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Performance Evaluation of Hyperbolic Position Location Technique in Cellular Wireless Networks

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PERFORMANCE EVALUATION OF HYPERBOLIC POSITION LOCATION TECHNIQUE IN CELLULAR WIRELESS NETWORKS

THESIS

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Abstract
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Position Location Technique in Cellular Wireless Networks

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Hakan Senturk

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Abstract

This study addresses the wireless geolocation problem that has been an attractive subject for the last few years after Federal Communications Commission (FCC) mandate for wireless service providers to locate emergency 911 users with a high degree of accuracy -within a radius of 125 meters, 67 percent of the time by October 2001. There are a number of different geolocation technologies that have been proposed. These include, Assisted GPS (A-GPS), network-based technologies such as Enhanced Observed Time Difference (E-OTD), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Cell of Origin (COO). This research focuses on network based techniques, namely the more prominent TDOA which is also called hyperbolic position location technique. The main problem in time-based positioning systems is solving nonlinear hyperbolic equations derived from set of TDOA estimates. Two algorithms are implemented as a solution to this problem: A closed form solution and a Least Squares(LS) algorithm. Accuracy and computational efficiency performances are compared in a wireless system established using DGPS measurements in Dayton, OH area.

Performance Evaluation of Hyperbolic

Position Location Technique in Cellular Wireless Networks

I. *Introduction*

Communication is so important to us that the ways to communicate advance further and further every day. From copper wires to fiber optics, an age has come where wired communication doesn't meet our needs. Computers have become small enough to carry, and portable computers have become the fastest growing product in the computer industry. The idea of truly mobile computing has started a new way of life, a novel way of thinking. The urge to communicate even by means of portable computers with interfaces to wireless networks has started the era of wireless communication. A recent survey found that one-third of the U.S. workforce, that is 43 million workers, are mobile and spend more than 20 percent of their time working away from their primary workplace [Yan97]. It is predicted that by 2003, more than 50 percent of new communication lines installed worldwide will be wireless [Tel01].

As interest in wireless communications has increased, new technologies have emerged. Geolocation has been a center of attention for many years. Geolocation is determining the geographic location i.e., the latitude and longitude of a mobile user. Wireless networks have lacked this technology since their establishment. This research study presents an overview of and performance comparison between wireless geolocation methods.

1.1 FCC Ruling

The primary drive for geolocation technology has been the Federal Communications Commission (FCC) mandate for wireless service providers to locate emergency 911 users with a high degree of accuracy -within a radius of 125 meters, 67 percent of the time by October 2001.

Before discussing the FCC mandate, we need to emphasize the importance of Enhanced 911(E-911). Statistics show that the emergency 911 calls from cellular phones are between 20 and 60 percent of all 911 calls [Sti95]. This ratio is growing every day as the number of cellular phone subscribers increase. From the standpoint of safety, wireless carriers are supposed to provide virtually the same emergency service as wired phones. In wired phones, when a 911 call is made, the nearest Public Safety Answering Point (PSAP) [Sti95] uses the phone number of the caller to look up the caller information and billing address. If a call is dropped, the operator at the PSAP can call back. This readily available information helps find and direct the closest police, fire, and medical agencies. All this helpful information is shown on the PSAP's screen immediately [Sti95]. However, this same information is not available for wireless subscribers. "Wireless callers are not associated with any location-this is why they buy the service [Sti95]." In the wireless case, no address, phone number, closest police, or other information is available, and the PSAP operator has to get this information by asking the caller. In addition, the caller must frequently be transferred to another closer PSAP in order to obtain emergency services. If a cellular call drops during the conversation, the caller has to call again and gathering useful data about the caller's name and location has to begin from start. This is the primary reason for the FCC mandate. The E-911 capability, when implemented, will require no overt action by the user in order to be located [Sti95].

The FCC E-911 mandate has been issued in two phases. Handset-based and hybrid methods were introduced in the re-issued Phase II requirements in September 1999. The new Phase II requires that wireless service providers identify the position of a mobile handset user calling E-911 within a radius of 50 meters for 67 percent of calls and 150 meters for 95 percent of calls. For network-based solutions, the requirement is 100 meters for 67 percent of calls and 300 meters for 95 percent of calls [FCC96].

1.2 Geolocation Based Services

Wireless geolocation has a great number of applications called location-based services which can be defined as value added services that utilize the knowledge of the mobile user's geographical location [Sun00]. This information is helpful and actually essential for a great number of reasons. It is useful to categorize the uses of geolocation in two groups: Geolocation for Military and Geolocation for Civilian and/or Commercial purposes.

1.2.1 Geolocation for Military. Although the primary drive behind geolocation technology is the FCC mandate for E-911 safety purposes, it has many application areas in the military as well. Starting with battlefield, locating an infantry soldier or a vehicular unit and tracking them via a Command and Control Center may be achieved by means of wireless geolocation technologies. This capability in military wireless networks would enable Command and Control Centers to be fully informed about their units' positions. In addition, it would be easy to locate an injured soldier even when he couldn't speak. His cell phone, laptop or other wireless device could transmit the necessary location signal which would be used in order to provide his geographic location information.

Another application area is the electronic surveillance of a network coverage area for security purposes. Wireless geolocation capability can also be used in mobile wireless networks, so in that aspect we don't want any unauthorized user using a laptop or pda to move into our area and listen to our communication. In this case, geolocation technology could help to locate an unauthorized user.

1.2.2 Other Geolocation Services. Studies on how to implement geolocation have created another interesting research area which has many potential uses and applications for civilian, commercial purposes: Wireless Geolocation Services. As noted before, the primary use of geolocation is in locating emergency 911 callers for safety purposes. Other geolocation services could include:

- Roadside assistance (e.g., direction finding, mapping, navigation assistance, traffic information). Questions such as "Where is the nearest gas station?" or "I lost my way, how can I get to I-95?" could be readily answered,
- Tracking. Both people such as children, seniors, mentally handicapped and car or asset could be tracked,
- Intelligent transportation system applications such as fleet management
- Automatic Crash Notification (ACN), reports a crash of an automobile to necessary places, such as fire and PSAP (Public Safety Answering Point),
- Location-based billing,

- Location based services "4-1-1", location specific information such as local weather, mobile yellow pages, etc. and
- Mobile e-commerce, wireless advertising and instant messaging.

Wireless Geolocation can also help solve a network routing issue. Accurate routing is an important performance issue in computer networks, especially in mobile ad hoc networks [CaL00]. Using location information, Location Aided Routing (LAR) protocols have been proposed to decrease routing overhead, thus improving performance. Some hybrid solutions using location information with routing protocols like the Zone Routing Protocol (ZRP) have been studied. These studies demonstrate the potential use of geolocation in wireless networks [BoS01].

1.3 Background

There are a number of different geolocation technologies that have been proposed. These include, Assisted GPS (A-GPS), network-based technologies such as Enhanced Observed Time Difference (E-OTD), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Cell of Origin (COO).

1.4 Research Objectives

This research studies these techniques along with their strengths and weaknesses. The focus will be on network based techniques, namely the more prominent TDOA which is also called hyperbolic position location technique. The primary goal of this research is the evaluation of hyperbolic position location technique in cellular wireless networks.

1.5 Organization of the Document

This chapter gives a brief introduction to wireless networks and geolocation technologies. The goal of the research and organization of the document is also presented.

The second chapter presents an overview of different approaches used in geolocation. The overview of literature about the network-based geolocation technologies, i.e., E-OTD, TDOA, AOA, COO as well as the Assisted-GPS technique is provided.

The third chapter presents the methodology. This chapter outlines the system and the component under test, system parameters, the factors that we vary during the simulations and also the performance metrics we use. Moreover, the design of experiments and the workload is also presented in this chapter.

Chapter four presents the description of the simulation and analytical models implemented throughout the study.

The fifth chapter contains the results of the simulation runs. The evaluation of the geolocation technologies is presented along with the simulation results.

Chapter six presents the summary, conclusions drawn from the results of the research and the recommendations for future studies.

II. Literature Review

2.1 Introduction

Wireless geolocation seeks to determine the position of a mobile user in a wireless network. It has attracted significant attention in recent years. So far, existing cellular networks have lacked this capability. The need to include geolocation technology into the wireless network is driven by two critical factors:

1. First and primarily, the FCC E-911 mandate requires that wireless service providers must identify the position of a mobile user calling 911 within a radius of 50 meters for 67 percent of calls and 150 meters for 95 percent of calls for handset-based solutions. For network-based solutions, location within 100 meters for 67 percent of calls and 300 meters for 95 percent of calls are the required location estimate errors [FCC96].
2. The second factor is that many new types of commercial services are being developed to take advantage of a geolocation capability such as zone-based billing, mobile yellow pages, improved roadside assistance, personal direction finding, intelligent transport systems [RRW96] (e.g., fleet management and vehicle tracking), mobile directory assistance, and services for public safety and security.

There are several geolocation technologies; current studies in this area have been done for both existing Global System for Mobile Communications (GSM) networks and third generation Universal Mobile Telecommunications System (3G UMTS) networks.

This chapter presents a literature survey of different approaches in the implementation of wireless geolocation in cellular networks. The goal in this literature review is to examine the proposed geolocation technologies with their accuracy, advantages and disadvantages and also look into hyperbolic position location technique, i.e., TDOA closely.

Wireless geolocation technologies will be presented in three groups. First, network-based geolocation technologies, next handset-based geolocation technologies and finally, hybrid technologies. Under network-based geolocation technologies, Cell-Id, Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) techniques will be discussed and evaluated. Under handset-based geolocation technologies, handset-based method using system signals and Stand-alone GPS will be evaluated. Under hybrid technologies, Assisted-GPS (A-GPS) and Enhanced Observed Time Difference (E-OTD) techniques will be evaluated.

2.2 Wireless Geolocation Technologies

2.2.1 Network-based Geolocation Technologies. In network-based technologies, the cellular network uses the signals transmitted by the Mobile Station(MS) and calculates its position using those signals. The Cell-Id method, Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) fall into this category.

2.2.1.1 Cell Id Based Technique. Cell Id method is the simplest geolocation technology. With this technique, the MS's location is determined with the knowledge of its serving base station cell area. This method uses the basic positioning location capabilities that all the cellular networks have today. When a mobile phone is on, it is served by the nearest base station, and the cell area of that base station is used as the location of the MS. This method often incorporates Timing Advance (TA) information. TA is an estimate of the distance from the mobile to the base station using the measured time between the start of a radio frame and the arrival of bursts from the mobile station. This information is already built into the network and the accuracy is acceptable when the cells are small (a few hundred meters) [Sun00]. For services where proximity is the desired information (e.g., show me a restaurant in this area), this is a very inexpensive and useful method. It works with all existing terminals, which is a big advantage. This method, called Cell Global Identity-Timing Advance (CGI-TA) has been described and standardized in [Swe99]. It is one of Ericsson's (a cellular service provider) possible solutions for geolocation problem.

The accuracy of this method depends upon size coverage of the cell i.e., the type of the cell that the MS is in. Table 2.1 gives an overview of different cell types in cellular networks. In urban areas where the pico cells are deployed, the accuracy is between 100 and 200 meters. If the Timing Advance (TA) is applied, the accuracy again, depending on the cell size, varies from 10m (a microcell in a building) to 500m (in a large outdoors macrocell) [Swe99].

Table 2.1. Cell Types

Cell Type	Cell Dimension (km)
Large Macrocell	3-30
Small MacroCell	1-3
MicroCell	0.1-1
PicoCell	0.01-1
NanoCell	0.001-0.01

The response latency of the technique is about 1-5 seconds [CBD01]. The advantages are that location can be determined in about 3 seconds, it can be used with existing handsets, and no modification to handsets or network infrastructure is needed. One disadvantage is that, due to low accuracy, FCC requirements are not met.

2.2.1.2 Time Difference of Arrival (TDOA) Technique. The principle of TDOA is to determine the relative position of the MS by measuring the time differences at which the signal transmitted by the MS arrives at multiple base station receivers, rather than using the absolute arrival time [RRW96], [ChH93]. Assuming radio waves travel at a constant rate of 300,000 km/s, and using the difference in arrival times, it is possible to calculate hyperbolas on which the MS is located. The equation of the hyperbolas is

$$R_{i,j} = c(t_i - t_j) = d_i - d_j \quad (2.1)$$

$$R_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2 + (Z_j - z)^2} \quad (2.2)$$

where t_i and t_j are the Time of Arrival(TOA) estimates of the signals from base stations i and j, d_i and d_j are the distances from the mobile to base stations i and j, c is the speed of light, (X_i, Y_i, Z_i) and (X_j, Y_j, Z_j) denote the coordinates of the base stations and (x, y, z) is the unknown coordinate of the mobile station.

As seen in the Figure 2.1, at least three base stations are required in order to obtain a location estimate. Studies show that if more than three base stations are involved in measurements, more accurate location estimates are achieved [LKC00].

