EVALUATION OF TDOA TECHNIQUES FOR POSITION LOCATION IN CDMA SYSTEMS

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Abstract

The Federal Communications Commission (FCC) has adopted regulations requiring wireless communication service providers to provide position location (PL) information for a user requesting E-911 service. The Time Difference of Arrival (TDOA) technique is one of the most promising position location techniques for cellular-type wireless communication systems. The IS-95 Code Division Multiple Access (CDMA) system is a popular choice for the companies deploying new cellular and PCS systems in North America. Hence, the feasibility of TDOA techniques in CDMA systems is an important issue for position location in the wireless systems of the future.

This thesis analyzes the performance of TDOA techniques in the CDMA systems. A comparison and assessment of different algorithms for finding the time difference estimates and for solving the hyperbolic equations generated by those estimates has been made. This research also considers a measure of accuracy for TDOA position location method which is shown to be more suitable for CDMA systems and more closely matches to the FCC requirements. Among the other contributions is a proposed method to perform cross-correlations to identify only the desired user's TDOA in a multiuser environment.

This thesis also evaluates the feasibility and accuracy of TDOA techniques under varying system conditions that might be encountered in real situations. This includes varying conditions of Additive White Gaussian Noise (AWGN), Multiple Access Interference (MAI), power control and loading. The effect of the mobile position and of different arrangement of base stations on TDOA accuracy is also studied. Performance comparison in AWGN and Rayleigh fading channels is made. The feasibility of using increased power levels for the 911 user in combination with interference cancellation is also studied. The effect of using a single stage of parallel interference cancellation at neighboring cell sites has also been explored. Non-ideal situations such as imperfect power control in CDMA operation has also been investigated in the context of position location. This thesis also suggests a method to correct TDOA estimation errors in CDMA. It is shown that this improvement can give greatly improved performance even under worst-case situations. Performance comparison of results with and without that modification has also been made under various conditions.

Acknowledgment

All praise and thanks is due to God, the one, the only and the indivisible creator and sustainer of the worlds. To Him, we belong and to Him, we will return. I wish to thank Him for all that He has gifted us with, although, He can never be praised or thanked enough.

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Chapter 1

Introduction

The problem of providing reliable and accurate position location of mobile units in wireless communication systems has attracted a lot of attention in recent years. The main factor behind the recent interest in position location has been the adoption of certain regulations by Federal Communications Commission (FCC) [1], that require wireless communications licensees to incorporate position location capability in their systems in order to provide Enhanced-911 (E-911) service. However, there exist many incentives for wireless service providers to have such a system in place. They can use reliable position location as a means to optimize the performance and design of the wireless networks and can also offer additional features to the subscribers.

In this chapter, we will discuss the present motivations and incentives for wireless service providers to incorporate position location capability in their cellular systems. We also discuss different methods used for this purpose which are relevant from the application point of view. We finish this chapter with an outline of the research and results presented in this work.

1.1 Motivations for Position Location Solutions

1.1.1 FCC Regulations for Wireless E-911

Emergency 911 service has achieved a widespread popularity and use. A study by FCC's Network Reliability Council indicates that 89 percent of the wireline access lines in the United States are served by some form of 911 service [2]. The main purpose behind the introduction of the 911 emergency number was to provide subscribers with an easily memorized number. The 911 service was developed to provide a forwarding arrangement with a public safety agency. When a 911 call is received by a telephone switch, it is directed to the appropriate public safety answering point (PSAP) over dedicated emergency telephone lines. However, this mechanism was not resulting in the most efficient response time because the PSAP handling the call may not be the PSAP nearest to the caller and vital information, such as the caller's location or phone number, was not always available. Thus, the need for a more efficient 911 service was conceived, which consequently lead to the development of the Enhanced 911 (E-911) service.

E-911 service is provided by approximately 85 percent of emergency 911 systems and it helps emergency services personnel achieve the shortest possible response time to emergency requests [3]. The minimum E-911 service provides the PSAP with Automatic Number Identification (ANI) of the calling party. The ANI, which indicates the calling party's phone number, permits call-back capability in the event the call is disconnected. A fully enhanced 911 service not only displays the ANI, but also permits the PSAPs to identify the calling party's address through the use of an Automated Location Identification (ALI) database. This ALI information also permits selective routing (SR) of the call to the appropriate PSAP for the identified location [3].

Although some wireless systems are capable of providing basic 911 service, few provide E-911 service. The ability of the public safety agencies to respond is severely hindered by the inability of the wireless systems to provide the ALI information of the caller requesting assistance. This information is not accessible in the ALI database associated with wireline telephone users. Furthermore, wireless service providers are unable to provide call-back capability, the number of the caller, or indicate the type of service required. The inability of wireless service providers to offer comparable E-911 service has become a major safety issue that concerns the FCC, public safety organizations and the wireless industry.

