 512-526 and ARFCN786-800 was collected in the testing area. Two drive test measurements were performed in this measurement campaign. The first one occurred before the frequency plan change, the other one after the change.

Figure 3.1 and Fig. 3.2 show the routes of the drive test measurements. Data was collected on all high ways and major roads within the test area. Only a portion of minor streets were driven, although all streets in the downtown urban section were driven at least once.

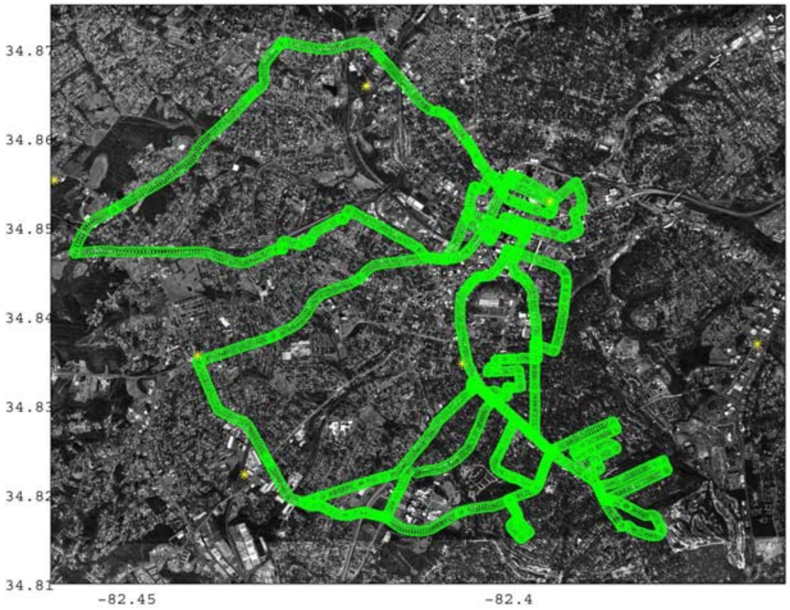

Figure 3.1 Drive test measurement routes collected on Dec 16, 2004 in Greenville, SC.

3.2.2 Walking Measurement

Because the drive test measurements are limited to roadways, the RSS inside a building or on a pedestrian path cannot be measured. Walking measurements become the key for filling in the gaps in the RF maps database (also called PSD). The field engineer must walk and collect data both inside and outside a building while holding the handset in a realistic position to make the RSS have the same propagation features as an active call made by a cellular phone customer. Thus, our active call data contains polarization, body shadowing, and pedestrian-speed, small-scale fading effects.

The outdoor walking measurements collect the RSS and serving cell information in the form of an NMR. Most importantly, the outdoor walking measurements may contain a GPS fix reported from the Garmin GPS V unit with accuracy better than

Figure 3.2 Drive test measurement routes collected on Feb 01, 2005 in Greenville, SC.

10 m. These outdoor walking measurements can be used to verify the GPS correction for walking measurements made inside adjacent buildings. All the NMRs collected during the outdoor walking measurement were split into two groups: one group to calibrate the PSD and the other group to test the RSS location. These groups of data are kept separate so that we are not testing the location engine with the same data used to calibrated it, thereby making the results seem overly optimistic.

Because the outdoor walking measurements are primarily meant to assist indoor GPS corrections and help in penetration loss calculations, they should follow two requirements: 1) they must be performed under a clear sky condition (if possible) to provide a good satellite channel for the GPS unit to have an accurate location fix. 2) they must follow a pedestrian style walk while the field engineer maintains the posture of a typical cell-phone call with handset pressed to head.

Figure 3.3 and Figure 3.4 show typical outdoor walking measurements.

Figure 3.3 Georgia Tech student research Albert Lu and Jian Zhu take an outdoor walking measurement

Figure 3.4 Georgia Tech student research Albert Lu and Jian Zhu take an outdoor walking measurement

The indoor walking measurements collect NMRs for calls originating indoors. Because there is no “open sky conditions” the GPS unit is not providing any location fix during the indoor walking measurement. The GPS fix program “GPSFixerV3.fig” was used to correct the GPS location by converting the selected path on an aerial photograph of the test spot into a GPS location fix. Thus, all of our indoor data is stamped with a precise longitude and latitude.

Figure 3.5 and Figure 3.6 show typical outdoor walking measurements.

Figure 3.5 Georgia Tech student research Jian Zhu and Professor Gregory Durgin take a walking measurement in a downtown Greenville eatery.

The following procedure for indoor measurement should be followed to ensure an accurate data collection:

1. Decide a measurement route in each room that covers most of the area, space permitting.
2. Move at a constant speed. If the route is less than 10 meters, move backward and forward several times to make sure the measurement time lasts at least 30 seconds.

Figure 3.6 Georgia Tech student research Jian Zhu and Professor Gregory Durgin take a walking measurement on the 9th floor of an office building.

3. Mark the route on a map in real time at each turn point.
4. Repeat 1-3 for all routes within the same building.
5. Walk around the outdoor perimeter and mark down the outdoor route in real-time for GPS correction verification.

3.3 GIS Data

The principle source of GIS in the study is a high-resolution database of aerial photographs of the city of Greenville. This GIS image contains photographic pixels with 1 m × 1 m resolution. The image was constructed in 1994 – nearly 10 years prior to the measurement campaign. Some of the buildings are not on this image and some buildings have been replaced.

Ths source of this GIS data is Terra Server USA at terraserver-usa.com. Small map pieces are downloaded in 200 m by 200 m size and reassembled to form an aerial photograph for the entire test region.

Chapter 4

DATA ANALYSIS

4.1 Handset RSS Distribution

Just as in the previous location experiment on the Georgia Tech campus, the information used to discriminate between the indoor and outdoor calls is mainly embedded in the absolute value of the RSS. *Received signal strength aggregate* (RSSA) was used to decide whether a call comes from an indoor or outdoor location.

4.1.1 Indoor RSS Distribution

RSSA is defined as the linear average RSS over the six neighbor DCCH channel [Zhu04]. The RSSA is assumed to be log-normally distributed. Figure 4.1 shows the comparison between the theoretical log-normal assumption and the statistical result. The biggest discrepency between the empirical distribution and the empirical log-normal distribution is the noise floor of the handset RF chain. The handset can only measure signals with strengths higher than -109 dBm and the linearity for the signal with strengths between -109 to -100 dBm is poor. For the indoor case, the peak at -107 dBm is mainly the result of this noise floor.

Based on our experiment, the mean of indoor RSSA is -96.0 dB and the standard deviation is 7.1 dB. The statistics from the measurement and the theoretical distributions are shown in Figure 4.1.

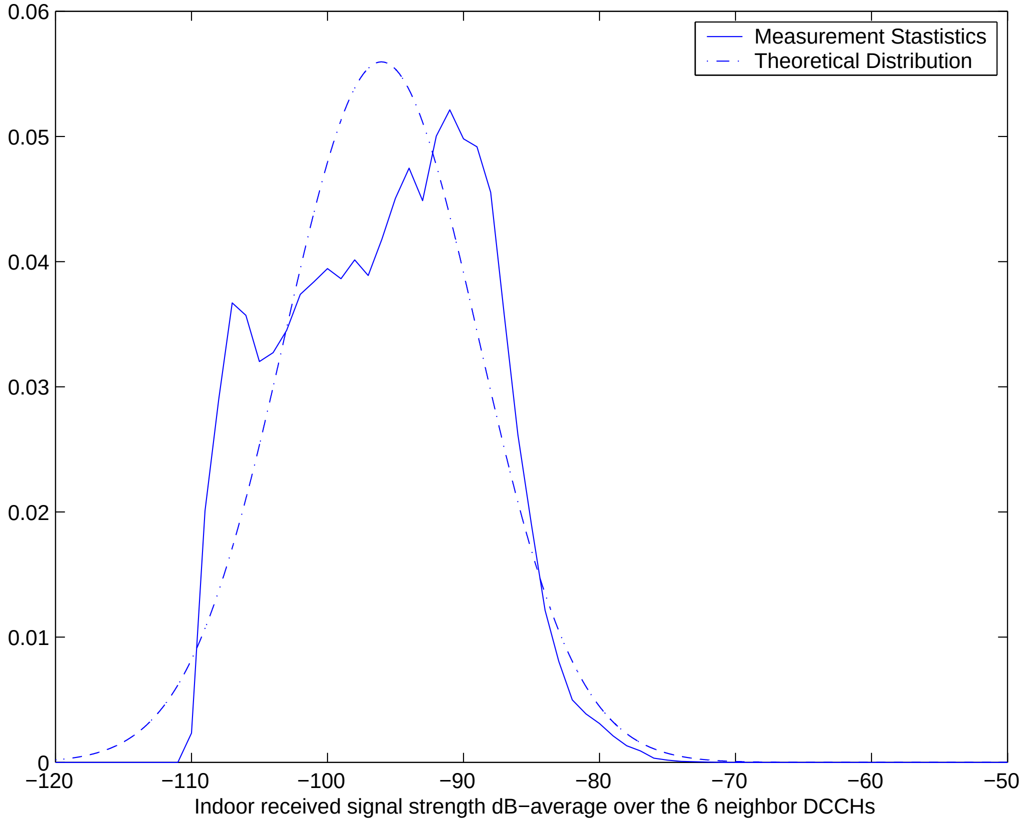

Figure 4.1 Indoor Received Signal Strength Aggregate (RSSA) distribution measured in Greenville, SC.

4.1.2 Outdoor RSS Distribution

The local peaks at -101 and -110 dBm are also the results of noise-induced nonlinearity of the handset RF chain.

Based on the active call data, the mean outdoor RSSA is -86.7 dBm and the standard deviation is 5.6 dB. Figure 4.2 shows the empirical distribution for outdoor RSSA.

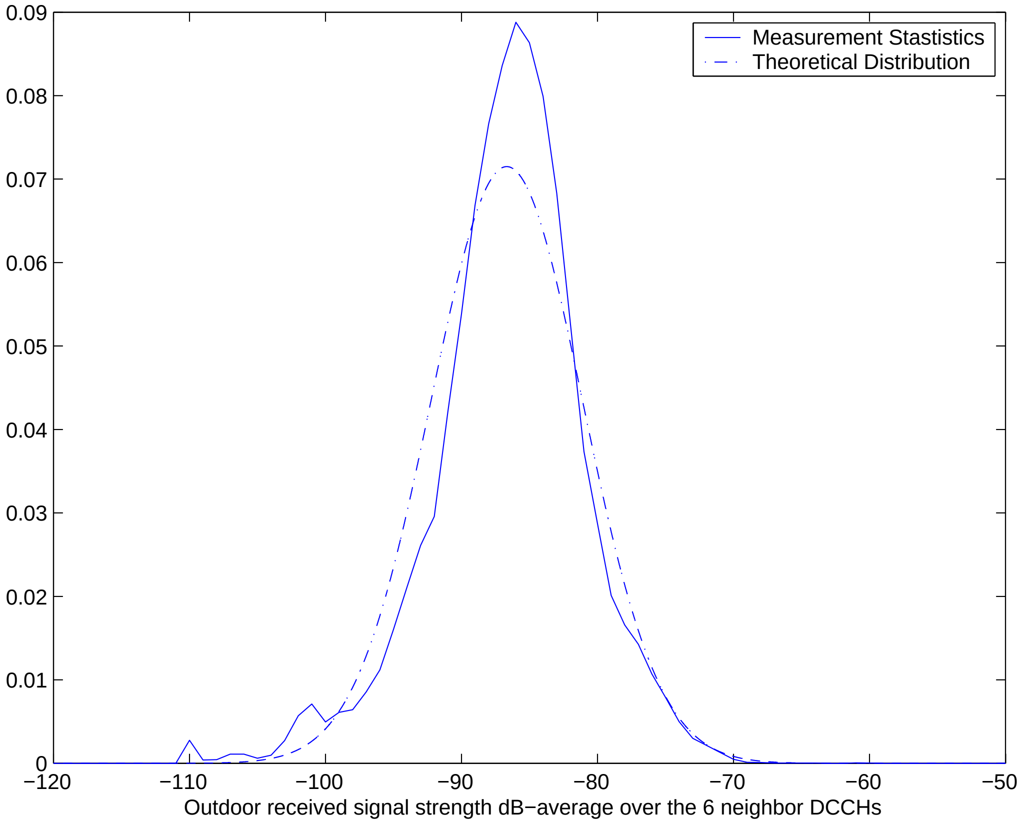

Figure 4.2 Outdoor Received Signal Strength Aggregate (RSSA) distribution measured in Greenville, SC.