Among all the wireless geolocation techniques, the TDOA method using PN code correlation characteristic has drawn more attention because it does not require the syn-

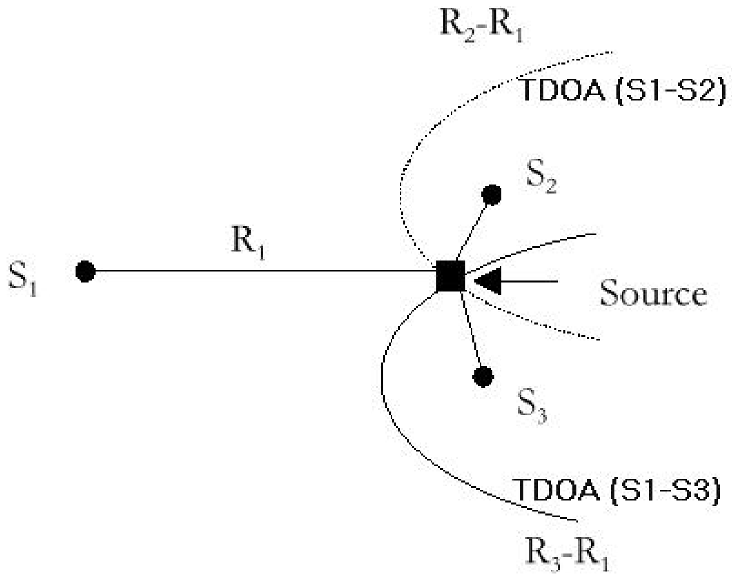

Figure 2.1. Time Difference of Arrival Technique

chronization between MS (Mobile Station) and BS(Base Station) [JYL00]. The studies on TDOA estimation in CDMA networks mostly focus on receiving a reverse traffic channel of a MS at several BSs or several forward pilot channels of BS at a MS. A technique based on estimating TDOAs has been proposed for forward channel CDMA networks in [Hep99a]. Hepsaydir, in this and another study [Hep99b], proposed a method using pilot tones from different base stations. The MS acquires the pilot channel in the CDMA forward link to synchronize to the Pseudo Noise (PN) code phase. Since each base station transmits different PN codes, this helps mobile station recognize different PN codes of different base stations. When synchronized to the base station or cell, the mobile station measures the "PilotArrival" time of the cell. Using the three different PilotArrivals it receives, the mobile station can make a location estimate of itself using the TDOA technique described above. Sunay and Tekin [SuT00] notes that "in the current IS-95 based CDMA networks, all base stations continually transmit pilot signals which amount to approximately 20 percent of the total transmitted power. Therefore, forward link time difference of arrival (TDOA) algorithms are readily applicable to IS-95 systems" [SuT00].

The authors in [HHH00] improve TDOA estimation using wavelets in GSM networks. By reducing the effective noise at the receivers, they achieve lower mean square error values with the implementation of Modified Approximate Maximum Likelihood (MAML) method. [Che99] proposes a cellular based mobile tracking system using range measurements from TDOA estimates, and uses a NLOS mitigation algorithm in order to decrease the NLOS errors in location estimates. [MBP00] studies a method with a neural network as data fusion algorithm using AOA, TOA and TDOA measurements. They report a RMSE of 73 m. [OsB01] applies a data fusion architecture which uses TOA and TDOA measurements in one method. [WYK00] analyzes the performance of TDOA and AOA, and examines the measured TDOA error that is satisfied with FCC E-911 requirements, the maximum error that satisfies the requirements is reported as 500 ns.

The TDOA method offers about 80 meters of accuracy. Hepsaydir in [Hep99a] achieves a RMS error of 74 meters in Gaussian-like channel at an Ec/Io (signal-to-interference ratio) value of -13 dB in simulations and an average of 83 meters in real time measurements. The time before location is determined for the technique is about 10 seconds [CBD01]. It has advantages of no additional network element, such as a Location Measurement Unit (LMU) and uses existing CDMA network features (when used in CDMA networks). The disadvantages are it requires base stations to be synchronized to better than 100 ns using GPS or atomic clocks at each base station. This capability is found in CDMAOne networks in the USA, but is not found in GSM networks. Additionally, multipath propagation, noise and interference results in inaccurate intersections of the hyperbolas. When the multipath channel was introduced, RMS error of 74 m was observed to increase significantly to 250 meters [Hep99b].

2.2.1.3 Angle of Arrival (AOA) Technique. The Angle of Arrival method uses simple triangulation based on estimated Angle of Arrival (lines of bearing) of a signal at 2 or more base stations to estimate the location of the MS. Figure 2.2 shows the idea behind that technique.

“The most common version of this technique is known as small aperture direction finding which requires a complex of 4-12 antenna arrays in a horizontal line at each of several cell site locations. The antennas work together to determine the angle from which a signal originated. When several sites can each determine their respective angles of arrival,

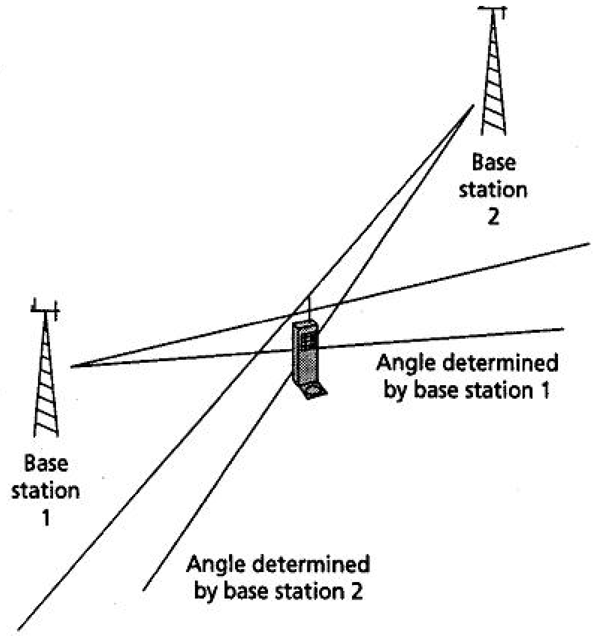

Figure 2.2. Angle of Arrival Technique

the location of the MS can be estimated from the point of intersection of projected lines drawn out from the cell site at the angle which the signal originated [Buc99]."

In [DeF00], a location algorithm proposed using a hybrid method that incorporates TOA and AOA methods using a Least Squares algorithm. They report that their proposed algorithm satisfy the location error requirement of FCC in urban, suburban and rural environments.

The most significant disadvantage with the AOA technique is the cost of installing antenna arrays. Although [LiR94] concludes that adaptive antenna arrays increase the capacity of cellular systems, they would only be needed in the areas where the capacity enhancement will be required. Thus, it is impractical to install antenna arrays at every cell site for the purpose of geolocation.

The accuracy of AOA is reduced with increasing distance between the MS. Lee, Kim and Chung [LKC00] have studied position location error using AOA technique in CDMA networks. The accuracy they report is between 45 and 97 meters. In their study, the more base stations involved in the network the better the accuracy [LKC00]. The time needed to determine a location estimate is about 10 seconds. The most important advantage is that only two base stations are required to get a location estimate. The disadvantages are that it shows very poor performance in rural areas because of the linear orientation of base stations along major roads and requires adding expensive and complex antenna arrays. A small angular error of the antenna array can produce a significant error in location estimate. Furthermore, in the absence of a LOS signal component, the antenna array will lock on to a reflected signal component and, even if a LOS is present, multipath propagation will cause errors with the angle measurements. [WYK00] analyzes the performance of AOA, and determines the measured AOA angle error that satisfies with FCC E-911 requirements. The maximum error that satisfies the requirements is reported as 2 degrees. In [BlF00], they propose "a relatively simple and robust interference-mitigated AOA estimation algorithm" and run real-time measurements using a multiuser AOA technique. They demonstrate that "the use of temporal multipath structure provides improved accuracy and their proposed technique can successfully operate in extreme interference environments" [BlF00].

2.2.2 Handset-based Geolocation Technologies. Using this approach, the mobile station (MS) calculates its own position using signals it receives either from base stations or GPS.

2.2.2.1 Handset-based method using system signals. In this technique, the mobile station uses the signals transmitted by base stations and performs algorithms such as Advanced Forward Link Trilateration (AFLT) [Sun00] to calculate its geographic position.

2.2.2.2 Stand-Alone GPS. In this category, handsets are equipped with stand-alone GPS receivers. Global Positioning System (GPS) is a world-wide radio-navigation system consisting of a constellation of 24 or more satellites orbiting the earth. Each of the satellites transmits its own position, time and a pseudo random noise code that provides range information. GPS works on a basis of measuring distances using the travel time of radio signals from at least 4 satellites to determine a 3-D position (such as latitude, longitude, and altitude) [DjR01].

A handset with a GPS receiver can determine its location with an accuracy of 10 meters or less. In [NRM00], a root mean square error (RMSE) of 7 meters with a signal to noise ratio (SNR) of 20 dB, phase shift rate of 1 chip/s, and user velocity of 30 m/s is reported. Centimeter level accuracy is achieved in [HMW00] by using stand-alone GPS receivers. The warm-up time of GPS receiver takes about 15 seconds to 15 minutes. As a result, the disadvantages are the warm-up time is long; it requires a clear view of sky, direct line of sight with the satellite; it doesn't operate indoors and it requires handsets to be equipped with GPS receivers introducing cost, size and power consumption problems.

2.2.3 Hybrid Geolocation Technologies. Hybrid solutions are the combination of the network-based and handset-based technologies. The overall idea behind this approach is to overcome the disadvantages of handset and network based technologies i.e., limited availability of GPS and low accuracy of network based technologies. Wireless Assisted GPS (A-GPS) and Enhanced Observed Time of Difference (E-OTD) techniques fall into that category.

2.2.3.1 Assisted-Global Positioning System (A-GPS). This technique works on the basis of tracking the signals received from satellites in a way that works under very low signal strength such as indoors. The Assisted-GPS concept is shown in Figure 2.3. The main difference from stand-alone GPS is that whenever a MS's location is required, the network transmits an "assisting" message about exact position and direction of the visible satellites with the help of a reference server called A-GPS server, established in the network. The assisting message also sends information about the data in the GPS signal that enables the receiver to use high-gain processing techniques for weak signal detection and tracking. A-GPS servers are network entities with reference GPS receivers. The handsets which are equipped with partial GPS receivers use this assist information transmitted by A-GPS servers, and since the handset would not have to spend too much time in searching the satellites, the time to establish a fix is reduced to almost 5 seconds from several minutes [DjR01] with this technique. The signal received by the handset is sent back to A-GPS server, this server then makes the location calculations and measures the geographic coordinates of the handset. Having the Cell ID and sector ID information of the handset, the network can accurately predict the GPS signal the handset will receive so it can relay this information to the mobile station.

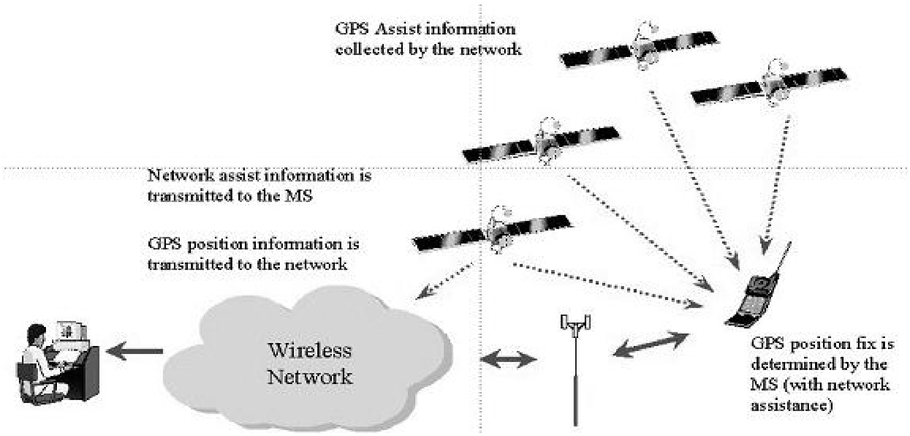

Figure 2.3. Assisted-GPS Technique

The technique produces "..50 meters accuracy indoors and 15 meters outdoors" [DjR01]. [CBD01] notes accuracy as 10-100 meters or Not Available. Depending upon the environment, a location estimate might not be available indoors. The time needed to determine a location estimate is about 6-15 seconds [CBD01]. As its advantages: GPS info can be used when the MS is indoors and it is also noted that "by distributing data and processing, as well as implementation costs, between the network and mobiles, A-GPS will optimize air-interface traffic" [DjR01].

The disadvantages of A-GPS are: it requires handsets to be equipped with GPS receivers; as pointed out in [HEW01], equipping handsets with GPS receivers is costly, and will increase handset size and power consumption and it requires A-GPS servers in the network. Furthermore, [CaS95] believes that the Non-Line of Sight (NLOS) situations yield the worst case results.

2.2.3.2 Enhanced Observed Time Difference (E-OTD). This method requires location receivers in the network infrastructure called a Location Measurement Unit (LMU) and operates using time measurements of signal travelling distances between the MS and the LMU as in the TDOA technique. Figure 2.4 shows the working principle of the technique. The LMUs are geographically dispersed in a wide area. Every 30 seconds, each base station broadcasts a signal in an asynchronous manner. When signals from at least three base stations are received by the handset and LMU, the time differences of arrivals of the signal from each base stations at the handset and the LMU are calculated. The differences in time stamps are combined to produce intersecting hyperbolic lines and finally the location estimate of the MS is determined by the intersection of the hyberbolas. As the authors point out, LMUs help to determine the clock offsets between base stations. One LMU is needed for every 3 to 5 base stations [HEW01].

It offers accuracy between 50 and 125 meters and the time to determine an estimate is between 5 and 10 seconds [CBD01].

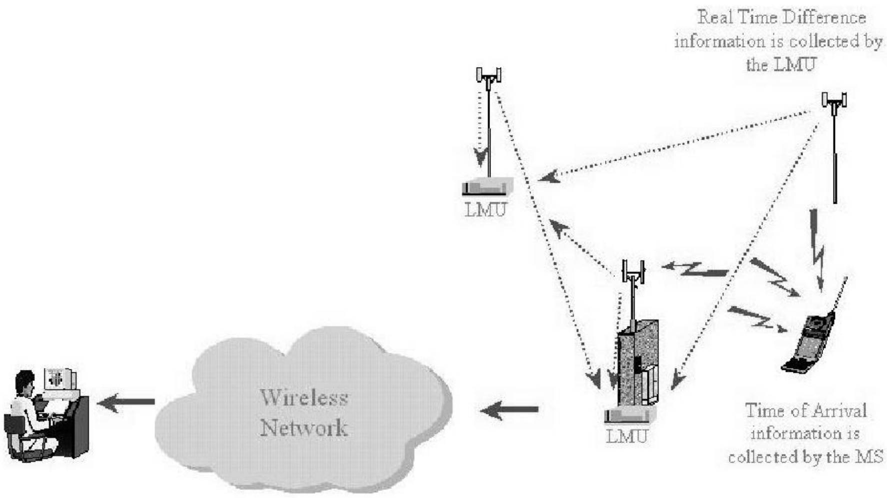

Figure 2.4. E-OTD Technique

The disadvantages are: It requires handsets to be modified with E-OTD software; requires LMUs in the network infrastructure; and is subject to urban multipath problems [Buc99].