In 1994, the FCC proposed to amend its regulations to address issues raised by the provision of 911 and E-911 service through wireless communication systems [3]. The FCC proposed to adopt rules that would require wireless, in particular commercial mobile radio services that provide real time voice services, to include features that will make E-911 services available to mobile radio callers. These features include Station Number Identification (SNI), Automatic Location Information (ALI), Selective Routing (SR), and other features for 911 calls provided over wireless systems.

The FCC recognized that in order to provide a functionally equivalent E-911 service to wireless customers, the mobile unit must be able to communicate to the base station (BS) the information required by E-911 service (ALI and SNI). The base station must be able to interpret this information, provide proper handling of 911 calls, and forward sufficient information to the PSAP to provide call-back capability, location information enabling selective routing, and the determination of the type of service to be provided. Proper handling of 911 calls includes giving 911 calls priority over non-emergency calls and without the validation usually required.

Under a 1996 FCC rule making order [1], wireless service providers are required to implement E-911 in three stages. In the first stage, wireless service providers are required to transmit to the PSAPs any 911 calls from a handset that transmits a Mobile Identification Number (MIN), or its functional equivalent, without any interception by the carrier for credit checks or other validation processes. This step is to be completed within twelve months of the effective date of the rules. The commission also allows the PSAPs the discretion to require cellular, PCS and SMR licensees to transmit 911 calls that originate from phones that do not transmit the MIN without any credit checks or validation. In the second stage, beginning twelve months after the effective date of the rules and ending after eighteen months, wireless service providers must provide a cell-site location mechanism in their wireless systems along with providing the the PSAPs with the caller's phone number. If possible, they must also indicate the sector in which the 911 call is received, in case the cell of interest is sectorized. This stage ends near the end of 1997. In the last stage, which should be finished within five years after the rule making, i.e., around 2001, the wireless service providers will have to achieve the capability to identify the location of the mobile unit making a 911 call within a circle of radius of no more than 125 meters in at least 67 percent of all cases.

These regulations will affect all present and future wireless communications systems. To meet FCC regulations, wireless service providers are actively looking into techniques and solutions which will enable them to meet the FCC requirements and which will be economically feasible with minimum changes in the existing infrastructure.

1.1.2 Position Location as an Attractive User Option

Although the main incentive to incorporate position location technologies in wireless systems is the E-911 requirement, there are many other secondary reasons which make the incorporation of position location capability attractive for the wireless service providers.

With the introduction of new PCS service providers in the wireless communication market, increased competition is expected between the service providers to attract the customers. Position location capability may be offered as an additional service to the customers, along with the standard voice services. This may allow the position of any user to be traced at any given time, if requested. However, some customers may still not want this feature for the sake of privacy. Automated position determination will also help in providing emergency road-side services quickly and efficiently. Position location systems may also be very helpful in fleet management and can be used for traffic routing and scheduling of vehicles in real time [4]. There can also be a number of potential applications of position location systems for in-car navigation systems and for direction finding from known position to given destinations.

Apart from the above cited advantages, law enforcement agencies may benefit considerably from such systems which may be used to increase their crime-fighting capability [4]. Real-time position location may be used to track the location of officers and agents. Such information may also be used to track suspected criminals and to recover stolen vehicles.

Hence, addition of position location information to the existing services being offered by the wireless service providers will be encouraged by a wide section of the customers. Therefore, the wireless service providers can safely assume that they can find a market for position location information if they invest in installing such systems.

1.1.3 Advantages in System Design and Optimization

Position location services will not only provide new customer options and products for wireless carriers, but will also provide features that could differentiate services in different markets (i.e., differentiation between PCS, cellular, and specialized mobile radio) [4]. Location systems will also provide wireless carriers and vendors who use position location the ability to charge for service based on location, within a particular cell site, or in a specific location such as an office, home, or car. This will allow wireless service providers to control customer usage by offering cost incentives that match service plans for the wireless infrastructure and networking resources.

Geographical information about the service usage will also enable the service to have real-time information about areas having concentration of usage and such information will facilitate cellular planning. It will also be easier to locate the sources of fraudulent cellular telephone traffic and fraud 911 calls and thus the business loss which results from fraud can be reduced. Location information of mobile users can also be used to increase the hand-off efficiency. Design of efficient hand-off algorithms is an important issue in cellular design [5] and position location information may help in avoiding unnecessary hand-offs that may result because of local fading [6] and hence may help reduce the processing load.

1.2 Different Ways of Incorporating Position Location

There are numerous techniques that can be considered for use in wireless position location systems. However, we will discuss only those techniques that can be practically incorporated in cellular-type systems. Such techniques can be broadly classified into two categories. Either the position location system will require a modification in the existing handsets or the system can be designed in such a way that all the modifications take place at the base stations or the switching center with no modifications in the existing handsets.

1.2.1 Modified Handset Techniques

Modified Handset solutions can considerably ease the technical requirements and may result in higher accuracies than the solutions that work with the existing handsets. However, the biggest drawback of this method is the extra cost involved in reissuing new handsets. Besides, additional hardware may result in the increased weight and size of the handsets which is contrary to consumer desires. Lighter and smaller mobile phones are more popular with the customers.