4.1.3 Indooor/Outdoor Comparison

Figure 4.3 shows the difference between indoor calls and outdoor calls in side-by-side plots. Recall that there is a large standard deviation of indoor RSSA (14.1 dB) when compared to outdoor RSSA (9.7 dB) in the Georgia Tech campus measurement campaign. The trends of a large standard deviation of indoor RSSA (7.1 dB) compared to outdoor RSSA (5.6 dB) is also observable in the Greenville measurement campaign. The mean indoor RSSA is 9.4 dB lower than the outdoor RSSA, which is a smaller difference than that observed in the Georgia Tech campus campaign (12.3 dB). There are several reasons for the difference. First, the building construction materials are different. Most of the buildings in the Georgia Tech campus are made of brick and concrete. The buildings in Greenville measurement campaign are made of mixed materials such as modular pieces and wood as well as brick and concrete. Second, the difference between the RF chains of GSM vs. IS-136 handsets may also lead to discrepancies. Third, the carrier frequency was 850MHz for the Georgia Tech campus measurement and 1920MHz for the Greenville measurements; this difference is likely large enough to change large-scale path loss characteristics.

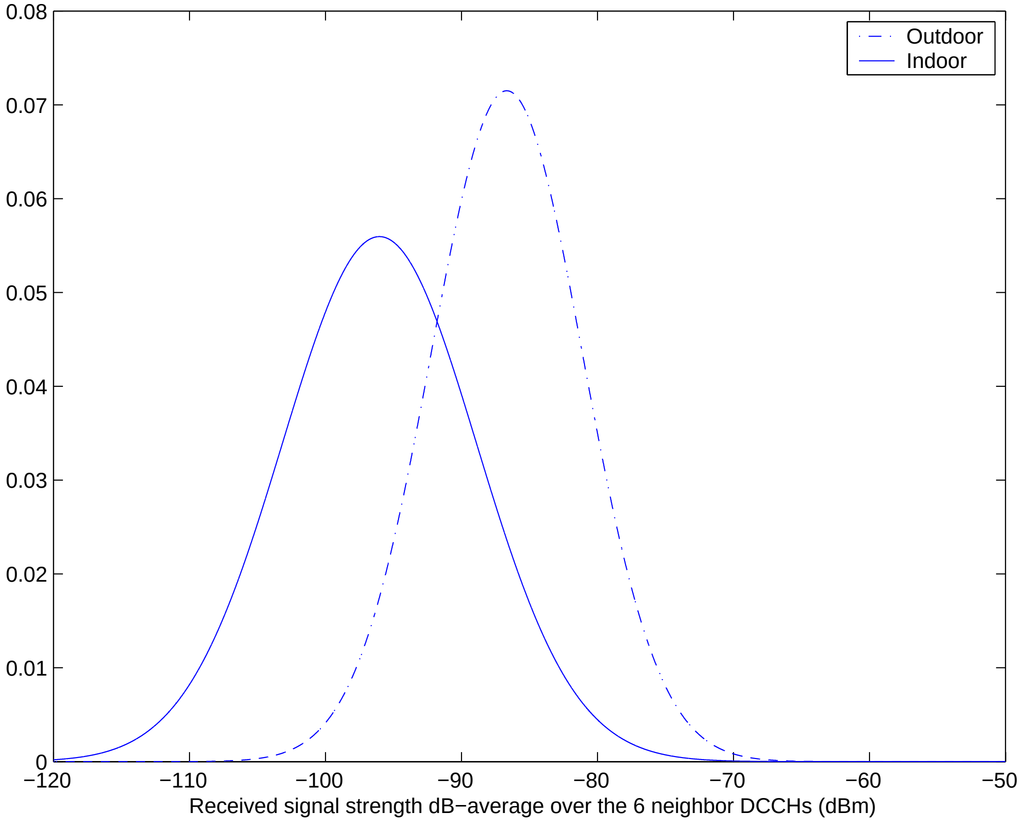

Figure 4.3 Indoor and outdoor RSSA theoretical distribution.

4.2 Indoor/Outdoor Discrimination Rate

Based on the RSSA theoretical distribution. The threshold (x_{th}=-91.8 dBm) is calculated in Equation 4.2.1:

$$\frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{(x_{th}-\mu_i)^2}{2\sigma_i^2}} = \frac{1}{\sqrt{2\pi}\sigma_o} e^{-\frac{(x_{th}-\mu_o)^2}{2\sigma_o^2}} \tag{4.2.1}$$

The decision of Indoor/Outdoor is made by comparing RSSA with the threshold. If the RSSA is lower than the threshold, the decision is "indoor". Otherwise, the decision is "outdoor".

Table 4.1 shows the proposed discrimination method made correct decisions 76% of the time, which is the number of indoor test points that were correctly identified (35.9%) plus the number of outdoor points that were also correctly identified (40.1%).

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%		

4.3 GPS effectiveness

Global Positioning System (GPS) is an accurate location technology which provides location fixes with less than 10 m of two-dimensional error in the best-case scenarios. However, these "best-case scenarios" require line-of-sights from the GPS receiver to several GPS satellites. Such conditions generally do not exist for indoor cases and are infrequent outdoors when the GPS receiver is close to a building or comparable shadower. This means that conspicuous position errors may exist even if a GPS location fix is reported by the hardware.

A Garmin GPS V device is used in our experiment to provide GPS location information. The Garmin GPS unit updates location fixes every two seconds. Because the Garmin GPS V unit cannot always get a GPS fix, the GPS correction program "GpsFixerV3" was written to fill the GPS information.

Our experiment takes measurements inside a building as well as the outside perimeter of the building. Among all the outdoor data points, 9.2% of the NMRs do not have a location fix from the Garmin GPS unit. That means that the GPS unit is less than 91% effective outdoors when it is close to a building. As for the indoor cases, the GPS unit is only 10.4% effective.

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%)

During each field measurement, we measure indoor locations first, followed by a measurement of the outdoor perimeter of that building. Considering the satellite acquisition time for GPS, our statistics may be biased towards poor outdoor GPS effectiveness. Considering the “guess” ability of the Garmin V GPS, which uses the last known GPS location when a full satellite fix is unavailable, our statistics may be biased towards optimistic indoor GPS effectiveness.

Another issue is that the above statistics are measured by a $250 commercial Garmin V unit which is especially designed to acquire and maintain GPS location. It was designed to optimize the GPS estimate from the single-band antenna and RF-chain. This optimized structure does not exist in a GPS-enabled handset. Therefore a GPS-enabled handset will likely be worse in acquiring a GPS fix than the statistics above would suggest.

4.4 RSS in high-rise building

This section discuss the relationships between RSS and vertical position within a high-rise building. There are only several high-rise buildings in Greenville, so access is limited. We received access to two office buildings which are more than 10 stories in downtown Greenville. One of them has 18 floors and the other one has 12 floors. Active call data is collected in the stairwells of both building and on selected floors. Scanner data is also collected in the second stairwell of the 18-floor building.

Figures 4.4–4.6 show the relationship between the floor number and the received signal strength aggregate (RSSA). A clear trend of higher RSSA for higher floor level is apparent. In Figure 4.4, the lowest 3 floors have similarly low RSSA due to the surrounding buildings and trees. These nearby buildings and trees block the propagation path to the lower floors in the high-rise building. A high increase in RSSA occus at the 7-th floor due to renovations that were being performed at the time. There were no window blinds or furnishings on the 7-th floor, which led to much less shielding and obstruction for penetrating radio waves. The same trend is shown in Figure 4.6 which is taken in the same building but in a different stairwell. Figure 4.5 does not show the increase loss for the 7-th floor, since it is taken in a different building in which the 7-th floor is not under renovation.

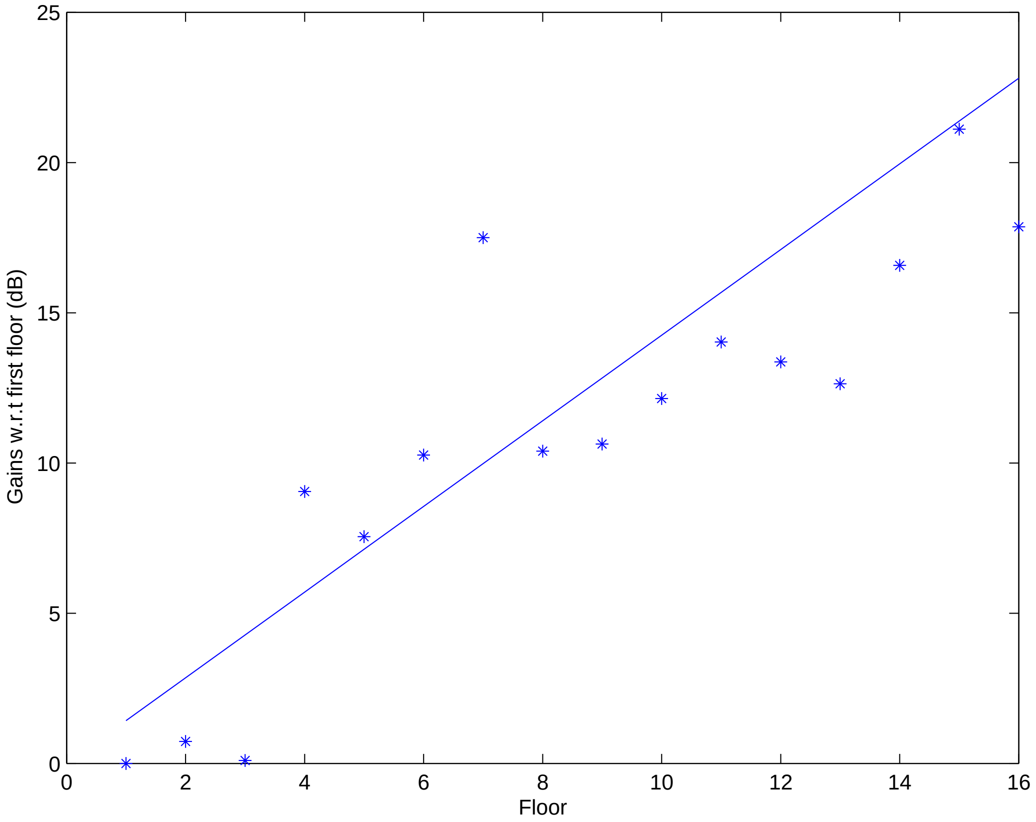

Figure 4.4 Signal gain vs. floor number, taken from active call data, 6 DCCH channels, slope +1.43 dB/floor.

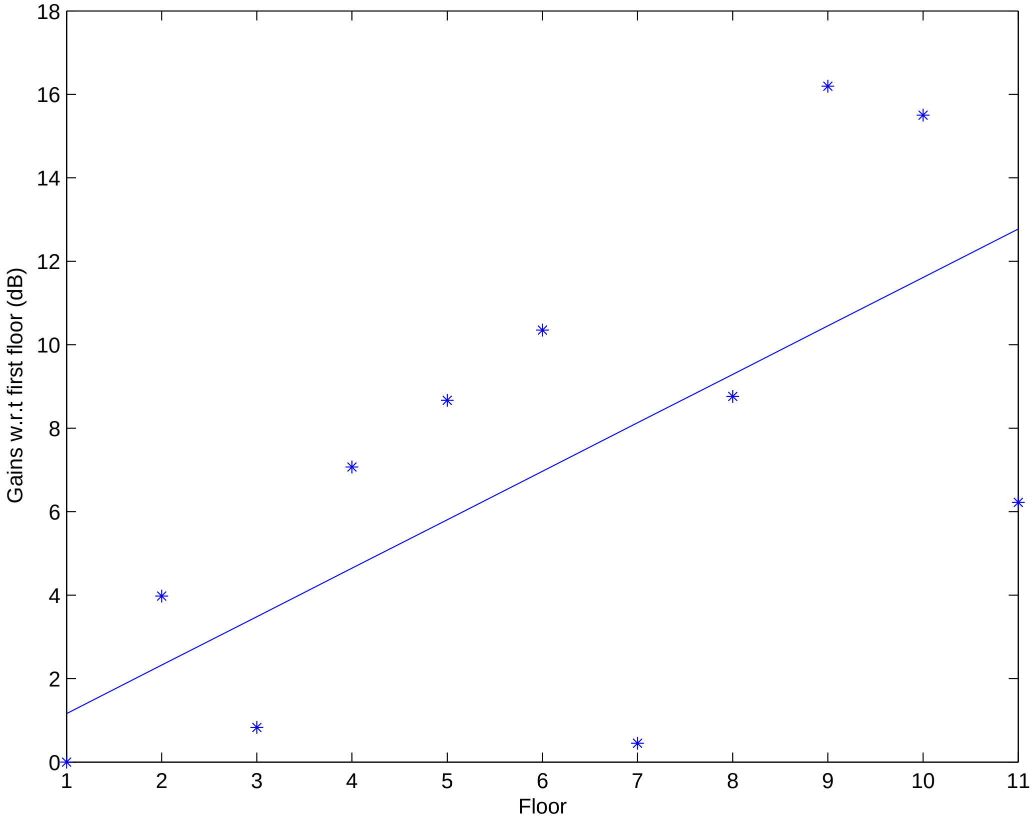

Figure 4.5 Signal gain vs. floor number, taken from active call data, 6 DCCH channels, slope +1.16 dB/floor.