2.3 Comparison of Geolocation Technologies

All the technologies examined above have advantages and disadvantages.

In terms of feasibility and implementation:

- A-GPS requires additional equipment (i.e., A-GPS servers) or modification to mobile stations

- E-OTD requires both network and mobile station modification, requires one LMU for every 3-5 base stations.

- TDOA requires mainly network modification. Modern handsets are supposed to support this technology.

- AOA requires network additional equipment to be deployed into the network i.e., antenna arrays.

- Cell Id requires no modification.

In terms of location accuracy:

- A-GPS offers the best potential accuracy i.e., 3-100 meters.

- TDOA offers an average of 80 meters accuracy.

- AOA offers between 60 and 130 meters.

- E-OTD offers between 50 and 125 meters.

- Cell Id cannot meet the FCC requirements.

Most of the above systems meet the FCC requirements, yet the accuracy, reliability, and more importantly, cost factor drive the quest for even more advances.

2.4 Assessment of Existing Technology

Among the geolocation technologies we have reviewed, there appears to be no clearly superior technology at the moment.

The T1P1 Committee, a sub-committee of the American National Standards Institute (ANSI) and the European Telecommunications Standards Institute (ETSI) have recently committed to the standardization of location finding systems using Enhanced Observed Time Difference (E-OTD), Time Difference of Arrival (TDOA), and Assisted GPS (A-GPS) in addition to Cell-ID [Buc99]. Recall that the primary drive for geolocation technology is the FCC E-911 mandate for wireless operators. Therefore, it is not hard to eliminate Cell-Id technology which cannot meet this mandate.

The CDMA community generally accepted A-GPS technology, and Snaptrack [MoK01] is the most successful example of this technique, offering up to 3 meters accuracy and handset cost of as low as 5 dollars. On the other hand, the E-OTD technique is the most prominent in GSM world.

Having chosen A-GPS as a candidate hybrid technology, we need to look at network based technologies as well for cost reasons. Putting GPS chipsets into handsets is unlikely since there are some size and battery drain issues which will come into play as [HEW01] points out. As [CaS95] and [WaG00] point out, NLOS is a problem for A-GPS technology. This is why researchers have a tendency to use a network based technology which does not require any modification to handsets. The most prominent example of this technology is TDOA which is also accepted as an ANSI and ETSI standard. The appealing features of TDOA is no modification to handsets and no requirement of synchronization between base stations and mobile stations. The only requirement is to have sychronized clocks at base stations at the nanosecond level (which is already provided as timing standards). This requirement makes TDOA more realistic than requiring each MS to have an accurate clock [RRW96]. Thus, TDOA is a viable technology for the wireless E-911 problem. [KBR97] notes that the cost and the maintenance advantages will make TDOA-based systems a more attractive geolocation solution.

2.5 Position Calculation with TDOA

As mentioned earlier, TDOA is a hyperbolic position location estimation technique. The location estimation using TDOA is achieved in two stages [RRW96]. First, the time differences from MS and BSs (TDOAs) must be estimated and in the second stage, estimated TDOAs are transformed into a set of nonlinear hyperbolic equations which upon solving, will provide the estimated position of the MS. Since the equations derived are non-linear, solution of those hyperbolic equations require use of efficient algorithms. In this section, a survey of different techniques and algorithms which may be used in TDOA estimation and solving hyperbolic nonlinear equations is provided.

2.5.1 TDOA Estimation Techniques. The TDOA of a signal can be estimated by two general methods: subtracting TOA measurements from two base stations to produce a relative TDOA, or through the use of cross-correlation techniques, in which the received signal at one base station is correlated with the received signal at another base station [DeF00]. Cross-correlation techniques are used extensively in estimating the TDOA. Two different cross-correlation techniques are used; distributed and centralized. In the former method, a cross-correlation is done at every base station, in the second method, every signal pattern from every base station is compared and correlated to a reference base station. The reference base station is the first base station which receives the signal from the MS.

2.5.1.1 Generalized Cross-Correlation Technique. A mathematical model for cross-correlation is presented below [ChH94].

Assuming a Gaussian-like channel with interference and noise and a signal s(t) being transmitted from a MS, a general mathematical model for the time-delay estimation between signals at two base stations BS1(t) and BS2(t) can be written as:

$$BS1(t) = A_1 * s(t - d_1) + n_1(t) \tag{2.3}$$

$$BS2(t) = A_2 * s(t - d_2) + n_2(t) \tag{2.4}$$

where A_1 and A_2 correspond to the amplitude of the signals at base stations, $n_1(t)$ and $n_2(t)$ are noise and d_1 and d_2 correspond to signal delay (arrival) times. It is assumed that $s(t)$, $n_1(t)$ and $n_2(t)$ are zero-mean (time-average) random processes and $s(t)$ is independent from $n_1(t)$ and $n_2(t)$. Assuming that BS1 is the reference base station ($d_1 < d_2$) the equations can be rewritten:

$$\begin{aligned} BS1(t) &= s(t) + n_1(t) \\ BS2(t) &= A * s(t - D) + n_2(t) \end{aligned} \tag{2.5}$$

where A=A_1/A_2 and D=d_2 - d_1 [KnC76].

An estimated cross-correlation function of these signals is:

$$R_{1,2}(t) = \frac{1}{T}\int_0^T S_1(t) * S_2(t+\tau)dt \quad (2.6)$$

where T represents the observation time. Once the cross-correlation function is computed at the reference BS, the value of τ that maximizes the above equation provides the TDOA estimate.

2.5.2 Solving Non-linear Hyperbolic Equations. After the TDOA estimates are obtained, we can define a set of non-linear hyperbolic equations by transforming TDOAs into range difference measurements. Since these equations are non-linear, solving them is not a trivial procedure [ChH94].

The range difference between MS and BS is

$$R_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2} \quad (2.7)$$

Recall that these range differences are equal to TDOA delay(D), and using a reference base station, we can write

$$R_{i,1} = c * d_{i,1} = R_i - R_1 = \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2} \quad (2.8)$$

where c is the speed of signal (approximately $3 * 10^8 m/s$), $d_{i,1}$ is the TDOA estimate, R_i is the distance between the reference base station and mobile station and $R_{i,1}$ is the range differences between the first(reference) base station and the *ith* base station. These equations together define the set of nonlinear hyperbolic equations, and solving these equations will yield the estimated position of the MS in terms of *x and* y.

In the remainder of this section, we consider the different algorithms proposed in order to solve these hyperbolic equations. They have different levels of complexity and yield different levels of accuracy. We will look at 3 different methods: the Taylor-series method, Fang's method and Chan's method. Other solutions requiring additional data have also been proposed including Spherical Interpolation (SI), and Divide-and-Conquer (DAC) method by Abel [Abe90]. Although other closed form solutions have been developed, their estimators are not optimum [ChH94].

2.5.2.1 Taylor-Series Method. The Taylor-Series method linearizes the set of non-linear equations by Taylor-Series expansion and then iteratively produces a solution[ChH94], [DeF00], [Foy76], [LAL00]. The method requires an initial guess and improves the estimate at each iteration by determining the local linear least-squares (LS) solution. We expect the algorithm to yield a solution within a few iterations. It benefits from extra measurements which is the case when there are more than three visible base stations. It is sensitive to the initial guess. The algorithm might not always converge under bad GDOP (Geometric Dilution Of Precision) circumstances. GDOP is a measure of how ranging error affects position error due to the geometry of base stations [Woo94]. [DeF00] considers LS as the most feasible algorithm to time-based positioning system.

Analytical Model for Taylor's Method. With a set of TDOA estimates $d_{i,1}$, the method starts with an initial guess (x_0, y_0) and computes the deviations of the location estimates using the below formula called as minimum variance estimation formula:

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = (G_t^T Q^{-1} G_t)^{-1} G_t^T Q^{-1} h_t \tag{2.9}$$

where Q is the equation error covariance matrix of the TDOA estimates,

$$h_t = \begin{bmatrix} r_{2,1} - (r_2 - r_1) \\ r_{3,1} - (r_3 - r_1) \\ \cdots\cdots\cdots \\ r_{n,1} - (r_n - r_1) \end{bmatrix} \tag{2.10}$$

$$G_t = \begin{bmatrix} (X_1 - x)/r_1 - (X_2 - x)/r_2 & (Y_1 - y)/r_1 - (Y_2 - y)/r_2 \\ (X_1 - x)/r_1 - (X_3 - x)/r_3 & (Y_1 - y)/r_1 - (Y_3 - y)/r_3 \\ \cdots\cdots\cdots & \cdots\cdots\cdots \\ (X_1 - x)/r_1 - (X_n - x)/r_n & (Y_1 - y)/r_1 - (Y_n - y)/r_n \end{bmatrix} \tag{2.11}$$

The values r_i= 1,2,...n are computed using

$$r_i^2 = (X_i - x)^2 + (Y_i - y)^2 \tag{2.12}$$

where initially $x = x_0$ and $y = y_0$. In the next iteration x_0 and y_0 are set to $x_0 + \Delta x$ and $y_0 + \Delta y$ and this iterative process is repeated until Δx and Δy are sufficiently small.

2.5.2.2 Fang's Method. Fang's non-iterative algorithm [Fan90] gives an exact solution only when the number of TDOA measurements are equal to the number of unknowns (coordinates of MS) [ChH94]. Although the algorithm works well when the base stations are placed arbitrarily, it cannot make use of redundant measurements such as when there are more than three base stations available to improve position accuracy.

2.5.2.3 Chan's Method. Chan's method [ChH94], [ChH97] is also a non-iterative algorithm that solves the problem by producing a closed-form solution valid for both distant and and close sources. The method produces its most accurate results when the TDOA errors, i.e., noise levels are small.

For three base stations with two TDOA estimates, *x and* y can be solved in terms of R_1 using

$$\begin{bmatrix} \mathrm{x} \\ \mathrm{y} \end{bmatrix} = \begin{bmatrix} X_2,1 & Y_2,1 \\ X_3,1 & Y_3,1 \end{bmatrix}^{-1} \times \left(\begin{bmatrix} R_2,1 \\ R_3,1 \end{bmatrix} * R_1 + \frac{1}{2} \begin{bmatrix} R_2,1^2 - K_2 + K_1 \\ R_3,1^2 - K_3 + K_1 \end{bmatrix} \right) \tag{2.13}$$

where

$$K_1 = X_1^2 + Y_1^2,$$
$$K_2 = X_2^2 + Y_2^2,$$
$$K_3 = X_3^2 + Y_3^2.$$

After solving the equation in R_1, substitute x *and* y into

$$R_i = \sqrt{(X_i - x)^2 + (Y_i - y)^2} \tag{2.14}$$

at $i = 1$ which gives us a quadratic in R_1. By substituting R_1 back into Equation 2.13, we obtain the solution. Sometimes, there may be two positive roots that produce two different answers; however, the ambiguity can often be resolved by restricting the mobile station's position to within the area of network coverage.

2.6 Summary

In this chapter, the techniques used in wireless geolocation has been explained along with their location accuracies, advantages and disadvantages. In the second section, a detailed description of hyperbolic position location techniques are given.

III. Methodology

3.1 Overview

In this chapter, the methodology used in this research is presented. In order to perform a complete analysis and to avoid common mistakes, the following methodology is used [Jai91]:

1. State the goals of the study and define system boundaries,
2. List the system services and possible outcomes,
3. Select performance metrics,
4. List system and workload parameters,
5. Select factors and their values,
6. Select evaluation techniques,
7. Select the workload,
8. Design the experiments.

3.2 Problem Definition

3.2.1 Goals and Hypothesis. The purpose of this research is a performance evaluation of TDOA technique or in other words hyperbolic position location technique in terms of location accuracy and computational efficiency. The research focuses on second stage of TDOA technique which is solving nonlinear hyperbolic equations derived from set of TDOA TDOA estimates (cf., Section 2.5.). Thus, this research presents a performance comparison of Taylor and Chan algorithms. Given the true location, the estimated location (within a range of error) of the mobile user is determined. The performance metrics used in the comparison along with all the specifications in implementation is provided in this chapter.

A comparison between TDOA technique and stand-alone GPS technique is also provided and presented within the scope of this thesis.

3.2.2 Approach. Real-time GPS positioning with both stationary and mobile GPS receivers is performed in the Dayton, OH area under five different environments and explained in Section 3.5. In order to simulate TDOA technique, cellular base stations are assumed to be located at specific locations with regard to the network coverage specified. Detailed information is provided in Chapter 4.

3.3 System Boundaries

3.3.1 System Under Test (SUT). A cellular network is the system under test. This network is located in Dayton, OH area. The four different environments tested are residential, highway, downtown and indoors. The number of base stations and geographic boundaries are specific to the particular environment.

3.3.2 Component Under Study (CUS). The component under study is the wireless geolocation technique. Since two algorithms are implemented and compared, the technique itself is defined to be component under study.

3.4 System Services

The service that is provided by the system is the location estimate of the mobile user. There are three possible outcomes of this service.

1. A successful location estimate is made (i.e., within the desired limits)
2. A location estimate cannot be made.
3. A location estimate is made but is not within the desired limits.

3.5 Performance Metrics

The following metrics are used to compare the geolocation technique's performance.

- Location Accuracy: Location accuracy of a geolocation method is defined to be the distance between the estimated location and the true location of the mobile station. Accuracy is expressed in meters.