GPS Based Position Location

One of the most straightforward solutions to meet the position location requirements is to use the Global Positioning System (GPS). This may involve installing a complete or a partial GPS receiver in the handset and then transmitting the received GPS data on the reverse link to the base station for further processing and position determination. However, this is not an attractive option because of a number of factors. Apart from increasing the size and weight of the handsets, the GPS receiver would result in additional drain for the batteries in the mobile phones. This will result in reduced talk time which would be highly undesirable. Since GPS operates in L-Band which is different from either of the cellular or the PCS frequencies, the mobile antenna would need redesigning. All these factors would result in increased cost for the handset. Another factor weighing against this solution is the “warm-up” time of the GPS. After being turned on, a GPS receiver takes at least one to one and a half minutes or even longer depending on the design, to start giving readings and, hence, this would be highly undesirable for an emergency 911 situation. To find the geographical location, the GPS receiver needs to have at least four satellites visible at all times, which is difficult in heavily shadowed and covered urban environments and impossible for indoor calls.

All of these factors make it extremely unlikely that a GPS-based solution will be used to solve the position location challenge in cellular-type systems. However, in vehicle based mobile phones, GPS is a more realistic option as it can be permanently installed in the car and may be used whenever the phone is being used from the car.

Mobile Assisted Time Of Arrival Technique

Absolute Time Of Arrival (TOA) for the signal from the handset to the base stations can be estimated in many ways. If the handset is able to stamp the current time on any outgoing signal,the base station can determine the time that the signal takes to reach the base station. Hence, the distance between the mobile and the base station can be determined. If at least three different receivers can receive the signal from the mobile, the position of the mobile can be found. However, this requires a very accurate timing reference at the mobile which would need to be synchronized with the clock at the base stations. Clearly, this solution is very difficult to achieve, as having an accurate and synchronized clock in the mobile is a difficult technical challenge and would again result in increased cost and size of the mobile handset.

Mobile Assisted Time Difference of Arrival Technique

In this technique, a secondary network of base stations at fixed locations is needed. These base stations effectively act as dummy handsets. At a synchronized time period, the mobile handset and a nearby dummy base station both capture a portion of the forward link signal from the actual base stations. The mobile then transmits its version of the captured signal to the dummy base station, which correlates that with its own version of the captured signal. Thus, the time difference of the signal arrival at the mobile and the dummy station is known. Since the coordinates of the dummy stations and the actual network base stations are known, this procedure gives the distance between the mobile and the actual base station. Performing three such measurements with three different actual base stations, the position of the mobile can be found using the triangulation method. It is obvious that this approach requires considerable change in the handset software along with additional hardware installations.

One such system called "Cursor", which is based on the GSM technology, is already available [7].

Another modified handset technique, based on finding TDOAs has been proposed for CDMA systems in [8]. This method uses the pilot tones from different base stations. In CDMA systems, the pilot tone transmitted by each cell is used as a coherent carrier reference for synchronization by every mobile in that cell coverage area. The pilot tone is transmitted at a higher power level than the other channels, thus allowing extremely accurate tracking. Each cell site transmits the same Pseudo Noise (PN) code in its reference channel with a unique code phase. This enables the mobile to differentiate each cell site's pilot tone. The mobile measures the arrival time differences of at least three pilot tones transmitted by three different cells. By intersecting hyperbolas the mobile's position can be estimated. It is obvious that this method requires all the processing to be done at the handset and then requires the PL estimate to be transmitted to the system on the reverse link.

1.2.2 Unmodified Handset Techniques

Unmodified handset solutions refer to techniques that would work with the existing handsets, without requiring any modifications. Thus, all the changes will be concentrated in the system infrastructure, i.e., base stations and the switching center. In the light of the above discussion, it is obvious that the optimum solution for wireless E-911 in the near term would have to work with existing handsets as any modified handset solution may not be feasible because of economic factors.

Angle Of Arrival (AOA) Technique

AOA methods are sometimes also referred to as Direction Of Arrival (DOA) methods. AOA methods utilize multi-array antennas and try to estimate the direction of arrival of the signal of interest. Thus a single DOA measurement restricts the source location along a line in the estimated DOA. If at least two such DOA estimates are available from two antennas at two different locations, the position of the signal source can be located at the intersection of the lines of bearings from the two antennas. Usually multiple DOA estimates are used to improve the estimation accuracy by using the redundant information. Figure 1.1 shows the method where the source location is found by the intersection of DOA of the signal for three antenna arrays.