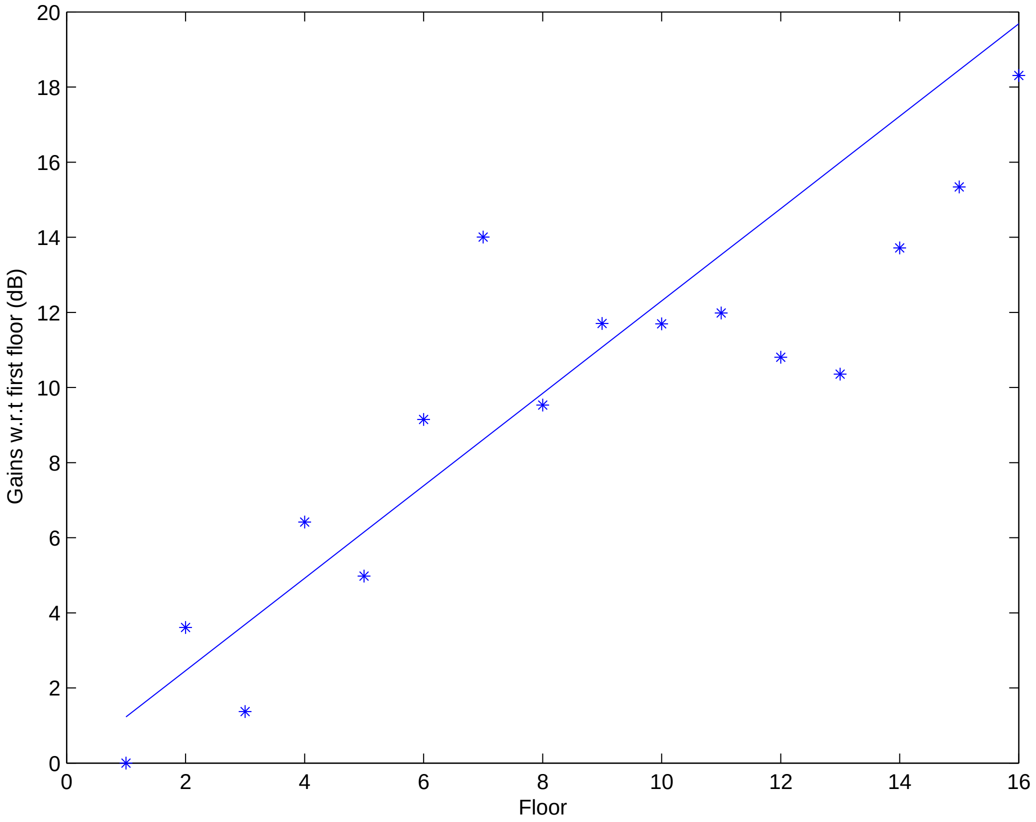

Figure 4.6 Signal gain vs. floor number, taken from scanner data, 15 DCCH channels slope +1.23 dB/floor.

Chapter 5

PREPARING RF MAPS

5.1 Equivalent Modification on DCCH Change

Network optimization is a routine procedure that every wireless service provider must perform from time to time. During the Greenville measurement campaign, the Dedicated Control Channel (DCCH) frequency plan was changed at the end of the first week (December 17, 2004). The change covered the entire test area. The DCCHs of all cells shifted down from Absolute Radio Frequency Channel Number(ARFCN) range 786-800 to (ARFCN) range 512-526, a total change of only 55 MHz on the carrier frequency of 1900 MHz. The new ARFCN of the DCCH became the old ARFCN of the DCCH minus 274. Few base stations in the surrounding area had previously used ARFCNs in the range of 512-526 before the frequency plan change. Furthermore, no transmit power was modified for any cell during the measurement campaign. Based on the fact above, one assumption for calibration of the PSD is that the propagation characteristics of ARFCN 786-800 were the same as or very close to the propagation characteristic of ARFCN 512-526. Another assumption is that the carrier-to-interference ratio (CIR) did not change much during this frequency plan update, because the entire area has almost the same relative DCCH pattern as before the frequency change.

Figure 5.1 and Figure 5.2 compare the DCCH setup in the test area before and after the frequency plan change for DCCH 786 and DCCH 512. Figure 5.3 and Figure 5.4 compare the DCCH setup in the test area before and after the frequency plan change for DCCH 787 and DCCH 513. These figures show that the base station distribution of DCCH 786 before the frequency change is almost the same as the base station distribution of DCCH 512. More comparison figures are available in Appendix A.

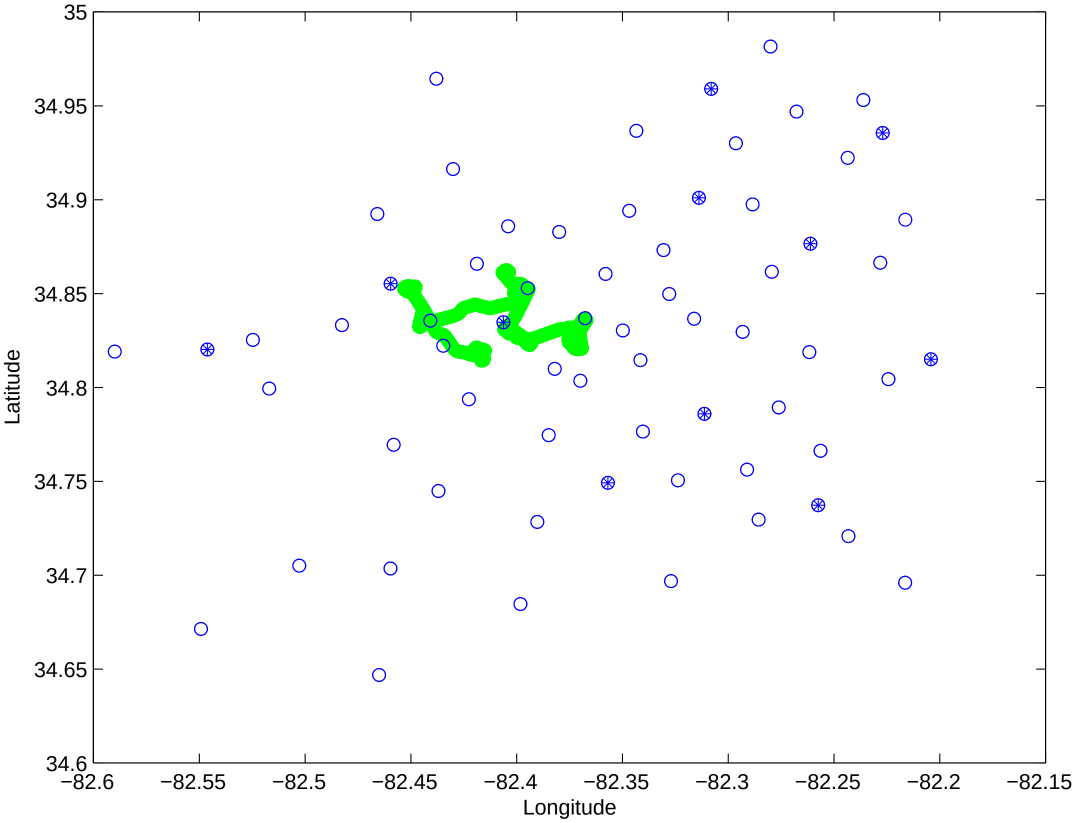

Figure 5.1 Longitude/Latitude map of base stations (* and O) at Greenville, SC using DCCH 786 on Dec 14, 2004. The thick path s a single drive-test route through the test area.

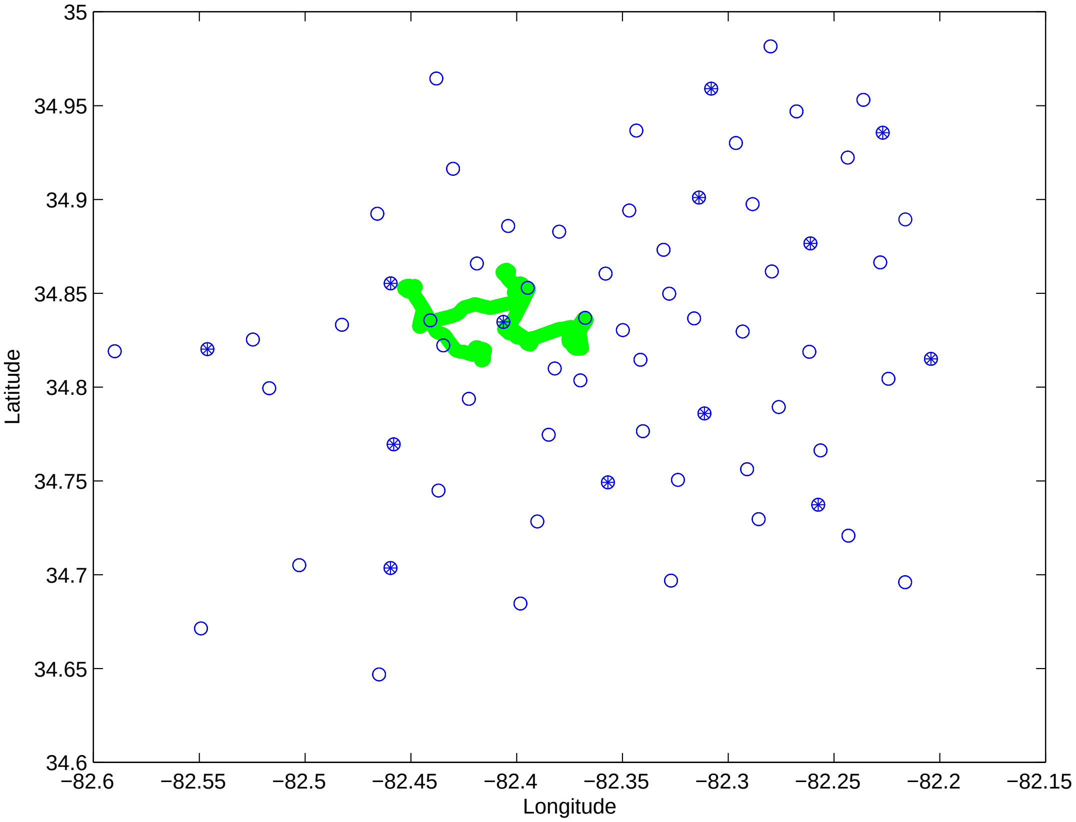

Figure 5.2 Longitude/Latitude map of base stations (* and O) at Greenville, SC using DCCH 512 on Dec 31, 2004.

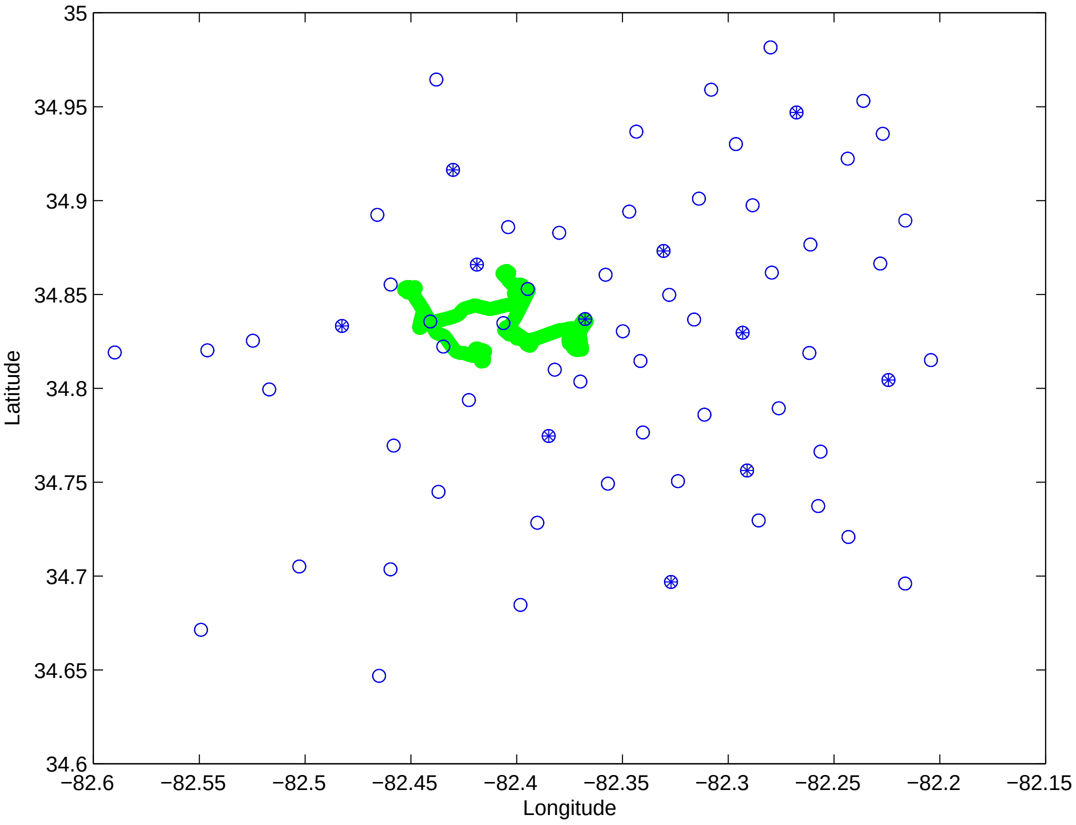

Figure 5.3 Longitude/Latitude map of base stations (* and O) at Greenville, SC using DCCH 787 on Dec 14, 2004.