There are a number of performance metrics for location accuracy in the literature: Root Mean Square Error (RMSE), Mean Squared Error (MSE), Circular Error Probability (CEP), and Cramer-Rao Lower Bound (CRLB). This research uses distance error and RMSE as performance metrics in order to evaluate and analyze location accuracy.

– Root Mean Square Error (RMSE): The below equation defines distance error as

$$d = \sqrt{(X_{est} - X_{true})^2 + (Y_{est} - Y_{true})^2} \tag{3.1}$$

where (X_{est}, Y_{est}) is the estimated coordinates, and (X_{true}, Y_{true}) is the true location coordinates of the mobile station.SO, we can define RMSE as

$$RMSE = \sqrt{\Sigma d_i^2 / n} \tag{3.2}$$

where d_is are distance errors and n denotes the number of location estimates. RMSE is the most applicable location accuracy performance metric in the literature, it is the most used and a simple metric. This is a lower better (LB) metric.

– Mean Squared Error(MSE): Mathematically RMSE is also defined as,

$$RMSE = \sqrt{MSE} \tag{3.3}$$

Thus, we can define MSE as

$$MSE = \Sigma d_i^2 / n \tag{3.4}$$

– Geometric Dilution of Precision(GDOP): GDOP is a performance metric that, when combined with a measurement error statistic, quantifies the location accuracy based on the geometric relationship between the mobile station and the base stations(for cellular positioning) or satellites(for GPS positioning). This relationship denotes to the geometric configuration of the mobile's position with regard to the receivers as poor or good depending upon its value. The Figure 3.1 shows an example of good and bad geometry. This is a lower better metric. We want GDOP value to be always minimum. Assuming a measurement accuracy of 10m and GDOP value of 5, our positioning accuracy becomes 50 m. If the GDOP value is close to unity, then our positioning accuracy gets close to our measurement accuracy [Kap96].

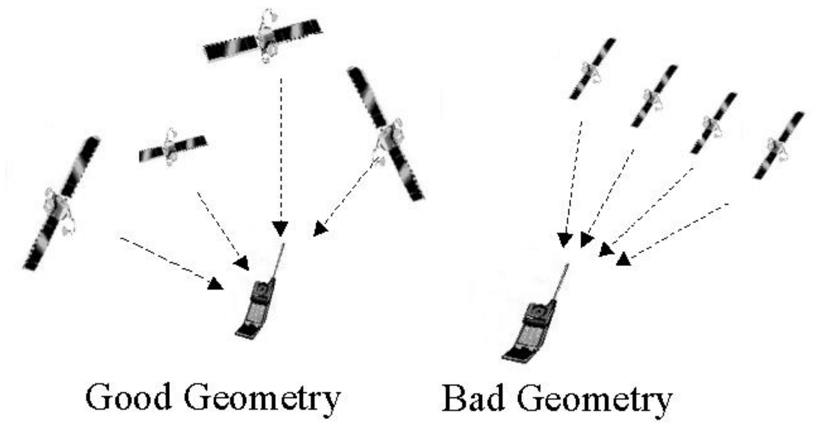

Figure 3.1. Geometric Dilution of Precision

Mathematically, GDOP for GPS positioning including 3 dimensional and time vectors is defined as the root sum square of these four variances [Kap96].

$$GDOP = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2 + \sigma_{tt}^2} \tag{3.5}$$

where $\sigma_{xx}^2, \sigma_{yy}^2, \sigma_{zz}^2$ and σ_{tt}^2 are the variances in x, y, z coordinates and time vectors respectively.

GDOP for a hyperbolic location estimate is given by [Tor84] as:

$$GDOP = \sqrt{\sigma_x^2 + \sigma_y^2}/\sigma_s \tag{3.6}$$

where σ_x and σ_y are the mean squared position errors in MS estimates and σ_s is the mean squared ranging error.

– Circular Error Probability (CEP)

CEP is based on the variances of the position estimate in the x and y directions. This gives an overall measure of the position estimator accuracy. The relationship between GDOP and CEP is shown as an approximation :

$$CEP = (0.75\sigma_s)GDOP \tag{3.7}$$

where σ_s is the standard deviation of ranging error.

– Cramer-Rao Lower Bound (CRLB) Chan [ChH94] derived the CRLB as,

$$\Phi = c^2(G_t^T Q^{-1} G_t)^{-1} \tag{3.8}$$

where G_t is Taylor coefficients matrix shown in Eq 2.11, Q is the covariance matrix of the TDOA estimates, and c is the speed of light.

- Computational Efficiency: This metric defines the number of Floating Point Operations (FLOPS) while the algorithm uses as it runs. Higher FLOPS indicate the algorithm is less computationally efficient.

3.6 Parameters

System parameters are characteristics of the system that may affect performance. These include

1. Mobility of stations,
2. Number of mobile stations,
3. Number of base stations,
4. Number of visible satellites,
5. TDOA estimation error,
6. Coverage area,
7. Environment Type,
8. Cell Size,

9. Geolocation Technique, and
10. Position of base stations and the mobile station within a cell

3.7 Factors

Parameters that are varied in the performance study are called factors [Jai91]. In this study, the following factors are chosen.

1. Mobility of Stations: In order to locate mobile stations, both stationary and mobile routes will be simulated. Levels : Stationary, Mobile. Stationary stations represent scenarios of either a cell phone or laptop users, e.g., a user requiring emergency aid. Mobile stations model cell phone users driving at 30 mph in downtown and residential areas and 60 mph on the I-75 highway. This level shows the tracking capability of the geolocation technique. Thus, mobile routes are chosen in order to test how well the geolocation technique will do in a mobile tracking application. The scenarios and the mobile routes are described in Section 3.10.
2. Number of Base Stations : The TDOA method requires at least three base stations in order to get a location estimate. Four or more base stations are expected to increase the location accuracy. At least three base stations are assumed to be present in the coverage area. Levels: 3 and 4
3. TDOA Estimation Error: This factor is also called as TDOA measurement noise. It defines the errors that would be present in the TDOA measurements themselves. The values for this factor are : 50 nanosecond(ns), 100 ns, 200ns, and 400 ns.
4. Environment type: The required accuracy of mobile user's location depend on the environment in which geolocation technique is applied. The mobile station's radio signal reaches the base stations via multiple paths, bouncing-off various man-made and natural obstacles. This factor, called multipath, has a direct effect on location accuracy. It is likely that the probability of observing multiple base station signals is higher in bad urban environments than in rural areas [WSN99]. Since environment has a significant effect on the performance metric chosen, this study takes into account

this dependence on the environment. The levels of this factor is : Bad Urban, Urban and Suburban.

Bad Urban is is defined as densely populated areas, multi-story buildings, offices, city centers. In the simulations, downtown is used as a representative of bad urban environment. Urban defined as sparsely inhabited areas, fields, forests. In the simulations, this level of environment is regarded as an area along the I-75 highway. Suburban is defined as populated areas, residential houses, villages. In the simulations, the Kettering residential area is regarded as suburban.

5. Geolocation technique: Since wireless geolocation techniques are compared, they are also a factor in this study. This factor has three levels : Taylor and Chan algorithms for TDOA, and real-life GPS measurements.

3.8 Evaluation Technique

The evaluation technique chosen for this research is both measurement and simulation. There are three evaluation techniques described in [Jai91]: analytical, simulation and measurement. Since there is no system that has the properties described in this research at present, use of only the measurement technique is not an option for this research. However, keeping the fact in mind that A-GPS requires mobile stations to be equipped with GPS receivers, we can use a GPS receiver for real-life GPS measurements in order to evaluate the location accuracy of GPS system in our research. Moreover, since a comparison is done between two different geolocation techniques, analytical or simulation technique could be used for TDOA technique. However, [Jai91] notes that for more accurate results, if the time required is available, simulation would make a better choice. As a result, simulation technique becomes the most suitable evaluation technique for TDOA. The MATLAB v6R12 [Mat00] tool is used for simulations.

3.9 Workload

The workload in this study is signal time difference of arrivals (TDOA). The simulation model use these TDOAs in order to produce nonlinear hyperbolic equations. By solving these equations using the algorithms selected, mobile location estimates are gathered.

3.10 Design of Experiments

The design of experiments used in this study is determined in two stages.

1- Experiments for mobile stations. 2- Experiments for stationary stations. For both stages a full factorial design is used [Jai91]. Each level of the 2nd, 3rd and 4th factors will be implemented in different simulation runs totaling 48 simulations. With 5 replications, this results in 240 simulation runs. The simulation setup and other experimental details are presented in Chapter 4.

3.11 Summary

This chapter presents the methodology used in this research. Section 3.3 gives the system boundaries and the objectives. System services and performance metrics are presented in sections 3.4 and 3.5 respectively. In section 3.6, system and workload parameters are given, followed by system factors in section 3.7. The evaluation technique is presented in 3.8. Section 3.9. contains the workload. Finally the design of experiments is given in 3.10.

IV. DGPS Measurements and Simulation Scenarios Setup

4.1 Introduction

In the first part of this chapter, the process of GPS application and simulation models for the algorithms used for solving hyperbolic nonlinear equations are provided. The assumptions made throughout the study are also given. In the second part, the results and analysis is presented.

4.2 General Procedures for Simulation and Analysis

As stated earlier, the general design of experiments will be held according to the given procedures below.

1. Real-time GPS measurements are held in 5 different environments comprising bad urban, urban, suburban and indoors (mall) and when MS is stationary.
2. From the above measurements, 5 different GPS maps of the above environments are prepared.
3. Assuming an ideal hexagonal cellular layout, the base station locations are determined and located onto the maps using environment-specific cells.
4. Having set up the cellular systems, two different algorithms specified below are implemented.
   - Chan's algorithm for closed-form solutions
   - Taylor Series Least Squares (LS) estimation algorithm for iterative approach.
5. Simulations are run.
6. Results and analysis are presented.

For GPS measurements, a conventional GPS receiver is used. Both stationary and mobile (GPS antenna installed on a moving vehicle) measurements are taken.

The true locations of the mobile stations are achieved using a differential GPS process including the use of a base station antenna at AFIT building on ECEF (Earth-Centered Earth Fix) 505991.88, 4882292.23, and 4059587.26.

The GPS maps are plotted with the AFIT antenna at (0,0) to provide easy reading.

The simulations were run on a Pentium III machine with MATLAB v5.3.R11 and v6.R12. In order to evaluate the computational efficiency of the algorithms, the number of floating point operations are considered as a metric. MATLAB's flops function is used for this purpose.

4.3 Assumptions

- True locations of the mobile stations are assumed to be the locations obtained from differential GPS positioning which is known to have a 1-3 meter accuracy.
- In order to provide a quick convergence for the Taylor algorithm, the actual mobile position is used as the initial guess.
- Depending upon the location of mobile station in network and geometry of the base stations layout, the Taylor algorithm may not always converge. The simulation runs that Taylor algorithm diverges were discarded in the analysis.
- The TDOA noise is modelled as an additive zero-mean Gaussian random variable.
- The cell size (radius) of 1 km and 5 km are used for microcells and macrocells respectively.

4.4 Cellular Network Models Setup

The setup of 5 different environments and stationary stations scenario are explained in this section. This process is the first 3 steps described in Section 4.2. General Procedures for Simulation and Analysis.

4.4.1 Bad Urban (Downtown) Scenario. Dayton downtown is used as representative of a bad urban scenario. GPS measurements can be seen in Figure 4.1.

Cells are assumed to be microcellular CDMA cells. A a radius of 2.5 km is chosen in order to place the base stations onto the GPS measurement map obtained. The system ready for simulations can be seen in Figure 4.2.

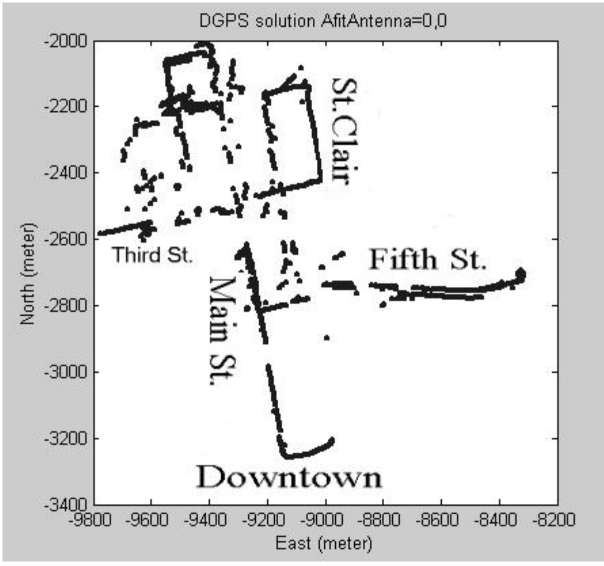

Figure 4.1. GPS Measurement Data Taken in Downtown Dayton

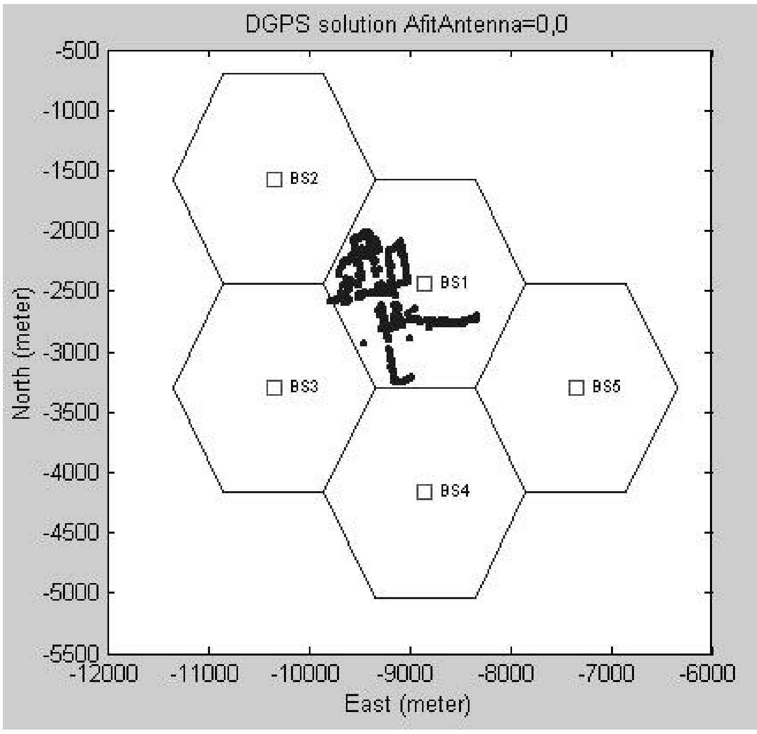

Figure 4.2. Downtown Scenario With Five Base Stations

4.4.2 Urban (Highway) Scenario. The reason for the selection of a highway as a representation of urban process is due to the significance of different performance of nonlinear hyperbolic equations solver algorithms under the conditions of linearly placed base stations which can be seen along the highways. For this scenario, I-75 Southbound is chosen as the highway under study. GPS measurements are taken on this highway starting from Main St. exit to south until Exit 23 Middletown, which is about 20 miles in distance. The real-time GPS measurement plot is shown in Figure 4.3.