To estimate the DOA, algorithms are used that exploit the phase differences or other signal characteristics between closely spaced antenna elements of an antenna array and employ phase-alignment methods for beam/null steering. The spacing of antenna elements

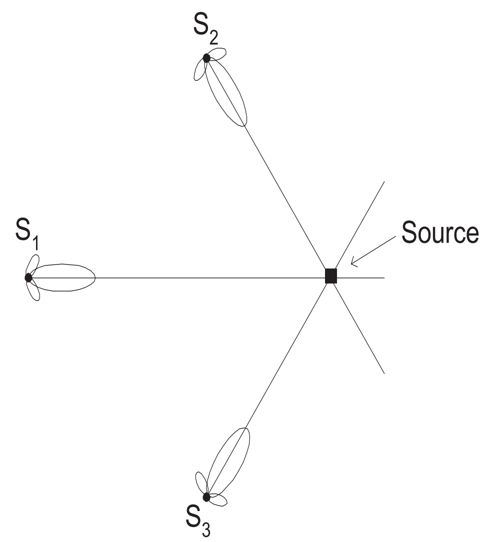

Figure 1.1: 2-D Direction Finding Position Location Solution

within the antenna array is typically less than 1/2 wavelength of all received signals. This is required to produce phase differences on the order of π radians or less to avoid ambiguities in the DOA estimate. The resolution of DOA estimates improves as the baseline distances between antenna elements increase. However, this improvement is at the expense of ambiguities. As a result, DOA estimation methods are often used with short baselines to reduce or eliminate the ambiguities and at other times with long baselines to improve resolution.

Although DOA methods offer a practical solution for wireless position location, they have certain drawbacks. For accurate DOA estimates, it is crucial that the signals coming from the source to the antenna arrays must be coming from the Line-Of-Sight (LOS) direction. However, this is often not the case in cellular systems, which may be operating in heavily shadowed channels, such as those encountered in urban environments. Another factor which is the considerable cost of installing antenna arrays. Although adaptive antennas hold considerable promise for improving the capacity of cellular systems [9], they would only be needed in the areas where capacity enhancement will be required. Hence, for rural and suburban areas which are sparsely populated, this would be a costly solution to meet the E-911 requirements. Even if antenna arrays are in place at some base stations, the position location system may need regular calibration since a minute change in the physical arrangement of the array because of winds or storms, may result in considerable position location error as the absolute angular position of the array is used as a reference for the AOA estimates. This is a problem that would be unique to position location as this will not affect the interference rejection capability of the array. Hence, if the arrays are to be used for position location they would either need extremely rugged installation or some other method of continuous calibration for accurate DOA estimates. Another problem with this method is the complexity of the DOA algorithms. Although there are some exceptions such as ESPIRIT algorithm [10], these algorithms usually tend to be highly complex because of the need for measurement, storage and usage of array calibration data and their computationally intensive nature [11].

Time Of Arrival (TOA) Technique

It may be possible for the base station to indirectly determine the time that the signal takes from the source to the receiver on the forward or the reverse link. This may be done by measuring the time in which the mobile responds to an inquiry or an instruction transmitted to the mobile from the base station. The total time elapsed from the instant the command is transmitted to the instant the mobile response is detected, is composed of the sum of the round trip signal delay and any processing and response delay within the mobile unit. If the processing delay for the desired response within the mobile is known with sufficient accuracy, it can be subtracted from total measured time, which would give us the total round trip delay. Half of that quantity would be an estimate of the signal delay in one direction, which would give us the approximate distance of the mobile from the base station. If the mobile response can be detected at two additional receivers then the position can be fixed by the triangulation method.

There are certain problems that this method could face. The estimate of the response delay within the mobile might be difficult to determine in practice. The main reason would be the variations in designs of the handsets from different manufacturers. Secondly, this method is highly susceptible to timing errors in the absence of LOS, as there would be no way to reduce the errors induced because of multiple signal reflections on the forward or the reverse link.

Time Difference of Arrival (TDOA) Technique

TDOA techniques are based on estimating the difference in the arrival times of the signal from the source at multiple receivers. This is usually accomplished by taking a snapshot of the signal at a synchronized time period at multiple receivers. The cross-correlation of the two versions of the signal at pairs of base stations is done and the peak of the cross-correlation output gives the time difference for the signal arrival at those two base stations. A particular value of the time difference estimate defines a hyperbola between the two receivers on which the mobile may exist, assuming that the source and the receivers are

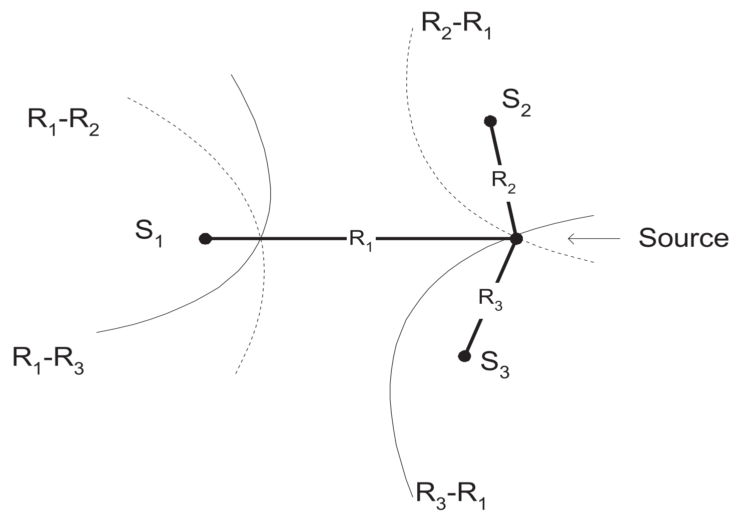

Figure 1.2: 2-D Hyperbolic Position Location Solution

coplanar. If this procedure is done again with another receiver in combination with any of the previously used receivers, another hyperbola is defined and the intersection of the two hyperbolas results in the position location estimate of the source. This method is also sometimes called a hyperbolic position location method.