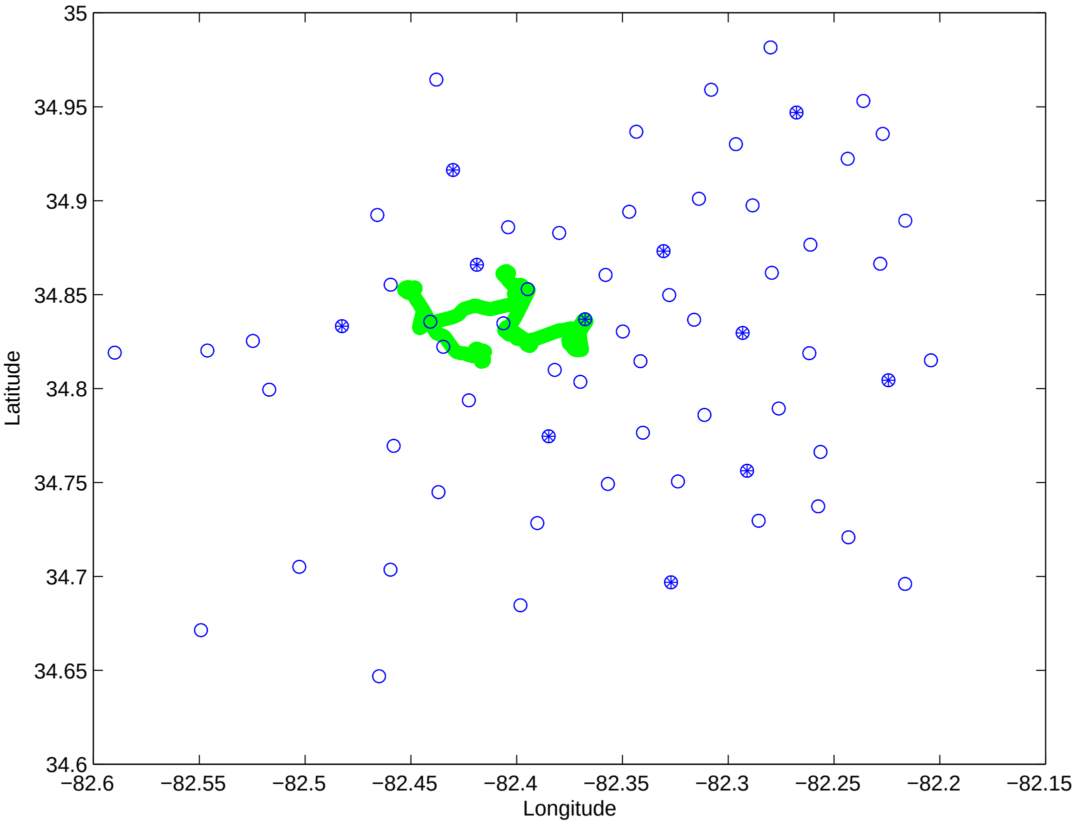

Figure 5.4 Longitude/Latitude map of base stations (* and O) at Greenville, SC using DCCH 513 on Dec 31, 2004.

5.2 GPS Manual Correction

The measurement campaign used a Garmin GPS V system to record real-time latitude and longitude for collected data. The unit provides GPS location estimates within 10 m of ground-truth in an open sky outdoor environment, and sometimes in excess of 25 m under thick cloud, trees, or besides large buildings. In these situations, the GPS often cannot even estimate position because it cannot acquire the minimum 3 satellites required for triangulation. Most of the time, the GPS signals vanish completely in an indoor environment.

The TEMS program collected data from both the testing handset and the Garmin GPS V unit. Network measurement reports were generated at a rate of 2 reports per second, which are stamped with system time and all network measurement report data from the handset.

The custom Matlab program GPSFixerV3 is used to correct location information from poor or missing GPS records. As handset measurements are collected, the field engineer clicks on the endpoints of the measurement collection path as seen from a geo-referenced satellite photograph (or aerial photo) of the test area loaded on the laptop computer. After clicking, the program GPSFixerV3 adds GPS coordinates to the scanner or active call records by assuming that the measurements are uniformly distributed along the line connecting the two end points.

During the measurement campaign, most of the indoor path is carefully estimated from the aerial photo. To prevent the marking of a wrong building, outdoor measurement collections were conducted under clear sky conditions around the building. The indoor GPS locations corrected by GPSFixerV3 were compared with any outdoor GPS locations from the Garmin V unit and aligned with the aerial photo. In this case the error of indoor GPS data should be less than 10 m.

5.3 Indoor Calibration

For indoor calibration of PSDs, we used the active call data collections with the Ericsson TEMS unit. The long list of 74,125 NMRs is grouped into 530 blocks of continuous NMRs taken during the same phone call. Each NMR in a single block is assigned a number showing how many NMRs come after the current NMR in the same block. The active call data is then separated into two groups. The first group contains all odd-numbered NMRs and the second group contains all even-numbered NMRs. The first group is used as indoor calibration data while the second group is used as location engine test data. In this case 37,064 NMRs were used to calibrate the indoor PSD and the remaining 37,063 NMRs were used to test location performance. Thus, we ensure that we are not tainting our tests by double-counting test data and calibration data.

The active call data was taken with a handset antenna. The GSM NMRs collected from active call contain Received Signal Strengths (RSS) of 6 DCCHs from neighbor base stations. The scanner data was collected with a high-gain antenna. The scanner data reports contain all RSSs for all DCCHs. Because scanner data is collected with a different antenna than a handset antenna, the RSSs taken from active call and scanning data have a dB offset between them. To get rid off the offset, the following operation is used in calibrating the indoor data.

Let $ACRSS_{m,n}$ denote the RSS of the n-th neighbor of the m-th active call record; let $ACDCCH_{m,n}$ denote the corresponding DCCH channels of the m-th active call record; let PSD denote a drive-test calibrated PSD; let the operation $(PSD(DCCH_{m,n}))$ give the RSS of the n-th neighbor DCCH channel of the corresponding m-th NMR at the same longitude and latitude as the location active call

NMR was measured. The dB-Offset will be calculated by

$$\text{Offset} = \frac{1}{6}\sum_{i=1}^{6}(ACRSS_{m,i} - PSD(ACDCCH_{m,i})) \tag{5.3.1}$$

This offset will be removed from the active call measurements. The corrected RSS value is then blended into the PSD with radius of 1 cell (10 m) to complete the indoor calibration. This RSS map blending process was described in detail in the first Georgia Tech radiolocation report [Zhu04].

5.4 Network Measurement Report (NMR) Matlab File Format

5.4.1 NMR Matlab Matrix Structure

The road measurements by the TEMS unit have been stored in a Matlab matrix format. For reproducibility and future research, the format of the Matlab file is briefly described in Table 5.1 and Table 5.2:

For easy access and fast indexing, the whole NMR matrix is in real number format.

- Date stores date information, i.e. 20041213. The functions floor() and/or round() functions can be used to extract year/month/day out of the date.
- Time cell stores time information count in seconds from 00:00:00 am. For example 9:15:12 am is equal to 9*60*60+15*60+12.
- Frame cell stores the frame number count by base station.
- Lat/Lon cell saves the GPS information either from GPS receiver or from indoor GPS correction program.
- GpsValid cell holds the information on how the GPS fix was generated. A value of "2" indicates that the GPS fix came from the Garmin GPS V unit and no

Table 5.1 Row format of matlab matrix file ”NMRxx.mat” from active call/network measurement report

1	2	3	4	5
Date	Time	Frame Number	Latitude	Longitude
6	7	8	9	10
GPS Valid	IndoorMark	Cell ID	DCCH Number	Tn
11	12	13	14	15
Maio	HSN	CI	BSIC	ARFCN
16	17	18	19	20
MCC	MNC	LAC	Rx Level	Rx Qual
21	22	23	24	25
Rx Level sub	Rx Qual sub	Time Advance	Tx Power	RLink Act
26	27	28	29	30
Rlink Max	C1	C2	DTX DL	FER
31	32	33	34	35 ··· 40
FER sub	SQI	GPS Correctable	Elevation	Reserved
41	42	43	44	45
No. 1 DCCH	No. 1 Rx Lvl	No. 1 BSIC	No. 1 C1	No. 1 C2
46	47	48	49	50
No. 2 DCCH	No. 2 Rx Lvl	No. 2 BSIC	No. 2 C1	No. 2 C2
51	52	53	54	55
No. 3 DCCH	No. 3 Rx Lvl	No. 3 BSIC	No. 3 C1	No. 3 C2
56	57	58	59	60
No. 4 DCCH	No. 4 Rx Lvl	No. 4 BSIC	No. 4 C1	No. 4 C2
61	62	63	64	65
No. 5 DCCH	No. 5 Rx Lvl	No. 5 BSIC	No. 5 C1	No. 5 C2
66	67	68	69	70
No. 6 DCCH	No. 6 Rx Lvl	No. 6 BSIC	No. 6 C1	No. 6 C2
71 ··· 86	87	88	89	90
Reserved	continuity*	RSV	Base station Lat.*	Base station Lon.*

*: Only exist in NMR6n.mat and NMR6tn.mat

corresponding time stamp was recorded in the GPS correction program; the final GPS fix is from the Garmin GPS unit. A value of “1” indicates that the GPS fix from Garmin GPS V is available, and that the time stamp was recorded in the GPS correction program; the final GPS fix is from the GPS correction program. A value of “0” indicates that the GPS fix from the Garmin GPS V is not available and the time stamp was recorded in the GPS correction program; the final GPS fix is taken from the GPS correction program. The NMRs that have no GPS fix from either the Garmin GPS unit or the time stamp recorded in the GPS correction program are discarded.

- IndoorMark cell identifies whether the NMR is taken indoors or outdoors. A value of “1” indicates that the NMR is gathered during an indoor call.

- CellId cell stores the cellID information. Since the cellID is a combination of numbers and alphabet, a combination of the ASCII value of each upper-case character is used instead of the original CellID. For easy indexing, no Matlab cell format is used. For example, ’A1E2’ will be convert into 65496950. (’a1e2’ will be changed to ’A1E2’ first.) For details and Matlab code, please check “ShowCellId.m”

- Continuity cell gives how many continuous NMRs follow the current NMR. For example, a number of 76 indicates that the following 76 NMRs are recorded from the same call. The number is generated by the program “ContinueNmrCounter.m”. NMRs are considered continuous if two adjacent NMRs have less that 10m change in each direction, and less than 5 seconds change in time, and have the same indoor/outdoor properties. * This only exists in NMR6n.mat and NMR6tn.mat.

- Base station Lat. cell and Base station Lon. cell are used to save base station latitude and longitude information. This data was mostly used for correlating radio environment information and user-to-basestation distance. * This is only exist in NMR6n.mat and NMR6tn.mat.

The second matrix keeps “Hex String”, “Channel Type”,“Channel Mode”,“Sub-Channel Number”,“Hopping”, and “CellID” information which is in string format, as shown in Table 5.2.

Table 5.2 Row format of matlab cell matrix file “NMRc.mat” only from active call/network measurement report.

1	2	3
Hex String	Channel Type	Channel Mode
4	5	6
Sub-Channel Number	Hopping	Cell ID

5.4.2 NMR file list

The following NMR files are available:

NMR.mat: This file contains original data in two matrices from the active call collections. The rows of this matrix correspond to the same NMR recorded in each matrix. The NMR matrix is a real number matrix and the NMRc matrix is a cell-format matrix. The NMR matrix follows the format in Table 5.1. The NMRc matrix follows the format in Table 5.2. Total row size is 89,651.

NMR6.mat and NMR6n.mat: These matrices contain only the NMRs with 6 sector information. The Cell ID information in NMRc matrix has been converted and saved in NMR matrix, as described in Section 5.4.1. The NMRc matrix has been discarded. NMR6n.mat also contains a continuous call counter. The total row size is 74,125.

NMR6t.mat and NMR6tn.mat: the even-numberd rows in NMR6 are used for testing location algorithms. (The odd-numbered rows were used in indoor calibration.) The total row size is 37,062.