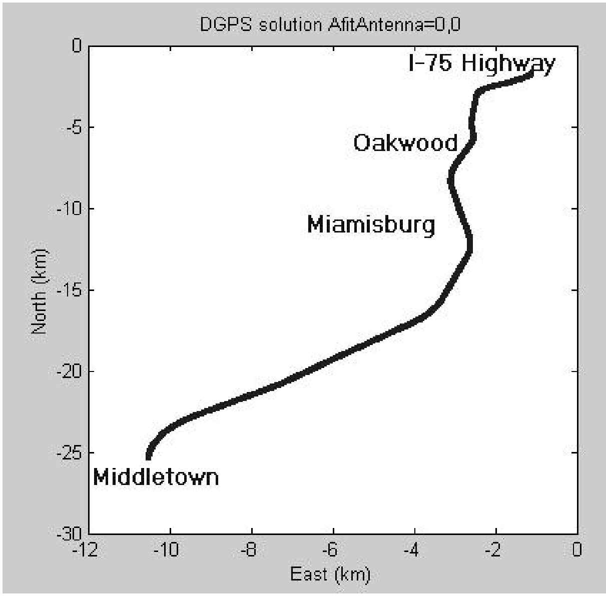

Figure 4.3. GPS Measurement Data (I-75 S.)

The distance between base stations is assumed to be 5 km. The system with base stations locations is at Figure 4.4.

4.4.3 Suburban (Residential) Scenario. Kettering is chosen as representative of a residential area in Dayton. GPS measurements can be seen on Fig 4.5. Cells are assumed to be macrocellular CDMA cells and the radius of 5 km is chosen in order to place the base stations onto the GPS measurement map obtained.

The distance between base stations is assumed to be 5 km. The system ready for simulations can be seen in Figure 4.6

4.4.4 Indoors (Mall). The mall at Fairfield Commons is used as representative of an indoors scenario. The GPS measurements are taken on the first floor. The mobile station was moving at a walking pace for the first two minutes and stayed stationary for the rest of the measurements.

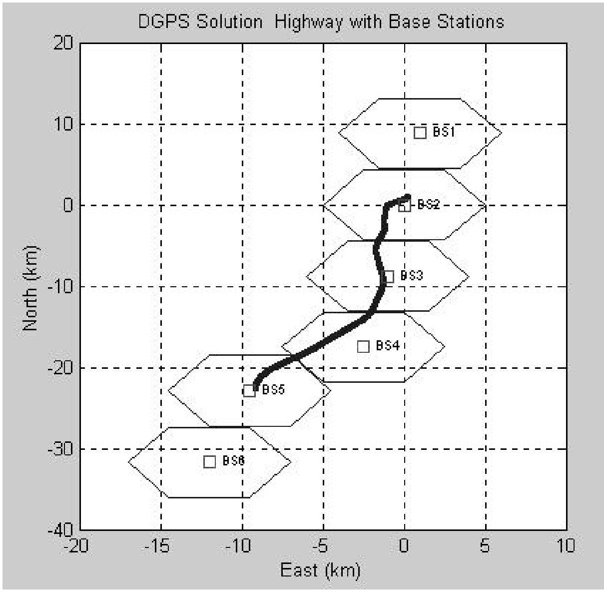

Figure 4.4. I-75 Highway With Base Stations

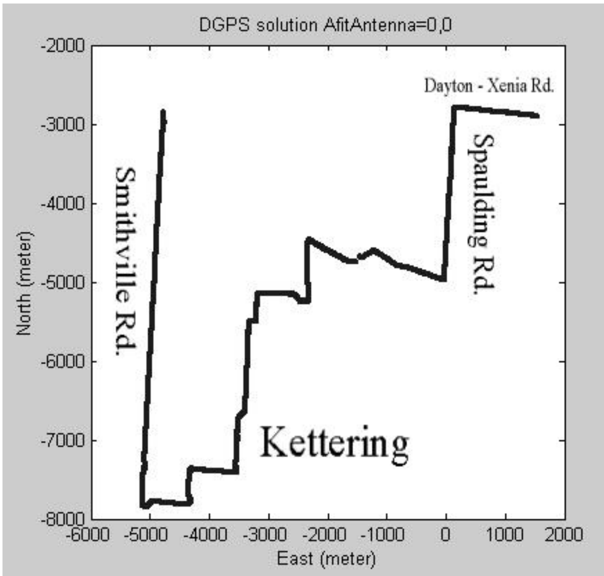

Figure 4.5. GPS Measurement Data Taken (Kettering, OH.)

Note : The mobile GPS receiver could not generate any positioning information. During the entire measurement process, there was only one SV (satellite vehicle) that the receiver could get data from. Since at least 4 satellites should be available for a 3D positioning, positioning data could not be obtained. A snapshot of the data from the

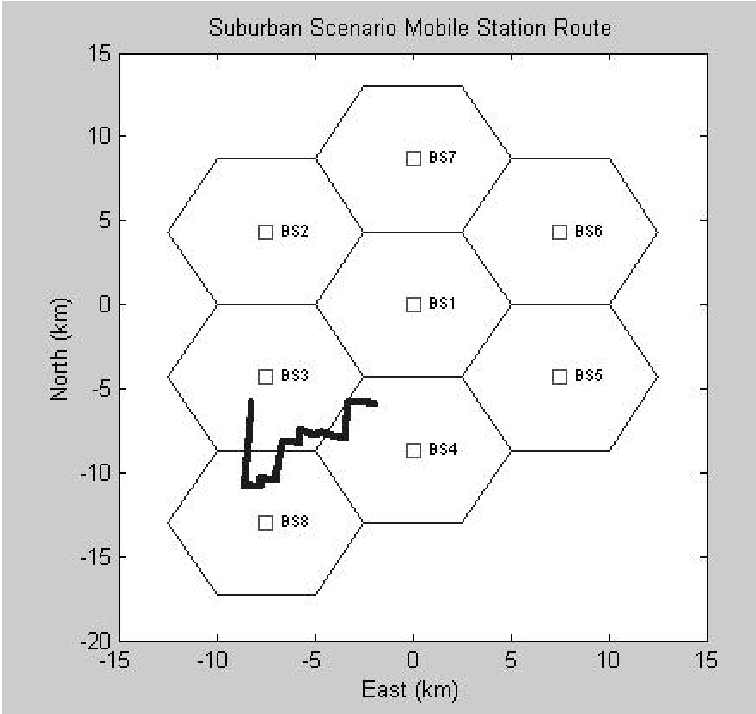

Figure 4.6. Suburban Scenario With Base Stations

mobile receiver is shown in Figure 4.7. The first column is the GPS week time (in seconds) and the second column is the PRN vector of the satellite in communication.

159410.000	27	20421995.302	20421993.777	-15767.074	-315.464	9	13	20422001.950	-8511.853	-245.816	13
159411.000	27	20421935.272	20421934.039	-16082.938	-316.188	9	13	20421942.116	-8757.981	-246.380	13
159412.000	27	20421874.812	20421873.167	-16399.352	-316.498	9	13	20421881.869	-9004.539	-246.622	13
159413.000	27	20421814.434	20421813.685	-16715.786	-316.588	9	13	20421821.792	-9251.112	-246.692	13
159414.000	27	20421753.850	20421753.983	-17032.041	-315.742	9	13	20421761.571	-9497.546	-246.033	13
159415.000	27	20421693.572	20421693.403	-17348.650	-316.946	9	13	20421700.888	-9744.254	-246.971	13
159416.000	27	20421633.633	20421633.556	-17665.957	-317.671	10	12	20421641.511	-9991.513	-247.536	12
159417.000	27	20421573.409	20421572.712	-17983.971	-317.981	9	12	20421581.025	-10239.318	-247.777	12
159418.000	27	20421512.728	20421511.732	-18302.013	-317.758	9	12	20421520.336	-10487.142	-247.604	12
159419.000	27	20421452.310	20421452.188	-18619.976	-318.957	9	12	20421459.423	-10734.906	-248.538	12
159420.000	27	20421391.688	20421390.160	-18939.342	-319.992	9	12	20421398.803	-10983.766	-249.344	12
159421.000	27	20421330.845	20421328.737	-19259.541	-320.106	9	12	20421337.531	-11233.273	-249.433	12
159422.000	27	20421269.371	20421267.712	-19579.651	-320.055	9	12	20421275.857	-11482.711	-249.394	12
159423.000	27	20421209.042	20421207.423	-19899.231	-319.146	9	12	20421215.522	-11731.734	-248.685	12
159424.000	27	20421147.582	20421145.203	-20219.698	-320.938	9	12	20421153.677	-11981.452	-250.082	12
159425.000	27	20421085.925	20421084.237	-20540.581	-320.748	9	12	20421092.682	-12231.489	-249.934	12
159426.000	27	20421025.008	20421023.975	-20861.193	-320.200	9	12	20421031.937	-12481.317	-249.506	12
159427.000	27	20420964.203	20420963.067	-21181.913	-320.272	9	12	20420971.034	-12731.228	-249.563	12
159428.000	27	20420902.957	20420902.856	-21502.756	-321.641	9	12	20420910.242	-12981.235	-250.629	12
159429.000	27	20420841.391	20420842.044	-21824.725	-321.293	9	12	20420849.437	-13232.121	-250.358	12
159430.000	27	20420780.330	20420779.281	-22146.080	-321.206	9	12	20420787.337	-13482.528	-250.290	12
159431.000	27	20420719.559	20420718.814	-22468.013	-321.956	9	12	20420726.661	-13733.388	-250.875	12
159432.000	27	20420658.332	20420657.546	-22790.696	-322.572	9	12	20420665.606	-13984.834	-251.355	12
159433.000	27	20420596.569	20420596.738	-23113.821	-323.383	9	12	20420603.409	-14236.622	-251.987	12
159434.000	27	20420535.971	20420534.857	-23436.995	-322.948	9	12	20420543.345	-14488.447	-251.648	12
159435.000	27	20420474.552	20420472.600	-23760.406	-323.550	9	12	20420481.523	-14740.460	-252.117	12
159436.000	27	20420412.717	20420411.167	-24085.207	-325.575	9	12	20420419.066	-14993.555	-253.695	12
159437.000	27	20420350.867	20420349.663	-24410.329	-325.027	9	11	20420357.413	-15246.895	-253.268	11
159438.000	27	20420289.460	20420286.753	-24734.754	-323.898	9	11	20420294.743	-15499.691	-252.388	11
159439.000	27	20420228.201	20420225.917	-25059.280	-325.095	9	11	20420233.218	-15752.566	-253.321	11
159440.000	27	20420166.177	20420163.717	-25384.357	-325.310	9	11	20420171.146	-16005.871	-253.488	11
159441.000	27	20420103.731	20420100.909	-25710.009	-325.464	9	11	20420108.591	-16259.626	-253.608	11
159442.000	27	20420041.858	20420039.516	-26035.684	-325.223	9	11	20420046.173	-16513.395	-253.421	11
159443.000	27	20419979.855	20419977.815	-26361.005	-325.481	9	11	20419984.573	-16766.890	-253.622	11

Figure 4.7. GPS Measurement Data Taken Indoors (Mall)

As a result, although we wanted to use indoors as one of the scenarios, we could not because of the fact that GPS does not operate indoors.

4.4.5 Stationary Mobile Station Scenario. This part of the simulations were held for single point GPS measurements. The measurements are collected for 20 minutes at a 1Hz rate. The mobile station's location and the GPS measurements can be seen in Figure 4.8.

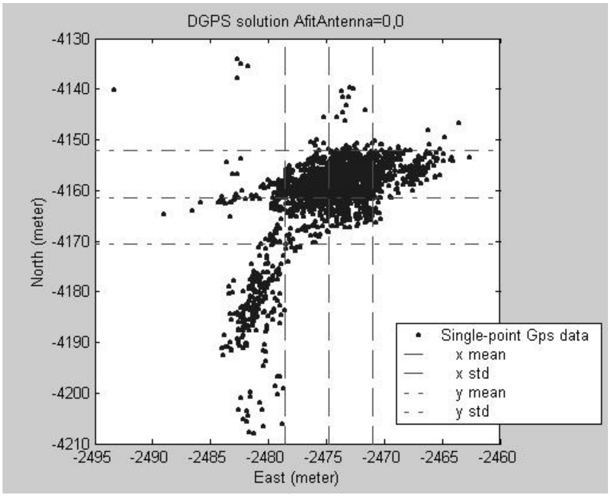

Figure 4.8. Single-point GPS Measurement Data

As seen in the plot, GPS measurements were quite erratic for the single point. The reason might be that there were trees around the GPS receiver. The range of measured positions is 30.68 east and 73.67 meters north. The mean and standard deviation values are also shown on the plot in order to show GPS's poor performance under heavy foliage conditions, such as in this scenario in a parking lot with high trees around. For this scenario, a comparison between a microcell and macrocell is intended, and a radius of 1 km and 5 km is chosen for micro and macrocells respectively. The three base stations layout with a single stationary mobile station can be seen in Figures 4.9 and 4.10.