This method offers many advantages over other competing techniques. Since, all the processing takes place at the infrastructure level, no modifications are needed in the existing handsets. In this respect, this solution would be more cost effective than a GPS-based solution. It also does not require knowledge of the absolute time of the transmission from the handset like a modified handset TOA method needs. Since this technique does not require any special type of antennas, it is cheaper to put in place than the DOA finding methods. It can also provide some immunity against timing errors if the source of major signal reflections is near the mobile. If a major reflector effects the signal components going to all the receivers, the timing error may get cancelled or reduced in the time difference operation. Hence, TDOA methods may work accurately in some situations where there is no LOS signal component. In this respect, it is superior to the DOA method or the TOA method.

The required changes to incorporate the TDOA method are only to be in the software of the system. However, dedicated lines for position location data may be used between the base stations and the switching center, if the position location technique is to be used often enough, to avoid a toll on the revenue generating voice traffic in the regular connection between the base stations and the switch.

1.2.3 Hybrid Techniques

It is possible to combine two or more of the techniques discussed above to offer a more reliable and accurate position location service than what can be offered by using just one of these techniques.

AOA/TDOA Hybrid Technique

It is possible to combine TDOA and AOA techniques into hybrid systems [4]. For example, the position location system developed by E-Systems for the Cellular Applied to IVHS Tracking and Location (CAPITAL) Beltway Project employs both techniques [12, 13].

The CAPITAL system geolocates the target mobile by monitoring at base stations the reverse link voice channel transmitted by the mobile user. Multiple base stations receive the signal, and the target position is determined by combining AOA estimates from each base station and TDOA estimates between multiple base stations. AOA estimates are made using an adaptive array and a variation of the maximum likelihood techniques described in [11, 14]. Times of signal arrival are measured at each base station and are time stamped with a GPS time reference to determine time-difference of arrival estimates. The impact of multipath is minimized by using highly directional adaptive antennas that offer spatial filtering [15].

This type of hybrid system is probably the most accurate and reliable type of cellular geolocation system that can be used. However, it is an important issue in such systems to make sure that both methods combine synergestically and that the inaccuracies from one method do not adversely affect overall position estimate.

AOA/TOA Hybrid Technique

This is the only type of cellular geolocation system that can be used when only one base station is able to receive the signal from the mobile. As it has been observed [16], under some conditions in CDMA systems, only one base station may be receiving a clear signal from the mobile and the signal level at other base stations might be too weak for them to participate in a DOA or a TDOA PL method.

This method obtains the TOA estimate by using the closed loop method described in 1.2.2. This reduces the possible mobile positions in a circle around the base station. Then, a direction estimate can be found using DOA techniques as described also in 1.2.2. The intersection of that line of bearing and the circle forms an estimate of the mobile position. Although this technique may not be as accurate as the ones discussed above, it may be the only unmodified handset PL solution possible when only one base station is able to receive the mobile signal.

1.3 Research Outline

1.3.1 Purpose of Research

The main purpose of this research has been to evaluate the feasibility and expected accuracy of the TDOA methods in CDMA systems, under different and varying conditions. Another purpose was to examine different algorithms available for use in different stages of the TDOA PL method and to recommend the ones most suited for cellular CDMA. It also included studying the performance under different types of channel environments, loading conditions and base station arrangements.

This research also suggests a method to cross correlate the composite CDMA signals so as to get the TDOA of only the desired user. It also proposes a new measure of accuracy to be used for position location suitable for that method. Finally, an improvement in the TDOA method is suggested that yields much improved results than the unmodified TDOA estimation.

1.3.2 Thesis Outline

The first chapter gives a general background and introduction to the problem of position location and different techniques for solving it. Chapter 2 explains the TDOA method, its different stages and algorithms in detail. Chapter 3 discusses the simulation models and procedures used for this research. Chapters 4, 5 and 6 present the simulation results. Chapter 4 presents general results, whereas, Chapter 5 is dedicated to issues that are faced in a multiuser CDMA environment. Chapter 6 discusses the improved TDOA estimation and the performance comparison of that method with the unmodified estimation method. Chapter 7 concludes the thesis by presenting the results and conclusions.