5.5 Scanner Drive Test Matlab File Format

5.5.1 Scanner Drive Test Matlab Matrix Structure

Scanner drive test data is used to calibrated the PSD. This file's format is described in Table 5.3.

Table 5.3 Row format of Matlab matrix file "xxxxdrscn.mat" from road scanner testing.

1	2	3	4	5
Date	Time	RSV	Latitude	Longitude
6 ··· 35	36	37	38	39
RSV	DCCH 512 RSSI	DCCH 512 BSIC	DCCH 513 RSSI	DCCH 513 BSIC
40	41	···	64	65
DCCH 514 RSSI	DCCH 514 BSIC	···	DCCH 526 RSSI	DCCH 526 BSIC
66	67	···	94	95
DCCH 786 RSSI	DCCH 786 BSIC	···	DCCH 800 RSSI	DCCH 800 BSIC

5.5.2 Scanner road measurment file list

Two scanner road test files are available.

- 1216drscn.mat is the scanner testing on Dec-16-2004. This file records RSS and BSIC info of DCCH 512-526 and DCCH 786-800.
- 0201drscn.mat is the scanner testing on Feb-01-2005. Because of the network DCCH change on Dec-17-2004, only DCCH 512-526 are active in the testing area. This file records only RSS and BSIC for DCCH 512-526.

Chapter 6

LOCATION PERFORMANCE STATISTICS

6.1 Location Algorithm and Performance

6.1.1 Metric of Location Performance

The distance in meters between a location estimate and the handset's groundtruth position is the *error distance.* For every location experiment in this study, we calculate and report the percentages of error distance values below 100m and 300m and the error distances corresponding to the 66.7% and 95% thresholds for cumulative distribution of location error.

6.1.2 Base Line: Relative method, 10 NMR-average

The relative method with RSS averaged over 10 NMR is reported because it was comparable to the location algorithm used in the Georgia Tech campus tests. As the average cell size increased from 500m in radius to 2000m in radius, the location performance drops when compared with the original Georgia Tech campus measurements.

We see from Table 6.1 that the location performance drops significantly. The main reason is that we are performing the test in a large area where large errors are possible. Because of the frequency reuse, a location estimate may fall at a point far away from the ground truth where DCCHs configuration and RSS are similar to those measured at original point. For this initial algorithm, the 300 m statistics (39% and 50%) in this Greenville test are even worse then the 100 m statistics (62% and 70%) in Georgia Tech campus test [Zhu04]. Because the average cell radius increased from 500 m to nearly 2000 m, the error statistics for this algorithm have increased by the same factor of 4– the 400 m statistic is close to the Georgia Tech campus 100 m statistics.

Because of the large test area, it is almost impossible to produce an indoor mask by hand. An egde detection algorithm in PhotoShop software was used to mark out the indoor areas, but misidentification occurred for more than 75% of the entire area. Manual indoor mask correction is required at most locations where we have collected active call data. The performance of the location algorithm is almost the same as that using Level 1 PSD (a PSD calibrated with only outdoor drive-test measruement) in the baseline algorithm. All indoor and pedestrian outdoor collections are omitted from this PSD. Furthermore, there is no attempt to model signal penetration through buildings. This type of RF map database represents the general purpose RSS position location solution proposed in [PB00],[Rao99]. It is the most practical solution since all measured signal strength data can be collected using standard cellular drive test procedures. Thus, the data collection is quick and economical. In this report we have not included the performance of Level 2 PSD (a PSD that is calibrated with outdoor measurements and indoor modeling) because of the inaccuracy of the indoor mask.

To improve the performance of the location method, we developed a novel search-area reduction technique which is discussed in the next section.

Table 6.1 Location error statistics of relative RSS-method. (Linear averaging of 10 NMRs, 6 sectors)

PSD level		Level 1 Outdoor Meas.	Level 3 Indoor/Outdoor Meas.
Error statistics	<100m	17%	31%
	<300m	39%	50%
Percentage statistics	66.7%	1080 m	310 m
	95%	5030 m	5120 m

6.1.3 Search Area Reduction Based on Linear Regression

Linear regression is a general method for spotting trends in large, complicated data sets. This technique is used here to calculate the relationship between the information recorded in NMRs, the ground truth of the caller, and the serving base station. This information is *not* limited to only the RSS data in the NMR. By estimating this distance we can improve the position estimate in the RSS-matching portion of the location algorithm.

In a network measurement report, serving sector information and radio environment information such as timing advance, received signal strength, and received signal quality are reported together with neighbor cell DCCH signal strength. Those pieces of information are very useful in reducing the initial search area. By limiting the initial search area, the final location estimate can be calculated much faster and with better accuracy.

Because timing advance (TA) is designed to correct the propagation delay of the wireless radio signal, the timing advance has a direct relationship to the distance from caller to basestation. Among all the additional information, TA is the most important information in reducing the searching area of a location engine. The TA's value is between 0 and 63 that is corresponding to a propagation distance between 0 km to 35 km. Theoretically, one step in TA is about 547 m (35 km/64 TA units).

However, through careful data mining, we show that one step of TA change is about 496 m of extra distance from the serving basestation and other information also contributes to the search area reduction. The pieces of information tested in this report include TXPOWER, RXLEVFULL, RXQUALFULL, RXLEVSUB, RXQUALSUB, TA, DTXDL, FER, FERSUB, and SQI. These pieces of information are reported in NMRs for the purpose of mobile-assisted hand over (MAHO). Detailed description for these pieces of information is available in [Hei99], [Meh97], [Red98]:

- TXPOWER is the transmit power.
- RXLEVFULL is the received signal strength (more specified C1=(RxLev-RxLevAm-MAX((MSTxPwr-MSMaxTxPwr),0))) calculated from continuous transmission.
- RXLEVSUB is the received signal strength (C1) calculated during discontinuous transmission.
- RXQUALFULL is the received signal quality derived from the BER (Bit Error Rate) with continuous transmission from the base station.
- RXQUALSUB is the received signal quality calculated from BER with discontinuous transmission from the base station.
- TA is timing advance.
- DTXDL is the status of the discontinuous transmission down-link.
- FER is the frame error rate of the down-link voice channel with continuous transmission.

- FERSUB is the frame error rate of the down-link voice channel with discontinuous transmission.

- SQI is service quality index, which shows the quality of the current communication status.

Let us assume that all available information in an NMR (timing advance, received signal level, received signal quanlity, etc.) is linearly related to the separation distance between a base station and a mobile user. Thus, we could relate a set of m distance measurements to a set of m corresponding pieces of NMR info with the following system of equations:

$$\begin{aligned} Ta_{11}c_1 + RxLvl_{12}c_2 + \cdots + RxQual_{1n}c_n &= Dist_1 \\ Ta_{21}c_1 + RxLvl_{22}c_2 + \cdots + RxQual_{2n}c_n &= Dist_2 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ Ta_{m1}c_1 + RxLvl_{m2}c_2 + \cdots + RxQual_{mn}c_n &= Dist_m \end{aligned} \tag{6.1.1}$$

Where $xxxx_{mn}$ denotes the nth piece of information from the mth NMR. The variable c_n represents the correlation between measured data (Ta, TxLvl, RxQual, TxLvlSub, TxQualSub) and the distance from the base station to the caller ($Dist_m$).

This system of equations can be written in matrix format

$$\begin{bmatrix} Ta_{11} & RxLvl_{12} & \cdots & RxQual_{1n} \\ Ta_{21} & RxLvl_{22} & \cdots & RxQual_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ Ta_{m1} & RxLvl_{m2} & \cdots & RxQual_{mn} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} = \begin{bmatrix} Dist_1 \\ Dist_2 \\ \vdots \\ Dist_m \end{bmatrix} \tag{6.1.2}$$

Let A denote the matrix of measured data with each row corresponding to a collection of data during one NMR.

$$A = \begin{bmatrix} Ta_{11} & RxLvl_{12} & \cdots & RxQual_{1n} \\ Ta_{21} & RxLvl_{22} & \cdots & RxQual_{2n} \\ \multicolumn{4}{c}{\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots} \\ Ta_{m1} & RxLvl_{m2} & \cdots & RxQual_{mn} \end{bmatrix} \tag{6.1.3}$$

Let $\vec{c}$ denote the best possible parameter vector that relates the measurements in A to the distances:

$$\vec{c} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} \tag{6.1.4}$$

Let $\vec{d}$ denote the distance vector for each measured point:

$$\vec{d} = \begin{bmatrix} Dist_1 \\ Dist_2 \\ \vdots \\ Dist_m \end{bmatrix} \tag{6.1.5}$$

In our data set, we trying to find the best values for 5 of the most important parameters in $\vec{c}$ from 37,063 NMR data points; thus we have many more equations than unknowns in the system represented by Equation 6.1.2. This type of system is solved using the *normal equation*:

$$\vec{c} = (A^T A)^{-1} A^T \vec{d} \tag{6.1.6}$$

Equation 6.1.6 produces a set of parameters $\vec{c}$ that minimizes the mean-square error between the right and left-hand sides of Equation 6.1.2. Once this vector is calculated from the measurement data, it can be used to estimate the handset's distance from the serving base station and generate the distance by using the equation:

$$distC = [Ta_1 \ RxLvl_2 \ \cdots \ RxQual_n]\vec{c} \tag{6.1.7}$$

From Equation 6.1.7, we can use information in the NMR other than RSS to calculate an approximate distance between user and serving base station. We can then filter the location estimate through a “probabilistic ring” around the serving base station to sharpen our final position estimate.

The Figure 6.1 shows the distribution of the error between the actual distance separating handset and server cell and the calculated distance for 37,062 NMRs analyzed with the regression analysis. On the horizontal axis is the difference between the measured radius and the radius estimated by Equation 6.1.7. On the vertical axis is the occurance of each error, which has been binned into 10 m increments.

Figure 6.1, we found 98% of calculated distances lie within ±600m of the measured distance and 99% within ±800m range.

This extra knowledge of predicted distance from the serving base station limits the searching area by a ring with median radius of the calculated distance (distC) and with a width of 1200 m (600 m towards inside and outside).

To decide which information is useful we calculate the effectiveness of each kind of information. The effectiveness of one kind of information is calculated as the distance corresponding to one unit change of that information multiplied by the average value of that kind of information.

Table 6.2 listed the information we found useful in the NMRs. Received signal strength level full, received strength level sub, and service quality index are also considered to be useful information besides timing advance.

The relationship between timing advance and user-base station separation distance is obvious because of the constant-velocity propagation of wireless signal; signals with

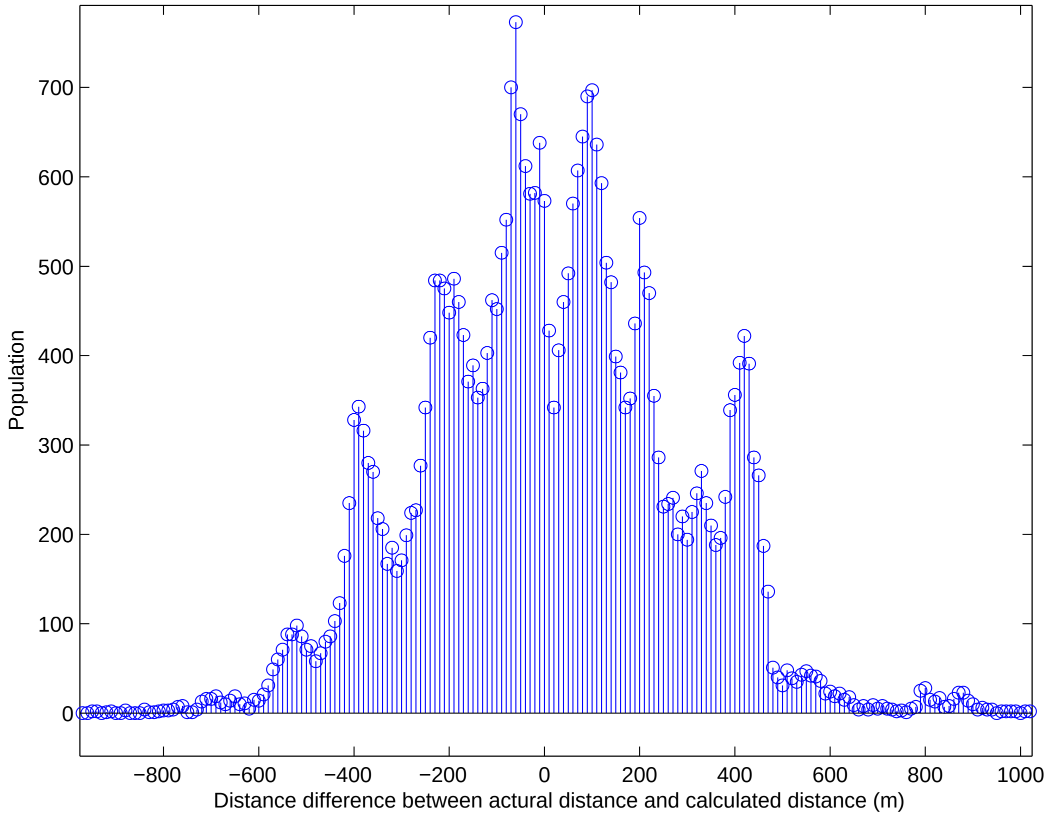

Figure 6.1 Histogram of base station and user separation distance error between calculated and measured radii. The mean is 13 m and the standard deviation is 289 m.

longer delays have usually travelled farther. The relationship of the received signal strength level sub and service quality index can be explained in this way: the further away the user from the base station, the lower the signal is received and the worse the service quality becomes. That is why the coefficient corresponding to received signal strength level sub and service quality index is a negative number. As for the received signal strength level full, this value is calculated from continuous transmission. To reduce the interference and conserve energy, the power control mechanism lowers the power level during a silence period for both the base station and the handset. This RXLEVFULL is more affected by this power control mechanism which makes it less correlated with the user-base station distance.