4.5 Summary

In this chapter, DGPS measurement process that is taken in Dayton, OH area and the 5 different scenarios setup is presented. Using the measurement data, cellular network models are prepared using a hexagonal cellular layout.

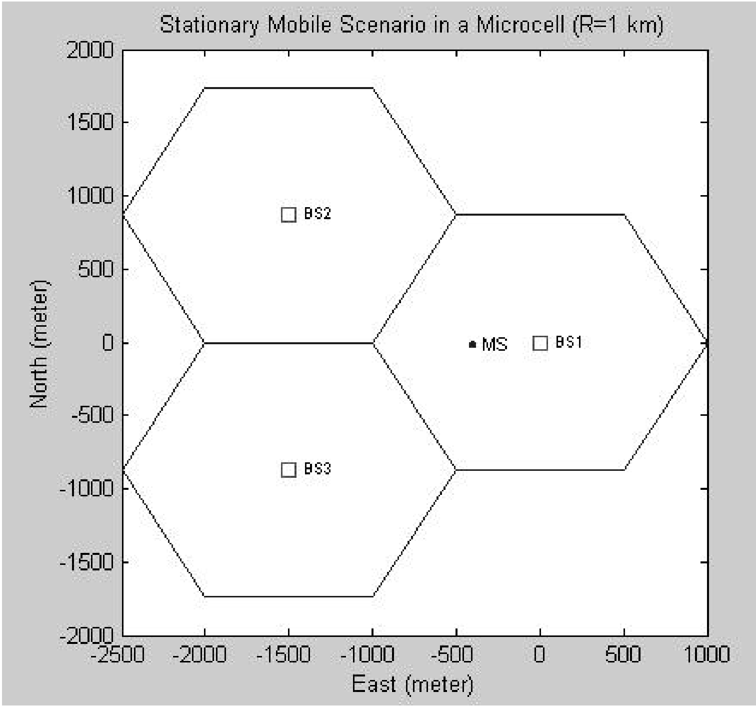

Figure 4.9. Single-point Microcellular Scenario (3 base stations)

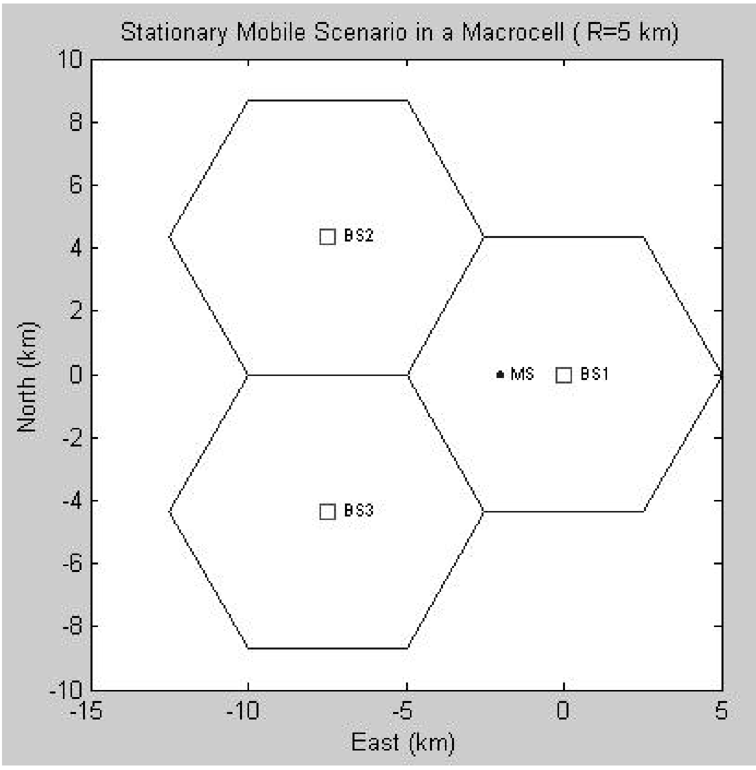

Figure 4.10. Single-point Macrocellular Scenario (3 base stations)

V. *Results And Analysis*

5.1 Introduction

This chapter presents the results of the simulation runs and analyzes the results using the performance metrics presented in Chapter 3. The iterative Taylor Least Squares and a closed form solution Chan's algorithm [ChH94] as explained in Chapter 2 is implemented as hyperbolic position location technique, and simulations are run using the setup and scenarios explained in Chapter 4. Differential GPS positioning is used for the true mobile station routes, and also non-differential GPS positioning is done in order to evaluate an accuracy of a conventional GPS receiver which a handset might be equipped with. First, the results and analysis of simulations for the scenarios are provided then additional explanatory simulation runs are explained and evaluated. The simulation runs are intended to evaluate the performance of GPS and hyperbolic position location technique.

A total of 3200 mobile locations are tested. Simulation results show the effect of the number of the base stations used in positioning, the location of the mobile station within the cell and the cell environment whether it is a microcell or a macrocell. The results also include a comparison between GPS positioning and TDOA positioning techniques using cellular network infrastructure identities.

5.2 Results And Analysis

In this section, the results of the simulations are presented. An analysis of the results are also included for every scenario.

5.2.1 Bad Urban (Downtown) Scenario. In this scenario, the performance of GPS positioning among large and tall buildings in downtown is evaluated using the Taylor and Chan algorithms. A total of 183 MS locations are tested and results are shown in Figures 5.1 and 5.2.

Figure 5.1 indicates that both of the algorithms perform slightly better with 4 base station configurations and as expected, as the TDOA noise levels increase, RMS error values increase, thus positioning accuracy degrades. Figure 5.2 shows the baseline results with 3 base stations along with GPS positioning. Results clearly indicate that GPS positioning outperforms the two algorithms again with RMS error values of 21.58 meter and 2D-RMS of 5.02 meters. The mobile GPS receiver had at least 5, and most of the time 6 satellites visible so that it could provide a better position fix. However, it should also be noted that in this scenario, a 2DRMS of 5 meters is the worst case of all the GPS scenarios, which is expected because of the multipath problem in bad urban environments.

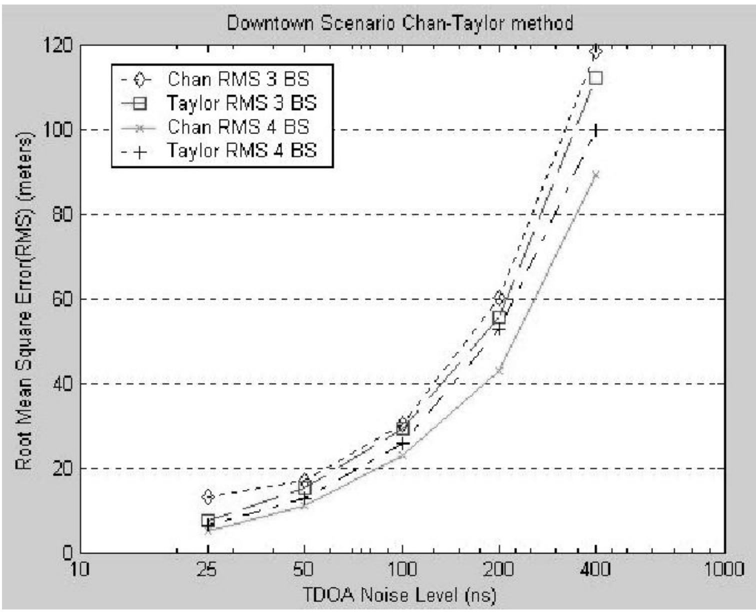

Figure 5.1. Downtown Scenario Chan And Taylor Method

Table 5.1 shows the number of floating point operations for the scenario. The results are averages of 5 replications over all locations. Since Chan's implementation for 3 and 4 base stations are different, this is reflected in the results as well. Chan algorithm with 4 BS is an approximation of a true Maximum Likelihood Estimator and works using a two-step Least-Squares (LS) procedure. Although multiple iterations are not needed most times, the computational efficiency degrades due to LS. Thus, for four or more base stations, it would be fair to say that efficiency of Taylor and Chan algorithms is similar, however, for 3 base stations Chan's algorithm is more efficient than Taylor.

5.2.2 Urban (Highway) Scenario. In this scenario, an important aspect of hyperbolic position location techniques are considered. When the base stations are positioned

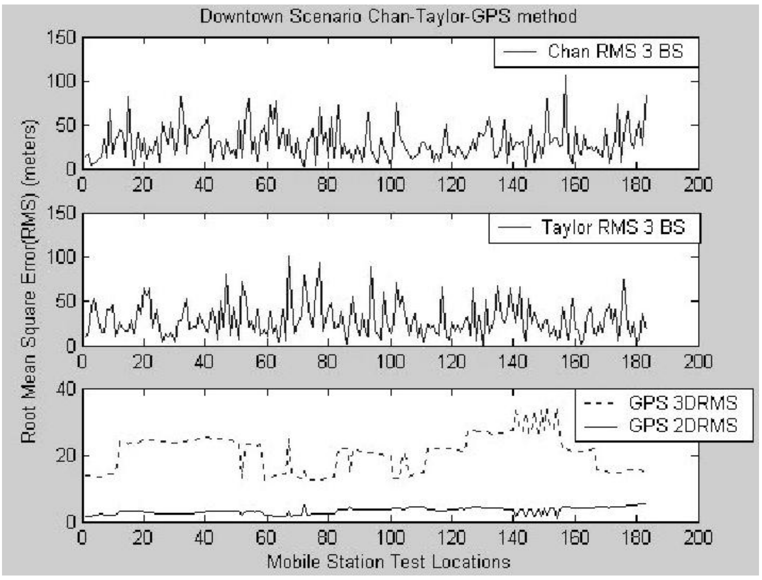

Figure 5.2. Downtown Scenario MS Test Locations RMSE Values

Table 5.1. Computational Efficiency Between Cell Sizes Bad Urban Scenario

Algorithm	Number of FLOPS
Chan 3 BS	262.02
Chan 4 BS	1775.14
Taylor 3 BS	557.3
Taylor 4 BS	1844.27

linearly, as on a highway, the matrices containing the coordinates of base stations in the algorithms become singular since the BS positions satisfy $y_i = ax_i + b$, i=1,2..N, where a and b are constants [ChH94].

This problem is hard to solve only using hyperbolic location technique. Simulation results will also show that the accuracy in this scenario is the least among the four scenarios. In order to improve accuracy, the most feasible solution is to integrate the AOA (Angle of Arrival) and TDOA methods. However, due to the cost issue, this solution is not preferred. In this study, a less costly solution is proposed. Base stations are placed along highways in order to guarantee coverage. However, because of the singularity problem, the algorithms either cannot estimate MS location or estimate it with large deviations. Installing additional base stations will improve the degraded accuracy in highway conditions.

Table 5.2. Computational Efficiency Urban Scenario

Algorithm	Number of FLOPS
Taylor 4 BS	2395.82

Due to large position variations, position estimates generally cannot be produced when there are 3 base stations visible. A simulation with Taylor algorithm using 4 base stations is run and figure 5.3 shows the simulation results. The results show that RMS values are larger than the other scenarios. The linear arrays of base stations degrade the performance to a great degree. In order to improve the performance, an additional base station (BS7) is added and placed in the system as shown in Figure 5.4. After 5 replications of simulation runs, a satisfactory result is achieved. Figure 5.5 shows the improved results. Overall, placing an additional base station improved positioning accuracy approximately 28 percent.

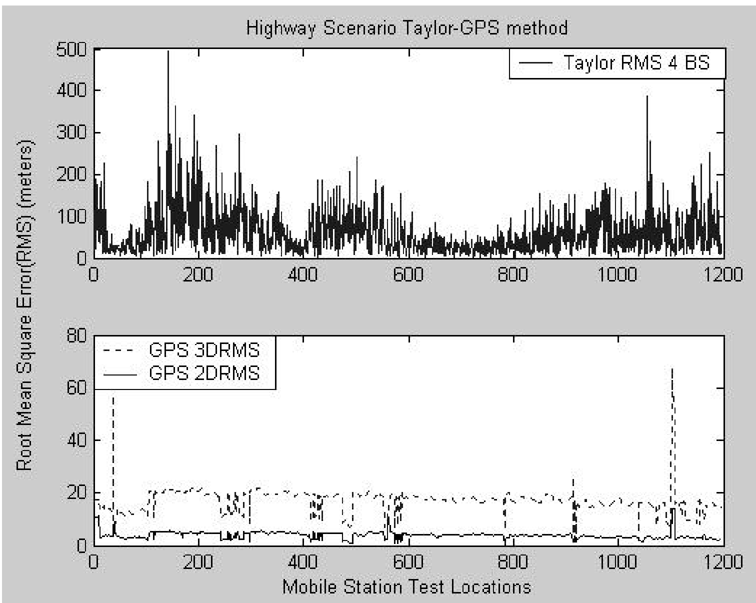

Figure 5.3. Highway Scenario Taylor and GPS Positioning Results

Table 5.2 shows the results for the number of floating point operations for the scenario.