Chapter 2

Time Difference of Arrival (TDOA) Position Location Technique

2.1 Introduction

In this chapter, we make a comparison of the TDOA PL technique with other PL techniques and discuss the comparative advantages. We also study the TDOA technique of position location in more detail and discuss different algorithms that are used to find the time difference estimates and to solve the resulting hyperbolic equations. We compare those algorithms that can be used in CDMA systems and then recommend the ones most suitable. Important aspects of the hyperbolic PL method for CDMA systems are also presented, including some of the advantages and disadvantages that the TDOA method faces in CDMA systems. The chapter also includes a discussion on the measures used to gauge the accuracy of position location estimation and introduces the measure of accuracy used throughout this work.

2.2 Comparison of TDOA Techniques with other Techniques

2.2.1 TDOA Technique Versus Modified Handset Techniques

As discussed earlier, there may be many solutions to the position location challenge if a modified handset solution is acceptable. The foremost of them is the incorporation of a GPS unit in the handset. This would concentrate most of the changes in the handset and the infrastructure would only need to receive the coordinates from the mobile unit and forward them to the PSAPs. Another solution, although technically difficult, is to put an accurate timing reference, such as a Cesium or a Rubidium clock, in the handsets which will help in synchronizing the handsets with the system and may be used to time stamp the signal going out on the reverse link. Hence, in this way TOA estimates can be made. Other techniques using modified handset TDOA finding methods were also discussed in 1.2.1.

The greatest problem that these methods face is the fact that these additions would increase the cost of the handsets by at least a few hundred dollars, besides increasing the weight and the size, which are also undesirable. Even if these problems are mitigated by a cheaper and lighter modification, it would be practically impossible to call back and retrofit the tens of millions of handsets already in use [5] to fulfill the E-911 requirement. Thus it has become quite clear that the foremost issue in wireless E-911 is the incorporation of PL techniques without significant cost burden on the service providers. Hence, unmodified handset TDOA techniques offer a more practical and economically viable solution to wireless E-911 than any of the discussed modified handset solutions.

2.2.2 TDOA Technique Versus Other Unmodified Handset Techniques

The method that appears to be the most practical alternative to the TDOA method is the direction finding method based on estimating AOA which has been discussed in 1.2.2. Although the most accurate cellular geolocation system might be a hybrid TDOA/AOA method, AOA techniques when used alone face certain problems. This includes the additional cost of adaptive antenna arrays on base stations. It is also a factor that the direction finding may not be accurate in the absence of LOS path between the source and the receivers, when compared with the performance of TDOA techniques in similar environments.

Techniques that try to estimate TOA through closed loop time interval estimation, discussed in 1.2.2, also do not offer any particular advantage over TDOA techniques. Those techniques are particularly vulnerable to errors in estimation of delay for processing inside the mobile. They also are more susceptible to errors from multiple reflections than the hyperbolic method.

The only requirement for the TDOA measurements is to have precisely synchronized clocks at the fixed location receivers. This corresponds to the timing standards already provided at cellular base station sites, making TDOA more realistic than requiring each mobile unit to have an accurate clock. Atomic clocks, such as a Cesium time source or a GPS receiver clock, are typically used for timing at base stations. Hence, it is concluded that the TDOA technique appears to be the most feasible option for the wireless E-911 solution.

2.3 TDOA Position Location Method

Hyperbolic PL estimation is accomplished in two stages [4]. The first stage involves estimation of the TDOAs of the signal from a source, between pairs of receivers through the use of time delay estimation techniques. In the second stage, the estimated TDOAs are transformed into range difference measurements between base stations, resulting in a set of nonlinear hyperbolic equations. The second stage then uses efficient algorithms to produce an unambiguous solution to these nonlinear equations. The solution provided by these equations results in the estimated position of the source.

Following is a survey of different techniques that are used to estimate the TDOAs. After that is a similar survey of the techniques and algorithms that have been proposed to accurately solve the nonlinear hyperbolic equations.

2.3.1 TDOA Estimation Techniques

The TDOA of a signal can be estimated by two general methods [17]: 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.

The first method is applicable if we have absolute TOA measurements. Superficially, there doesn't seem to be any advantage in converting TOA measurements into TDOA measurements, as we can triangulate the position of the mobile using the TOA measurements, directly. However, this may give us some increased accuracy when errors due to multiple signal reflections in pairs of TOA measurements are positively correlated because of having a common signal reflector. The more similar the errors in pairs of TOAs are, the more we can gain by changing them into TDOAs. However, this is practical only when we can estimate the TOA by having knowledge of the time of transmission. If we have no timing reference at the transmitter, then this method for estimating TDOAs cannot be used.

Because of the absence of a timing reference on the source-to-be-located, the most commonly used technique for TDOA estimation is the cross-correlation technique. The timing requirement for this method is the synchronization of all the receivers participating in the TDOA measurements, which is more practical to achieve in most position location applications. Because of these factors we'll discuss in detail only the cross-correlation technique for estimating TDOAs.