Table 6.2 Coefficient calculated by linear regression method

Timing Advance	474 m/TA step
Received signal strength level full	3.7 m/RXLEV change
Received signal strength level sub	-1.7 m/RXLEVSUB change
Service quality index	-3.8 m /SQI change

The base line algorithm in Section 6.1.2 searches the entire area for the location estimate based on the RSS of neighbor DCCHs. There is more information available in NMRs such as serving cell information and radio environment information. This extra information can be used to limit the searching area to a ring area surrounding the serving base station as discussed above. By using this method, location accuracy increases significantly as shown in Table 6.3.

In the Level 1 PSD results, position estimates are less than 100 m from ground truth 26% of the time and 300 m from the ground truth 62% of the time, which improved the 100 m statistics by 9% and 300 m statistics by 23%. For the Level 3 PSD, The searching-area reduction brings similar improvements. Position estimates are 100 m from ground truth 43% of the time and 300 m from the ground truth 71% of the time, which corresponding to increases of 12% and 21%, respectively.

Table 6.3 Location error statistics of relative RSS-method with limited search area. (Linear averaging of 10 NMRs, 6 sectors)

PSD level		Level 1 Outdoor Meas.	Level 3 Indoor/Outdoor Meas.
Error statistics	<100m	26%	43%
	<300m	62%	71%
Percentage statistics	66.7%	330 m	250 m
	95%	1060 m	1120 m

6.1.4 Continuous NMR VS. Average NMRs

In our baseline algorithm, 10 NMRs are linearly-averaged to get one averaged NMR that has less noise and fading than the individual NMRs. This averaged NMR will run through our simple relative RSS location algorithm to get a location estimate. The averaging process limits the availability of NMRs. First of all, it requires 10 continuous NMRs reporting from the same neighbor cells, which is not always possible in a GSM network. Second, the handover and neighbor list change provides extra information, which is very useful in limiting the searching area and improving the location accuracy. Third, the method of averaging is still vulnerable to measurement error and noise.

The improved method uses the search area reduction technique of Section 6.1.3. At the same time, continuous NMRs are not just averaged but used more effectively by making individual estimates on each NMR and post-processing these results.

In the relative RSSI location algorithm description in Section 6.2.2 of [Zhu04], the mean of each vector in the PSD is calculated in dBm. This mean is subtracted from the vector:

$$Prssr_{x,y,i} = Prss_{x,y,i} - \frac{1}{N}\sum_{j=1}^{N} Prss_{x,y,j} \tag{6.1.8}$$

where $Prssr_{x,y,i}$ denotes the received signal strength of the ith control channel at the location coordinates x, y.

The mean of the measured NMR vector is subtracted from the measured vector to form a new vector:

$$Nrssr_i = Nrss_i - \frac{1}{N}\sum_{j=1}^{N} Nrss_j \tag{6.1.9}$$

where $Nrssr_i$ is the received signal strength reported in the NMR in the ith channel.

After normalization, all vectors of received signal strength become independent of any Antenna/RF chain bias.

The relative signal vectors from the NMR and PSD are used to calculate the measurement distance for each raster point as in Equation (6.1.10).

$$M(x,y) = \sqrt{\sum_{i=1}^{N}(Prssr_{x,y,i} - Nrssr_i)^2} \tag{6.1.10}$$

This M(x,y) matrix is called “distance matrix” which represent the Euclidean distance between the RSS from the NMR and the RSS in the PSD. The coordinates x,y that yield the lowest measurement distance are chosen to be the location estimate.

In our improved algorithm, continuous NMRs are not just averaged and fed into the algorithm described above. Based on the assumption that the distance that the caller moves during a phone call or the period of 10 NMRs is relatively short (compared to the PSD raster point size), a “distance matrix aggregate (DMA)” is used instead of the averaged 10 NMRs. In the distance matrix aggregate method, each NMR will be used to calculate a distance matrix, all the distance matrices will be added together to form a distance matrix aggregate. Each roster point in this distance matrix aggregate is a measurement distance aggregate. The coordinates (x,y) that yield the lowest measurement distance aggregate are chosen to be the location estimate.

The Table 6.4 reports the performance of using 10 NMRs by calculating with the “Distance matrix aggregate” based on the assumption of the user will not move faster than walking speed.

Table 6.4 Location error statistics for the relative RSS-method with limited search area and distance matrix aggregate. (10 NMRs, 6 sectors)

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

Chapter 7

CONCLUSIONS

Overall, the Greenville, SC indoor/outdoor position location trials yielded some promising results for cellular carriers that are concerned about FCC E911 compliance in a GSM network loaded with indoor users. The only disappointing set of numbers was the indoor/outdoor discrimination rate, which dropped to 76% compared to a high value of 92% witnessed on the campus of Georgia Tech. This discrepancy is likely due to the more homogeneous building style that made the college campus much more predictable.

Still, the Greenville trial must represent a worst-case scenario for E911 position location: a rural network with low base station density. That the 100m and 300m cumulative location error distributions reach 51% and 79%, respectively, in such an environment is a testament to the resiliency of the technique. These numbers could be further improved by honing the location algorithm, incorporating better propagation modeling, and driving minor roads.

Chapter 8

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Appendix A

CAMPAIGN PHOTOGRAPH

Figures A.1 through A.25 shows some photographs taken during the measurement campaign and the variety of the measured buildings and environments.

Figure A.1 Downtown Greenville at the start of the December measurement campaign.

Figure A.2 Photograph of downtown Greenville shopping arcade.

Figure A.3 Photograph of a small shop in downtown Greenville.

Figure A.4 Indoor measurements conducted in a dressing store in downtown Greenville.

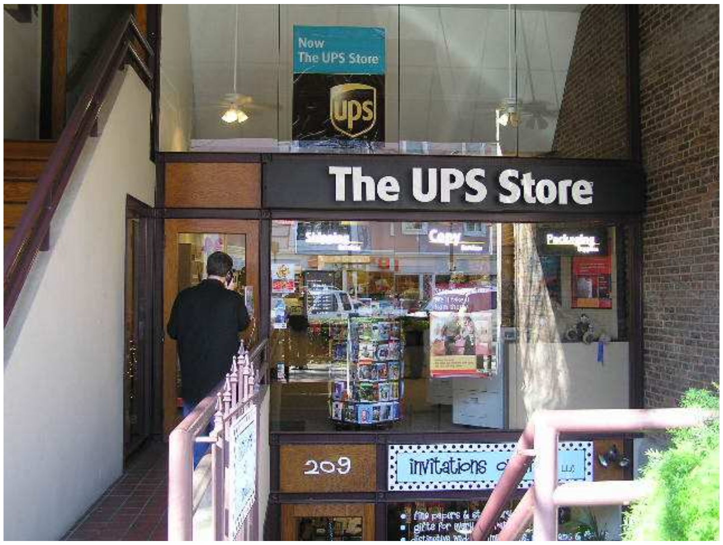

Figure A.5 Researcher entering a UPS store in downtown Greenville.

Figure A.6 Indoor measurement inside the UPS store in downtown Greenville made by Jian J. Zhu.

Figure A.7 Researchers Jian J. Zhu and Prof. Gregory D. Durgin entering a gift shop in downtown Greenville.

Figure A.8 Shop in downtown Greenville.

Figure A.9 Indoor measurement inside the gift shop in downtown Greenville.

Figure A.10 Indoor measurement inside a restaurant in Greenville.

Figure A.11 A restaurant build of brick in downtown Greenville.

Figure A.12 Indoor measurement inside a restaurant in Greenville.

Figure A.13 “Sticky Fingers” restaurant in downtown Greenville.

Figure A.14 Yenpao A. Lu and Jian J. Zhu take indoor measurements in downtown Greenville.

Figure A.15 Indoor measurement in a small office room in downtown Greenville.

Figure A.16 Indoor measurement ina clothing store in downtown Greenville.

Figure A.17 Indoor measurement in a day care/kindergarten in Greenville.

Figure A.18 “Family Dollar”grocery store in Greenville.

Figure A.19 “Hardee’s” measured in Greenville.

Figure A.20 McDonalds measured in Greenville.

Figure A.21 A laundromat in Greenville.

Figure A.22 Inside the laundromat in Greenville.

Figure A.23 Student researcher Jian J. Zhu is calibrating GPS on rooftop of a parking deck in downtown Greenville, SC.

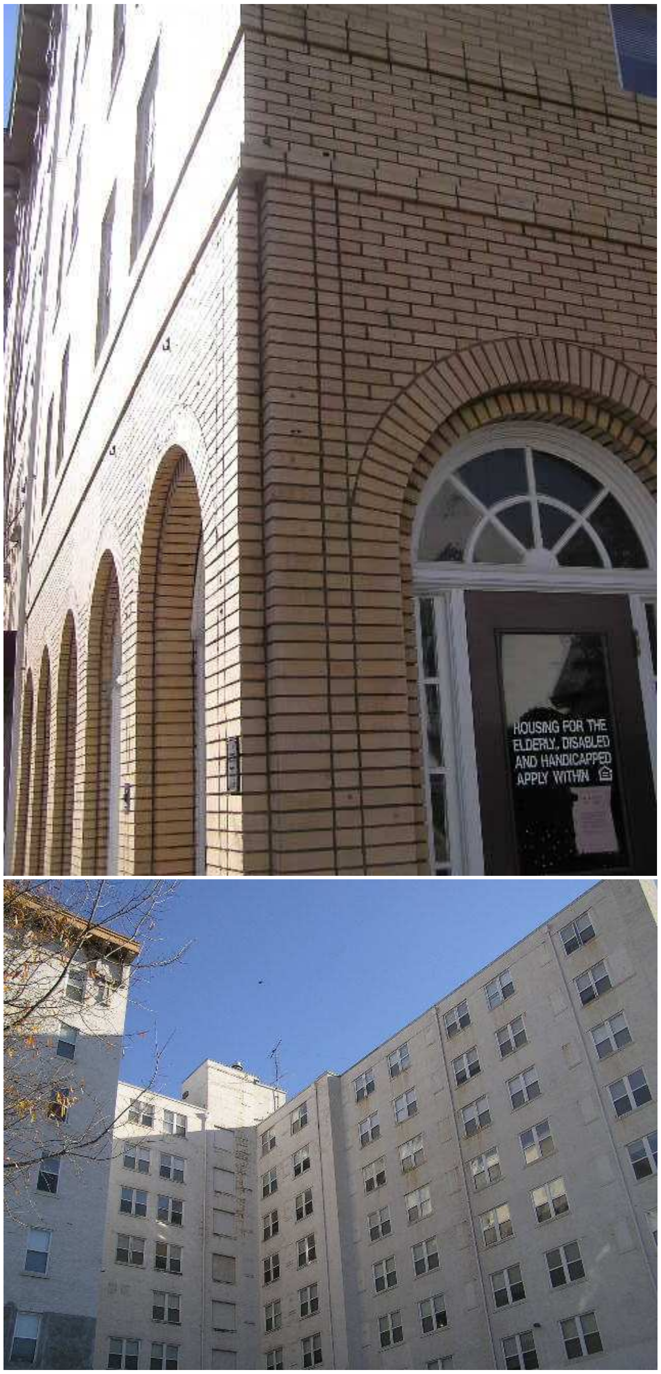

Figure A.24 The 8-story Greenville Summit Building close to downtown Greenville.

Figure A.25 Student researcher Jian Zhu and Prof. Gregory Durgin measure RSS for an office high-rise building in downtown Greenville, SC.

Appendix B

MAPS OF DCCH FREQUENCY PLAN

Figures B.1 through B.26 record the longitudes and latitudes of Greenville, SC base stations, grouped by DCCH. Maps for each DCCH are shown both before and after the major frequency plan change.