5.2.3 Suburban (Residential) Scenario. In this scenario, the performance of Taylor and Chan algorithm within a macrocellular environment is evaluated. The results

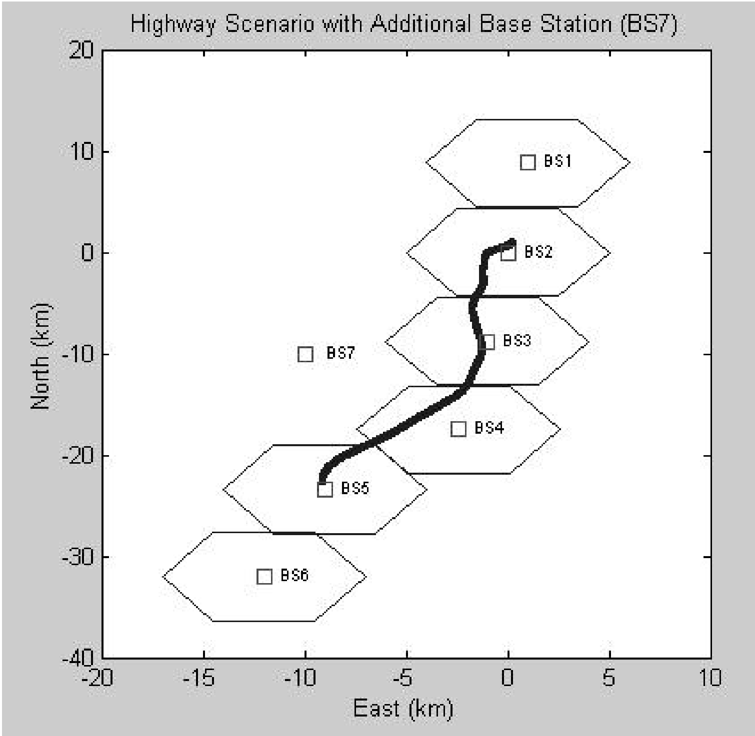

Figure 5.4. Highway Scenario Additional Base Station

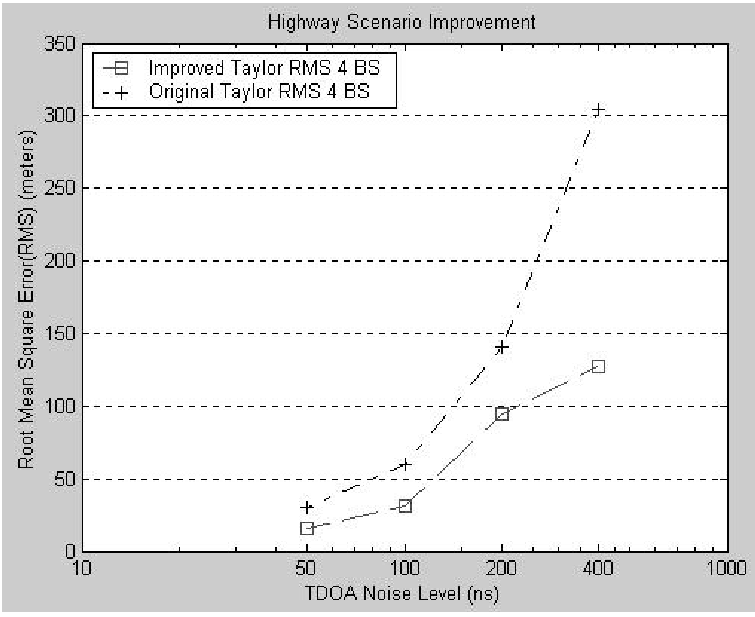

Figure 5.5. Highway Scenario Improved Results

are presented with the results taken from GPS positioning. TDOA noise level σ_d of 100 ns, is used for the simulation. Figures 5.6 and 5.7 shows the simulation results in terms of the mobile routes. Figure 5.7 zooms in the small circled area in Figure 5.6. From the plot, it can be seen that the closest estimates belong to GPS positioning (with star symbol) which is expected.

The simulation is performed for a cell size of 5 km, i.e., the environment is assumed to be macrocellular.

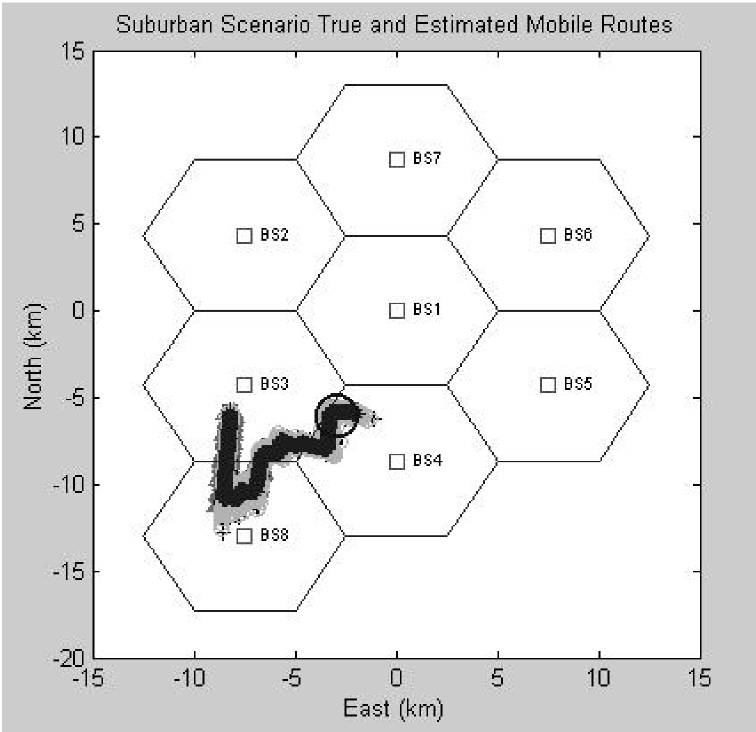

Figure 5.6. Suburban Scenario True And Estimated Mobile Routes-1

If we look at RMSE values as shown at Figure 5.8, GPS positioning yielded the best performance over the other two techniques. The 3DRMS Error value for GPS positioning is 25.4 meters where as the algorithms values (for standard deviation of 100 ns TDOA noise) with five replications are 99.9 and 56.4 for Chan algorithm and 97.7 and 53.8 meters for Taylor algorithm with 3 and 4 base stations respectively. The measurements using 4 or more base stations is likely to improve the accuracy. As seen from the RMSE values, using 4 base stations produces over 43 meters better accuracy for Chan and 44 meters

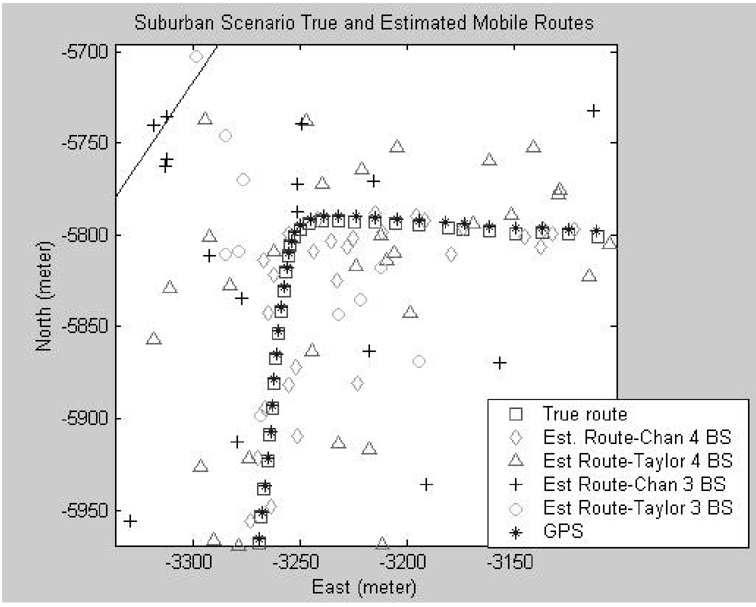

Figure 5.7. A Close Look Suburban Scenario True and Estimated Mobile Routes-2

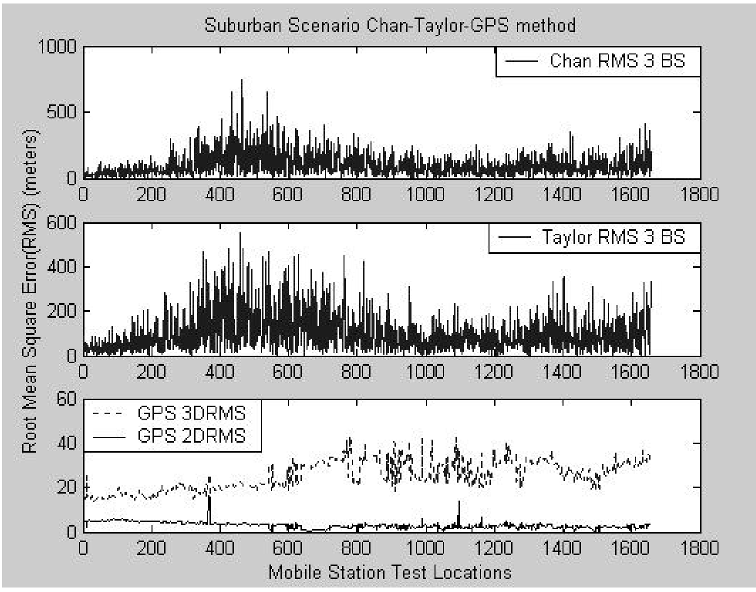

Figure 5.8. RMS Values Suburban Scenario

for Taylor LS algorithm. Figure 5.9 shows that the positioning accuracy changes linearly with the changes in TDOA noise levels. Simulation results with varying TDOA noise levels show that a dramatic increase in position location error is seen as the TDOA noise levels increase. Furthermore, as the noise gets higher than 500 ns, the Taylor algorithm's

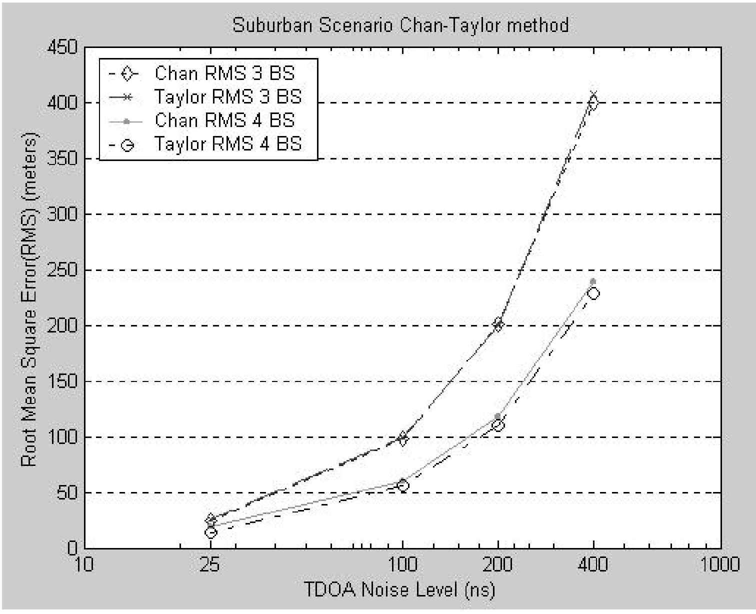

Figure 5.9. RMS Values vs TDOA Noise Suburban Scenario

Table 5.3. Computational Efficiency Suburban Scenario

Algorithm	Number of FLOPS
Chan 3 BS	202.002
Chan 4 BS	1586.04
Taylor 3 BS	718.14
Taylor 4 BS	1505.93

performance could not be evaluated due to divergence. Convergence cannot be guaranteed at high noise levels, thus a position estimate cannot be produced.

Table 5.3 shows the results for number of floating point operations for the scenario. The efficiency of Taylor LS algorithm is almost 4 times worse than Chan for 3 base stations. However, the results are close for four base stations.

5.2.4 Stationary Mobile Scenario. In this scenario, micro cells and macro cells are compared. For this purpose, the mobile station's true location, determined by differential GPS positioning, is considered both in a micro and macrocell. The simulation setup is shown on Figures 4.9 and 4.10.

Three different simulation runs are evaluated. In the first run, TDOA noise is set to 100ns and 5 replications are done. Since there is one location tested in this part of

Table 5.4. RMS Error Values Stationary Scenario

Algorithm	Accuracy (m)
Chan 3 BS MicroCell	68.84
Chan 3 BS MacroCell	63.11
Taylor 3 BS MicroCell	60.57
Taylor 3 BS MacroCell	54.26

Table 5.5. Computational Efficiency Between Cell Sizes Stationary Scenario

Algorithm	Number of FLOPS
Chan 3 BS MicroCell	232
Chan 3 BS MacroCell	232
Taylor 3 BS MicroCell	618
Taylor 3 BS MacroCell	618

the scenario, results are shown on Table 5.2. GPS positioning again outperforms the two algorithms with a RMS value of 24.43 meters. Moreover, if we consider the two dimension east and north only, GPS yields a 2DRMS value of 2.33 meters. Looking at the results, another conclusion can be drawn. Although not a significant difference, the results in Table 5.4 demonstrates that the positioning accuracy is slightly better in macrocell which in this case has a radius of 5 km rather than a microcell with a 1 km radius. Another conclusion could be drawn that an increase of distance between base stations improves positioning accuracy.

In the second simulation, TDOA noise is varied and the two algorithms' performance both in a micro and macro cell environment is observed. Figure 5.10 shows that for small noise levels the two algorithm perform similarly, both the Chan and Taylor algorithm in macrocell shows a consistent increase as the standard deviation of TDOA estimation errors increase. However at higher levels of errors, the macrocellular system deviates quickly and sharply, and thus produce large numbers of positioning errors.

Table 5.5 shows the number of floating point operations for two algorithms in two environments after 5 replications. As can be seen, computational efficiency is not affected by the cell size. Taylor's efficiency is about three times less than Chan method for this scenario.