Mathematical Model for Cross-Correlation Technique

For a signal, $s(t)$, radiating from a remote source through a channel with interference and noise, the general model for the time-delay estimation between received signals at two base stations, $x_1(t)$ and $x_2(t)$, is given by

$$\begin{aligned} x_1(t) &= A_1 s(t-d_1) + n_1(t) \\ x_2(t) &= A_2 s(t-d_2) + n_2(t), \end{aligned} \tag{2.1}$$

where A_1 and A_2 are the amplitude scaling of the signal, $n_1(t)$ and $n_2(t)$ consist of noise and interfering signals and d_1 and d_2 are the signal delay times, or arrival times. This model assumes that $s(t)$, $n_1(t)$ and $n_2(t)$ are real and jointly stationary, zero-mean (time average) random processes and that $s(t)$ is uncorrelated with noise $n_1(t)$ and $n_2(t)$. Referring the delay time and scaling amplitudes to the receiver with the shortest time of arrival, assuming $d_1 < d_2$, the model of (2.1) can be rewritten as

$$\begin{aligned} x_1(t) &= s(t) + n_1(t) \\ x_2(t) &= As(t-D) + n_2(t), \end{aligned} \tag{2.2}$$

where A is the amplitude ratio and $D = d_2 - d_1$. It is desired to estimate D, the time difference of arrival (TDOA) of $s(t)$ between the two receivers. It may also be desirable to estimate the scaling amplitude A. By estimating the amplitude scaling, selection of the appropriate receivers can be made. It follows that the limit cyclic cross-correlation and autocorrelations are given by

$$R^{\alpha}_{x_2x_1}(\tau) = AR^{\alpha}_{s}(\tau - D)e^{-j\pi\alpha D} + R^{\alpha}_{n_2n_1}(\tau) \tag{2.3}$$

$$R^{\alpha}_{x_1}(\tau) = R^{\alpha}_{s}(\tau) + R^{\alpha}_{n_1}(\tau) \tag{2.4}$$

$$R^{\alpha}_{x_2}(\tau) = |A|^2 R^{\alpha}_{s}(\tau)e^{-j\pi\alpha D} + R^{\alpha}_{n_2}(\tau), \tag{2.5}$$

where the parameter α is called the cycle frequency [18]. If $\alpha = 0$, the above equations are the conventional limit cross-correlation and autocorrelations.

If $s(t)$ exhibits a cycle frequency α, not shared by $n_1(t)$ and $n_2(t)$, then by using this value of α in the measurements in (2.3)-(2.5), we obtain through infinite time averaging

$$R^{\alpha}_{n_1}(\tau) = R^{\alpha}_{n_2}(\tau) = R^{\alpha}_{n_2 n_1}(\tau) = 0 \tag{2.6}$$

and the general model for time delay estimation between base stations is

$$\begin{aligned} R^{\alpha}_{x_2 x_1}(\tau) &= A R^{\alpha}_{s}(\tau - D) e^{-j\pi\alpha D} && (2.7)\\ R^{\alpha}_{x_1}(\tau) &= R^{\alpha}_{s}(\tau) && (2.8)\\ R^{\alpha}_{x_2}(\tau) &= |A|^2 R^{\alpha}_{s}(\tau) e^{-j\pi\alpha D}. && (2.9) \end{aligned}$$

Accurate TDOA estimation requires the use of time delay estimation techniques that provide resistance to noise and interference and the ability to resolve multipath signal components. Many techniques have been developed that estimate TDOA D with varying degrees of accuracy and robustness. These include the Generalized Cross-Correlation (GCC) and Cyclic Cross-Correlation (CCC) methods. Cyclostationarity-exploiting methods include the Cyclic Cross-Correlation (CYCCOR), the Spectral-Coherence Alignment (SPECCOA) method, the Band-Limited Spectral Correlation Ratio (BL-SPECCORR) method and the Cyclic Prony method [19]. While signal selective cyclostationarity-exploiting methods have been shown in [19] and [20] to outperform GCC methods in the presence of noise and interference, they do so only when spectrally overlapping noise and interference exhibit a cycle frequency different than the signal of interest. When spectrally overlapping signals exhibit the same cycle frequency, as is encountered in multiuser CDMA systems, these methods do not offer any advantage over GCC methods.

Generalized Cross-Correlation Methods

Conventional correlation techniques that have been used to solve the problem of TDOA estimation are referred to as Generalized Cross-Correlation (GCC) methods. These methods have been explored in [18, 20, 21, 22, 23, 24, 25]. These GCC methods cross-correlate prefiltered versions of the received signals at two receiving stations, then estimate the TDOA D between the two stations as the location of the peak of the cross-correlation estimate. Prefiltering is intended to accentuate frequencies for which Signal-to-Noise Ratio(SNR) is the highest and attenuate the noise power before the signal is passed to the correlator.