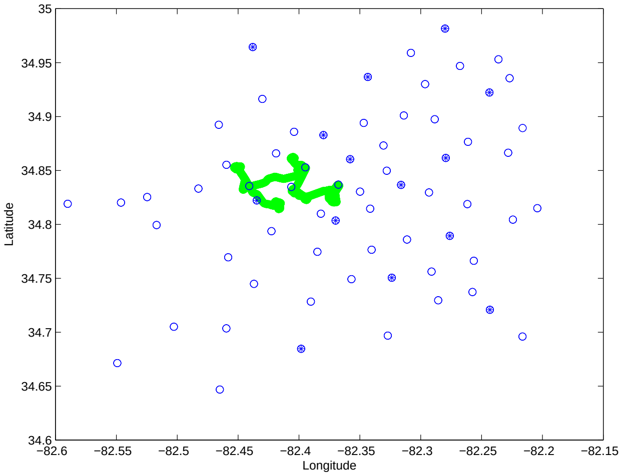

Figure B.1 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 788.

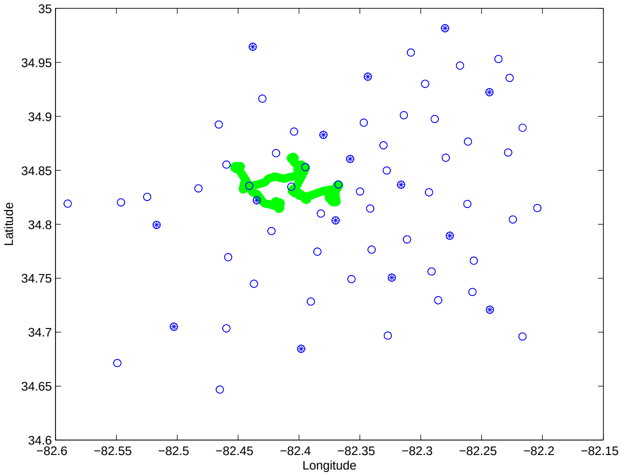

Figure B.2 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 514

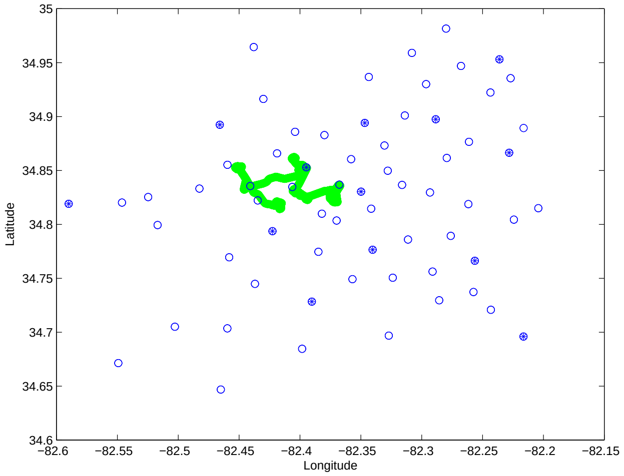

Figure B.3 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 789.

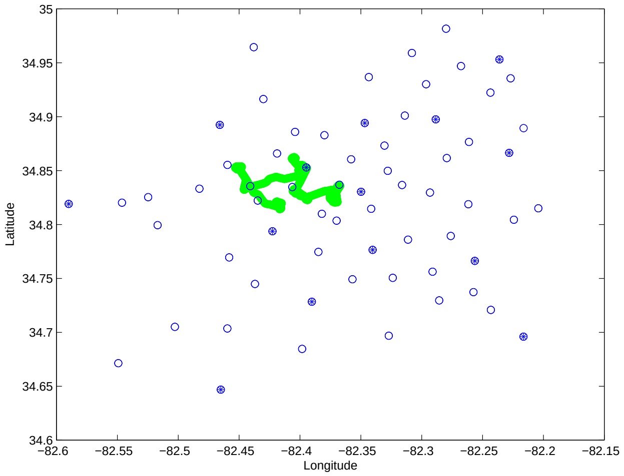

Figure B.4 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 515.

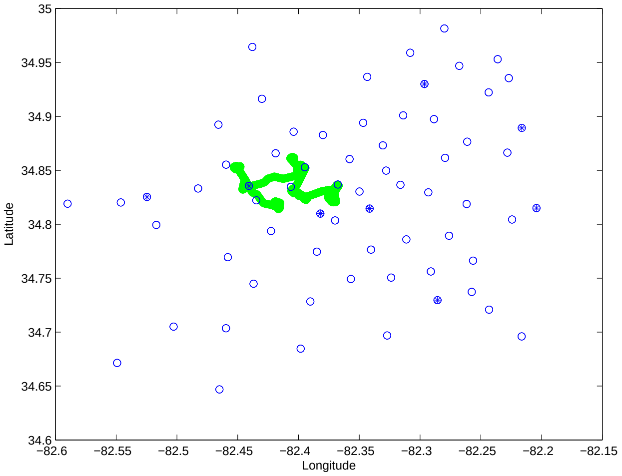

Figure B.5 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 790.

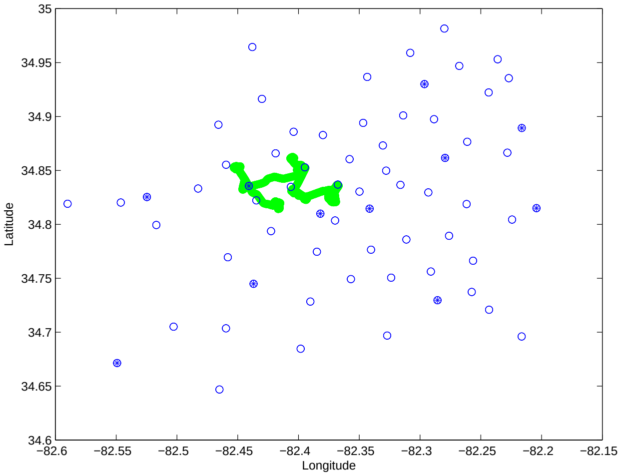

Figure B.6 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 516.

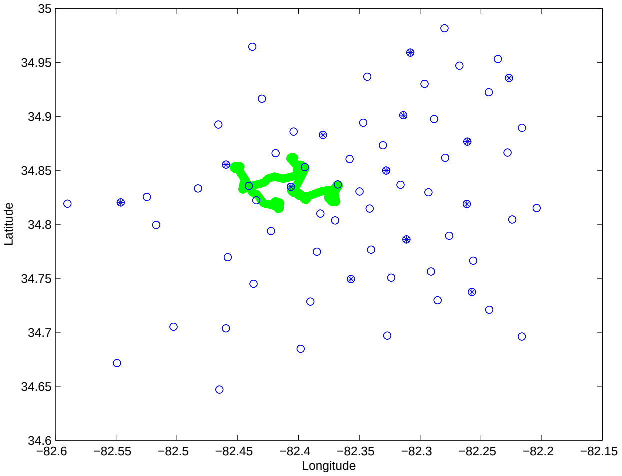

Figure B.7 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 791.

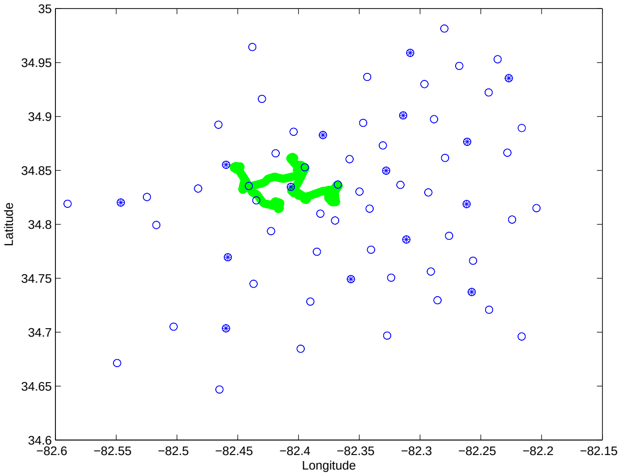

Figure B.8 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 517

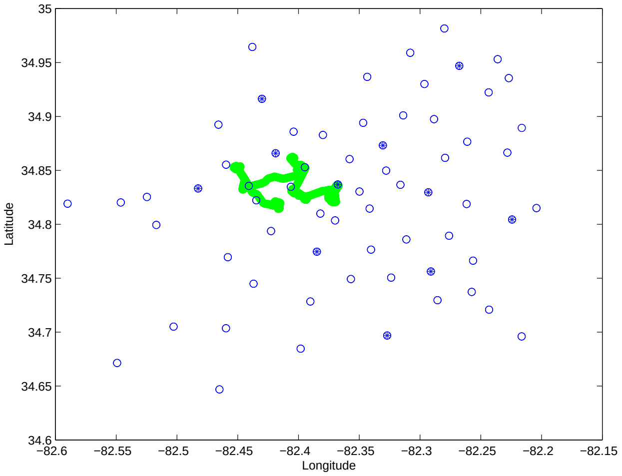

Figure B.9 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 792

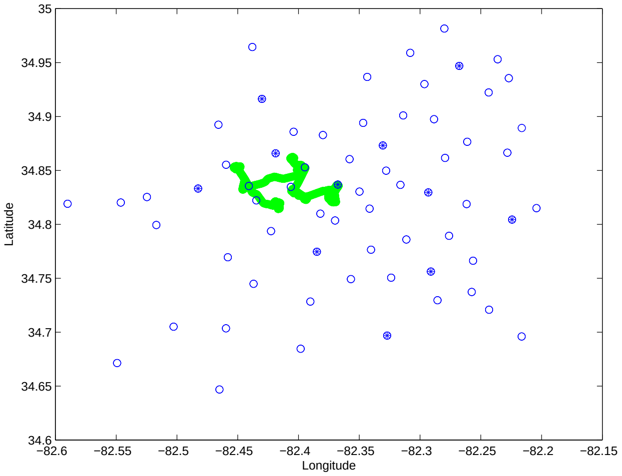

Figure B.10 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 518

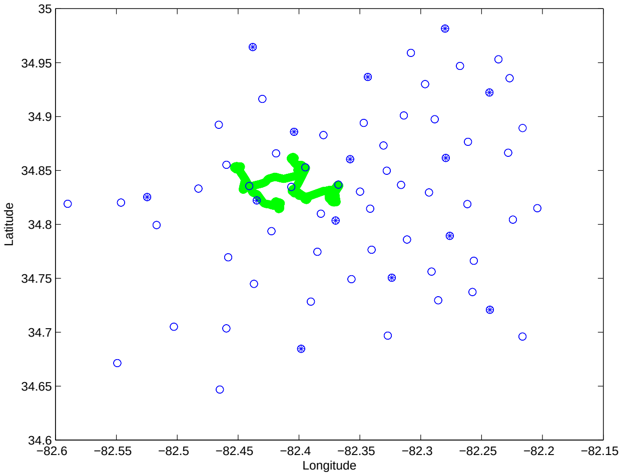

Figure B.11 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 793

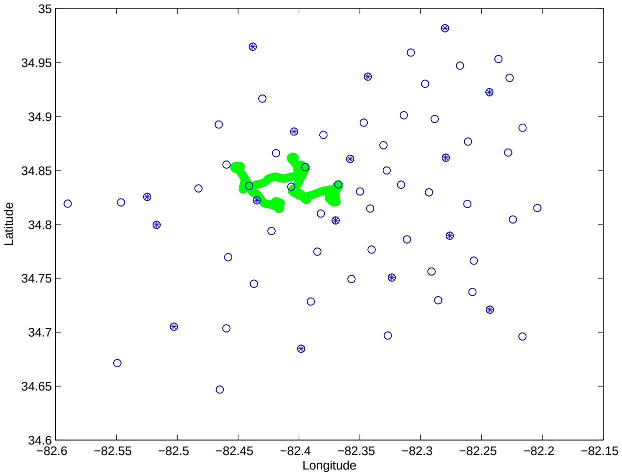

Figure B.12 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 519.

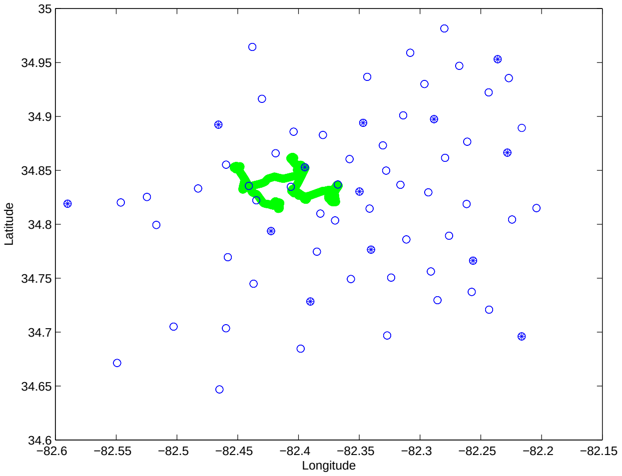

Figure B.13 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 794.