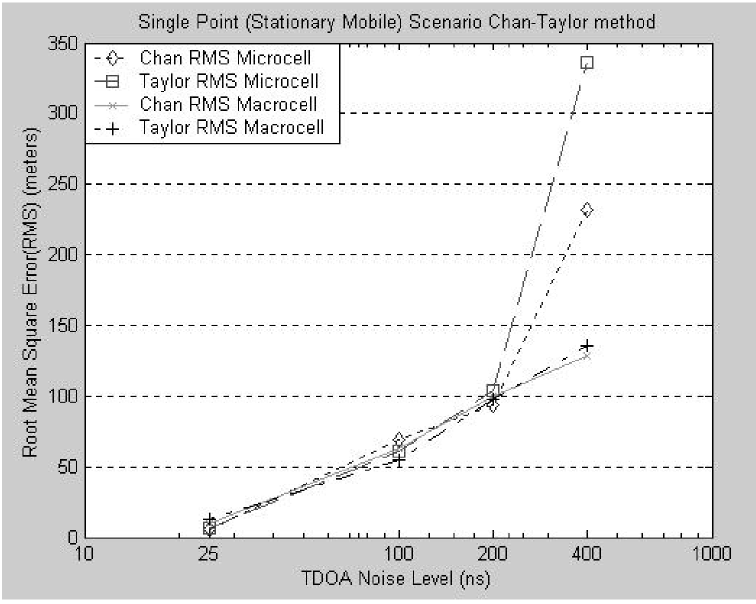

Figure 5.10. Stationary Scenario RMS Values

5.2.5 Comparison Between Scenarios. In this section, the results from the scenarios are presented together. Figure 5.11 shows that the location errors in urban scenario which is considered a typical highway in this study is larger than the other environments. The reason behind this is the linearly positioned base stations and the algebraic singularity problem in matrices caused by coordinates of the base stations. The problem is addressed in more detail in Section 5.2.2. Although the difference in RMS error values is not significant at small TDOA noise levels, as the noise increases which is expected in highway conditions, the RMSE curve (for highway) shows a dramatic increase.

As far as the FCC mandate is concerned, depending upon the TDOA estimation errors, both of the algorithms meet the requirements of 300 meter for 95 percent of the time for network based techniques as is the case here, until an estimation error of 400 nanoseconds.

Table 5.6 shows a comparison of FLOPS for Taylor with 4 BS for every scenario. The largest FLOPS value is observed in the urban scenario. In this scenario, the algorithm iteration is averaged at 4.8, whereas for the other scenarios the average iteration is between 3.3 - 3.5. Thus, we conclude that the number of iterations for Taylor LS algorithm

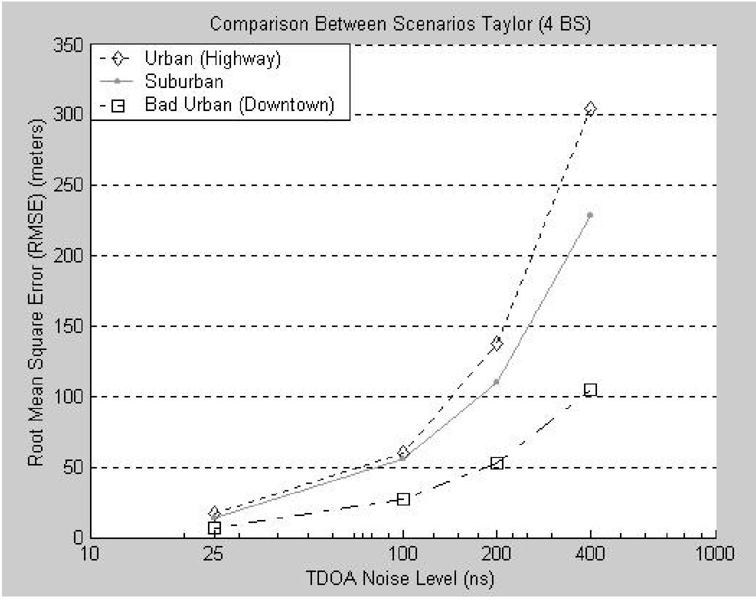

Figure 5.11. Comparison Between Scenarios Taylor (4 BS)

Table 5.6. Computational Efficiency Comparison Between Scenarios

Scenario	Number of FLOPS
Bad Urban	1844.27
Urban	2395.82
Suburban	1505.93

is a significant factor that affects and/or determines the computational efficiency of an algorithm.

Figure 5.12 shows the 3D distance error values for single-point(non-differential) GPS measurements for all the scenarios. For 3D values, urban scenario with a mean value of 16.751 is the best scenario, which is expected because urban scenario, herein, highway is an open field area, there are no tall buildings, high trees, or any other thing that might block GPS signals. The tables 5.7 and 5.8 show the 3D and 2D RMSE values for non-differential GPS measurements for all the scenarios.

As far as the 2DRMS values are concerned, it is seen that the stationary scenario has the best values, and also as one other expected result, the downtown (bad urban) scenario with a 2DRMS of 5 meters is the worst case of all the GPS scenarios which is mainly due

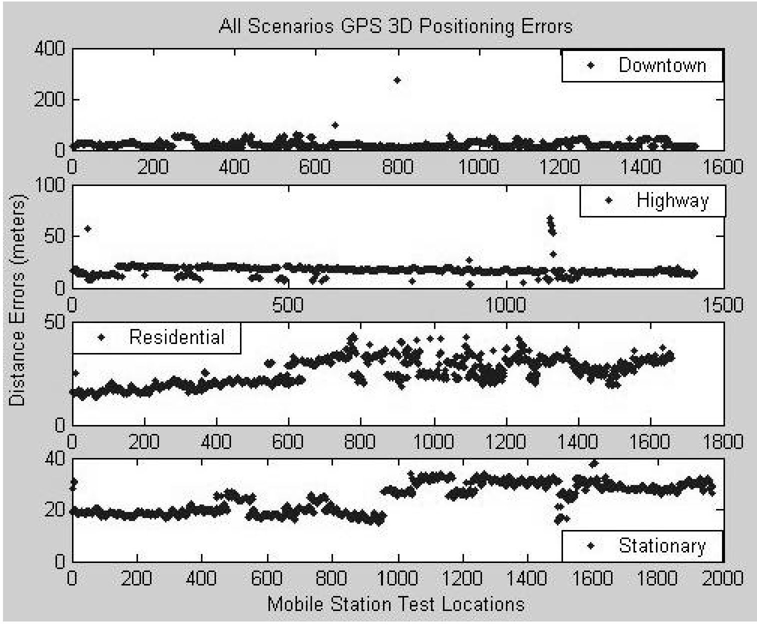

Figure 5.12. Comparison of GPS Measurements Between Scenarios

Table 5.7. GPS 3DRMS Values Comparison Between Scenarios

Scenario	3D-RMSE (meters)
Bad Urban	21.5817
Urban	16.7510
Suburban	25.4001
Stationary	24.4331

to multipath problem in densely populated areas and among tall concrete buildings which is the case that we have in downtown scenario.

Table 5.8. GPS 2DRMS Values Comparison Between Scenarios

Scenario	2D-RMSE (meters)
Bad Urban	5.0204
Urban	3.8070
Suburban	3.0651
Stationary	2.3310

VI. Summary And Recommendations

This research focused on hyperbolic position location techniques, namely TDOA in wireless cellular networks. Two algorithms have been implemented and tested under a total of four different scenarios. GPS positioning is used first for acquiring mobile station routes in Dayton area using Differential GPS positioning that are later on assumed to be true locations for the test cases, and also for comparing results of the two algorithms by implementing single point GPS positioning.

The simulation results showed that GPS positioning outperformed the hyperbolic position location technique in almost all cases where GPS positioning is available. GPS positioning was not available indoors in the Mall at Fairfield Commons.

6.1 Taylor LS And Chan Algorithms

Overall results showed that position accuracies of the two algorithm were very similar. At most of the test locations for 4 scenarios, one did not perform significantly better than the other. However, there are still many aspects that need to be taken into consideration.

As pointed out earlier, solving hyperbolic nonlinear equations is not a trivial implementation, so the computational efficiency should also be taken into consideration. We conclude that for situations where 3 base stations are involved in positioning, Taylor LS algorithm is much less efficient than Chan algorithm because it is iterative whereas Chan gives a closed form solution. Moreover, convergence of the Taylor algorithm is not guaranteed at high TDOA estimation errors. One disadvantage of Chan is that it must use different algorithms for different situations i.e., it uses a different algorithm when there are 3 BS, 4 or more BS, and when the base stations are placed linearly as in highway scenario. On the other hand, although iterative, Taylor algorithm works under all conditions tested.

Another aspect is the implementation capability in mobile tracking applications. From the simulations, Chan algorithm performs well only when the reference base station is at the origin(0,0), otherwise very large location errors are calculated. When a mobile tracking application is considered, the MS will continuously move within the coverage between cells. So, in this case the algorithm will not be able to work using the known coordinates of the base stations which is a disadvantage. Thus, another process will have to be implemented within the algorithm in order to manipulate base station coordinates, in other words, offset the coordinates of the cells according to reference base station, run the algorithm for location estimation, and then convert the cell coordinates back into their original values and pinpoint the location of the mobile station. Otherwise, the location estimate could be gathered with reference to origin (0,0), yet this location estimate will not help in a mobile tracking application. Although it requires only a transformation of base station coordinates, this might be considered as a disadvantage for mobile tracking applications since we need fast-working algorithms for fast mobiles. On the other hand, Taylor LS algorithm does not require any base station coordinates manipulation, so could be a better option for mobile tracking applications.

One other conclusion is, we observed that computational efficiency is not affected by the cell size.

6.2 Summary

Chapter 1 provided an introduction and background to the problem that was studied, and presented a brief overview of the objectives of this thesis and the organization of the document.

Chapter 2, different wireless geolocation techniques that are studied have been presented. The advantages and disadvantages along with a brief comparison of the techniques from previous works have been included. Additionally, the two algorithms namely Taylor LS and Chan algorithms which have been implemented and tested in simulations are studied extensively.

In Chapter 3, the methodology that has been followed throughout the research has been provided. The details of the objectives, system boundaries, performance metrics, system parameters, factors, evaluation technique, workload and design of experiments were included.

Chapter 4 presented the simulation setup. How we did Differential GPS positioning in Dayton area and obtained the actual mobile station routes for four scenarios, how we placed the base stations onto the GPS maps of the mobile routes are explained in this chapter.

Chapter 5 presented the results of the simulation runs. The results were given for four scenarios. And the conclusions drawn from the results and analysis were included.

Chapter 6 gives a summary of what has been done throughout the research, and a brief summary of conclusions. The document of the organization is also presented in this chapter. In the next section, future recommendations are provided.

6.3 Recommendations For Future Work

Wireless Geolocation is a broad research field, and it has many areas to be further investigated. This research focused mainly on second stage of hyperbolic position location technique which is solving nonlinear equations gathered from set of time difference of arrival estimates and producing a location estimate. Although the problems and some solutions are discovered in our scope of work, there are still more that can be explored at the first stage of hyperbolic position location technique as well, which is the estimation of Time Difference of Arrivals by using either Cross Correlation or other techniques. A future work would take multipath and MAI (Multiple Access Interference) (for CDMA networks) into consideration which are the parameters that significantly affect positioning accuracy. However well the algorithms work, it should be noted that the success and performance of the algorithms is bounded by TDOA estimation.

Another recommendation would be to study hybrid systems for wireless geolocation such as TDOA and AOA technology. Although GPS seems to be the first choice in positioning, the cost, battery and the size issues motivate the study on network-based geolocation techniques.

Although we gathered real-time GPS measurements in order to establish mobile test locations, the base station locations were placed theoretically since the cellular providers do not normally provide that type of information, thus the simulations and results do not reflect the actual field trials. A future work would also be a set of practical field trials that could use this research as a guide.

The two algorithms implemented in simulations, namely, Taylor least squares and Chan algorithm are validated against the results of [ChH94].

In a simple simulation, 3 sensors(i.e., base stations) are placed in positions at (BS1x=0 , BS1y=0), (BS2x=-5 , BS2y=8) and (BS3x=4 , BS3y=6). The source (i.e., mobile station) is at (MSx=8 , MSy=22). The TDOA variance is set to $0.001/c^2$ and the MSE=E$[(X_{est} - X_{true})^2 + (Y_{est} - Y_{true})^2]$ values are obtained from the average of 10 000 independent runs. We assume that the signal and noises are white random processes and that the SNR of all sensors are identical. Therefore, the TDOA covariance matrix Q is found to be σ_d^2 for diagonal elements and $0.5\sigma_d^2$ for all other elements [ChH94].

Table A.1. Validation of the Algorithms

Algorithm	Mean Squared Error (m)
Chan in [ChH94]	2.1726
Chan in Our Model	2.1861
Taylor in [ChH94]	2.1726
Taylor in Our Model	2.1833

Table A.1 shows that the results are in agreement with the results of [ChH94], and thus the validity of the algorithms used in simulations is verified.

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14. ABSTRACT

This study addresses the wireless geolocation problem that has been an attractive subject for the last few years after Federal Communications Commission (FCC) mandate for wireless service providers to locate emergency 911 users with a high degree of accuracy -within a radius of 125 meters, 67 percent of the time by October 2001. There are a number of different geolocation technologies that have been proposed. These include, Assisted GPS (A-GPS), network-based technologies such as Enhanced Observed Time Difference (E-OTD), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Cell of Origin (COO). This research focuses on network based techniques, namely the more prominent TDOA which is

also called hyperbolic position location technique. The main problem in time-based positioning systems is solving nonlinear hyperbolic equations derived from set of TDOA estimates. Two algorithms are implemented as a solution to this problem: A closed form solution and a Least Squares(LS) algorithm. Accuracy and computational efficiency performances are compared in a wireless system established using DGPS measurements in Dayton, OH area.

15. SUBJECT TERMS

Wireless Geolocation, Hyperbolic Position, Location Estimation, Time Difference of Arrival, GPS Positioning, Enhanced 911.

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