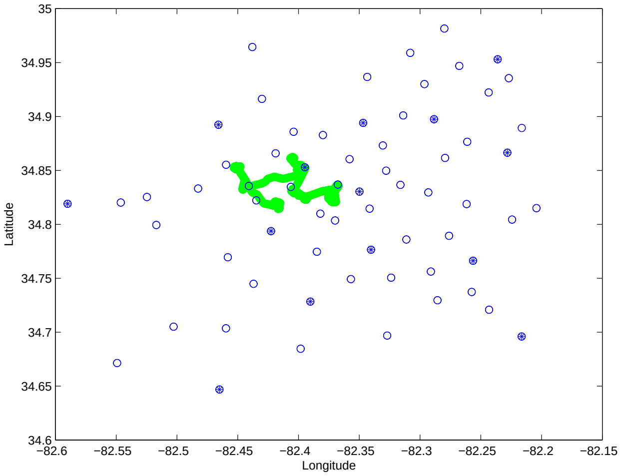

Figure B.14 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 520.

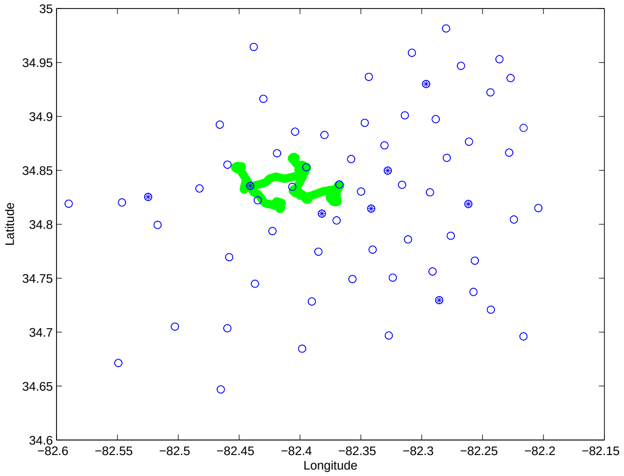

Figure B.15 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 795.

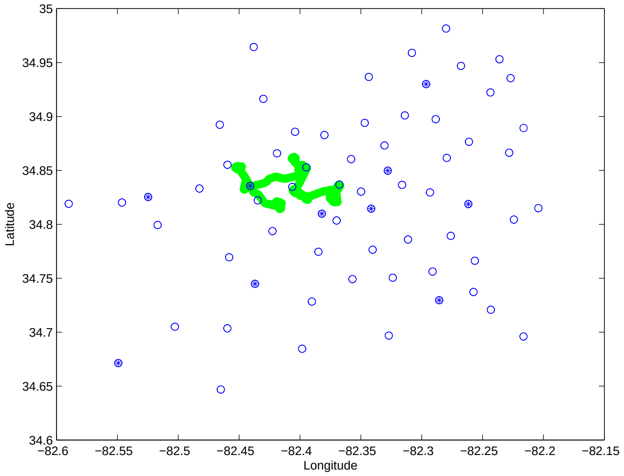

Figure B.16 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 521.

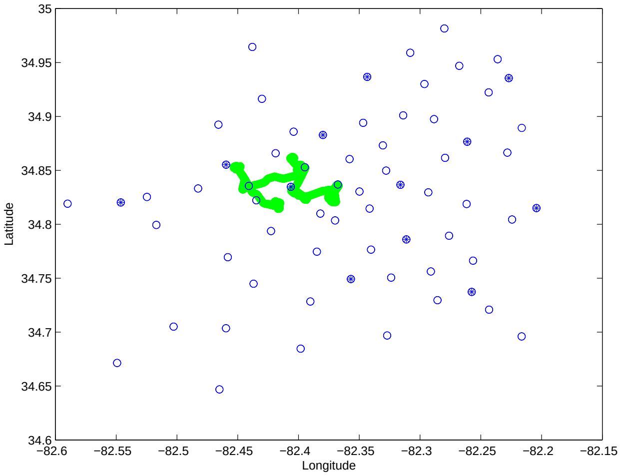

Figure B.17 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 796.

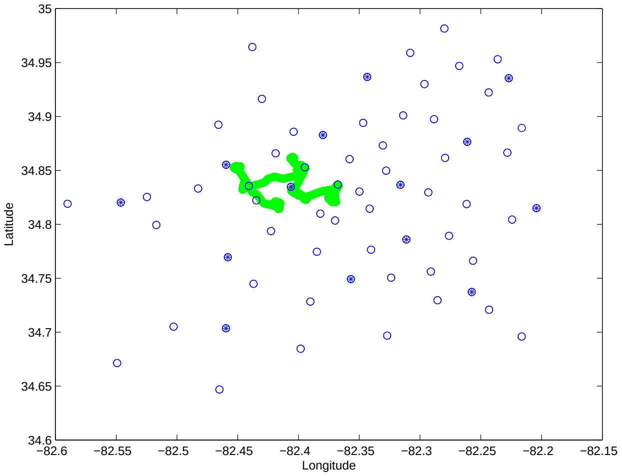

Figure B.18 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 522.

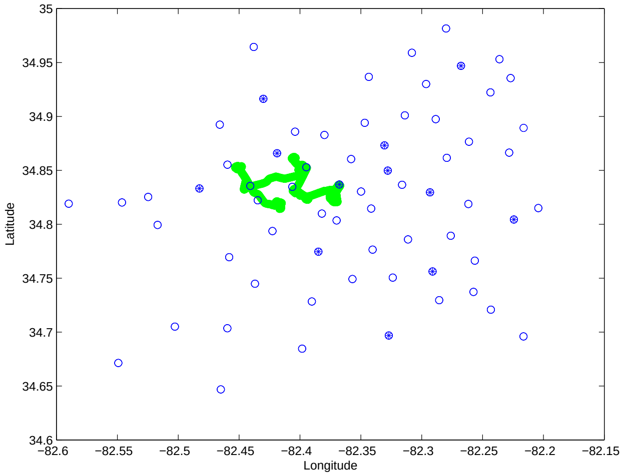

Figure B.19 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 797.

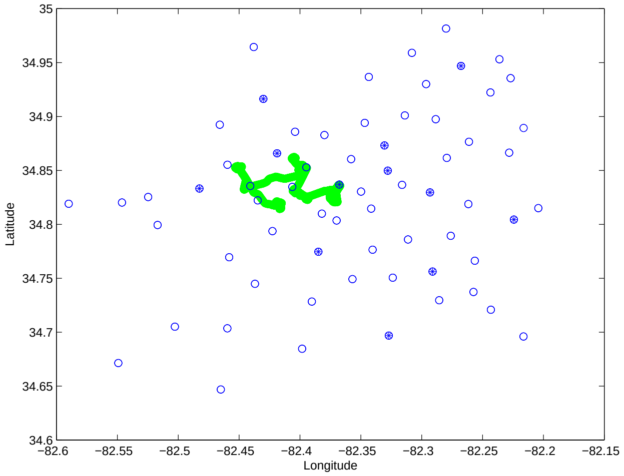

Figure B.20 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 523.

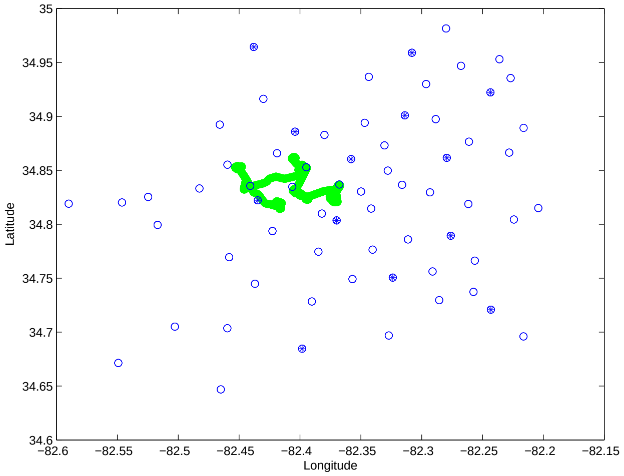

Figure B.21 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 798.

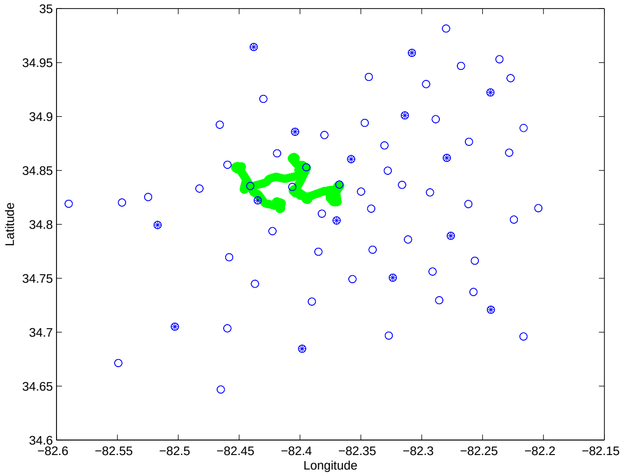

Figure B.22 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 524.

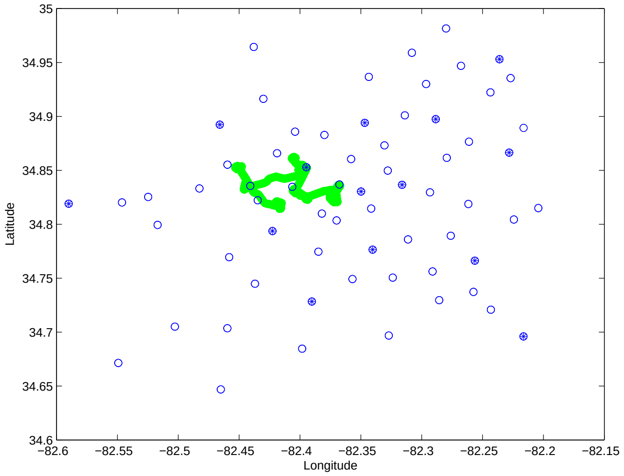

Figure B.23 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 799.

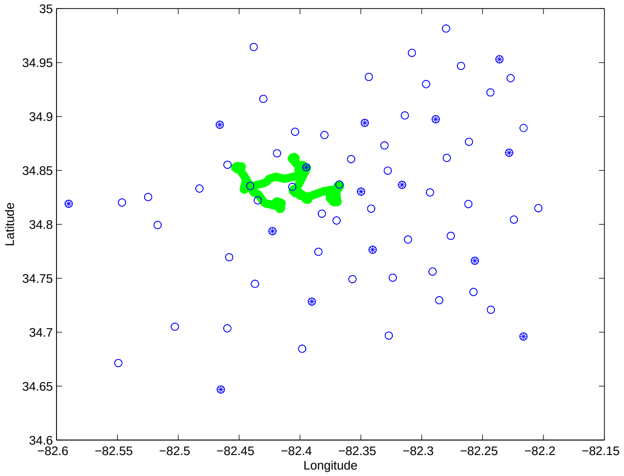

Figure B.24 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 525.

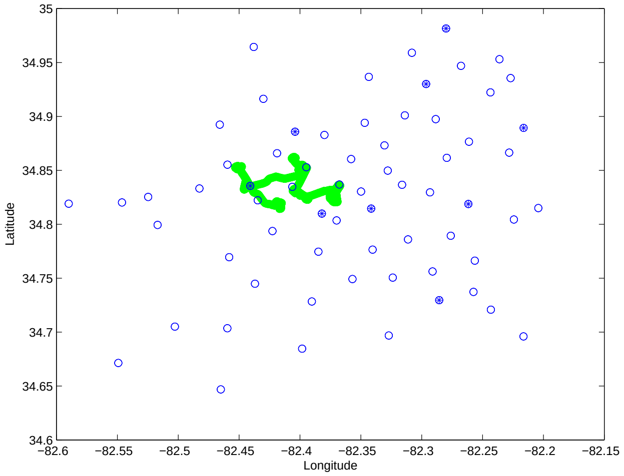

Figure B.25 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 800.

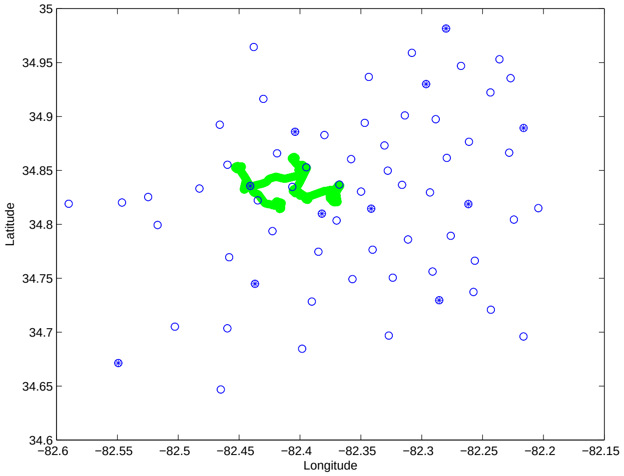

Figure B.26 Longitude/Latitude map of base stations (* and O) in Greenville, SC using DCCH 526.