Generalized cross-correlation methods for TDOA estimation are based on (2.7) with $\alpha = 0$ [18]. Thus (2.7) is rewritten as

$$R^{0}_{x_2 x_1}(\tau) = A R^{0}_{s}(\tau - D). \tag{2.10}$$

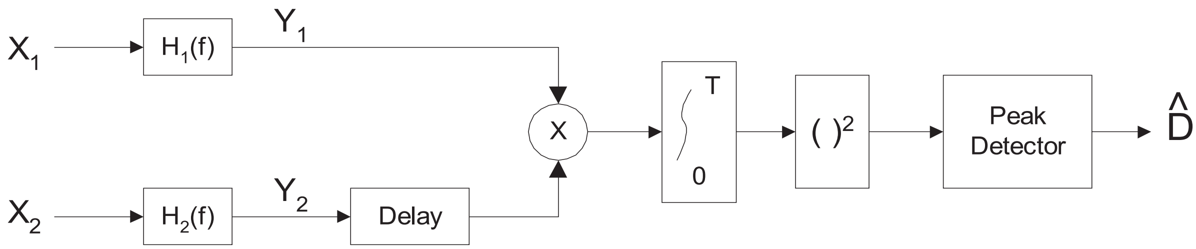

Figure 2.1: Generalized Cross-Correlation Method for TDOA Estimation

The argument τ that maximizes (2.10) provides an estimate of the TDOA D. Equivalently, (2.10) can be written as

$$R_{x_2x_1}(\tau) = R^0_{x_2x_1}(\tau) = \int_{-\infty}^{\infty} x_1(t)x_2(t-\tau)dt. \tag{2.11}$$

However, $R_{x_2x_1}(\tau)$ can only be estimated from a finite observation time. Thus, an estimate of the cross-correlation is given by

$$\hat{R}_{x_2x_1}(\tau) = \frac{1}{T}\int_0^T x_1(t)x_2(t-\tau)dt, \tag{2.12}$$

where T represents the observation interval. Equation (2.12) suggests the the use of an analog correlator. An integrate and dump correlation receiver of this form is one realization of a matched filter receiver [26]. The correlation process can also be implemented digitally, if sufficient sampling of the waveform is used. The output of a discrete correlation process using digital samples of the signal is given by

$$\hat{R}_{x_2x_1}(m) = \frac{1}{N}\sum_{n=0}^{N-|m|-1} x_1(n)x_2(n+m)dt. \tag{2.13}$$

The cross-power spectral density function, $G_{x_2x_1}(f)$, related to the cross-correlation of $x_1(t)$ and $x_2(t)$ in (2.12) is given by

$$R_{x_2x_1}(\tau) = \int_{-\infty}^{\infty} G_{x_2x_1}(f)e^{j\pi f\tau}df \tag{2.14}$$

or

$$G_{x_2x_1}(f) = \int_{-\infty}^{\infty} R_{x_2x_1}(\tau)e^{-j\pi f\tau}dt. \tag{2.15}$$

As before, because only a finite observation time of $x_1(t)$ and $x_2(t)$ is possible, only an estimate $\hat{G}_{x_2x_1}(f)$ of $G_{x_2x_1}(f)$ can be obtained.

In order to improve the accuracy of the delay estimate, filtering of the two signals is performed before integrating in (2.12). As shown in Figure 2.1, each signal $x_1(t)$ and

$x_2(t)$ is filtered through $H_1(f)$ and $H_2(f)$, then correlated, integrated and squared. This is performed for a range of time shifts, τ, until a peak correlation is obtained. The time delay causing the cross-correlation peak is an estimate of the TDOA $\hat{D}$. If the correlator is to provide an unbiased estimate of TDOA D, the filters must exhibit the same phase characteristics and hence are usually taken to be identical filters [24].

When $x_1(t)$ and $x_2(t)$ are filtered, the cross-power spectrum between the filtered outputs is given by

$$G_{y_2y_1}(f) = H_1(f)H_2^*(f)G_{x_2x_1}(f), \tag{2.16}$$

where $*$ denotes the complex conjugate. Therefore, the generalized cross-correlation, specified by superscript G, between $x_1(t)$ and $x_2(t)$ is

$$R^G_{y_2y_1}(\tau) = \int_{-\infty}^{\infty} \Psi_G(f)G_{x_2x_1}(f)e^{j\pi f\tau}df, \tag{2.17}$$

where

$$\Psi_G(f) = H_1(f)H_2^*(f) \tag{2.18}$$

and denotes the general frequency weighting, or filter function. Because only an estimate of $R^G_{y_2y_1}(\tau)$ can be obtained, (2.17) is rewritten as

$$\hat{R}^G_{y_2y_1}(\tau) = \int_{-\infty}^{\infty} \Psi_G(f)\hat{G}_{x_2x_1}(f)e^{j\pi f\tau}df \tag{2.19}$$

which is used to estimate the TDOA D. The GCC methods use filter functions $\Psi_G(f)$ to minimize the effect of noise and interference.

The choice of the frequency function, $\Psi_G(f)$, is very important, especially when the signal has multiple delays resulting from a multipath environment. Consider the optimal case in which $n_1(t)$ and $n_2(t)$ are uncorrelated and only one signal delay is present. The cross-correlation of $x_1(t)$ and $x_2(t)$ in (2.10) can be rewritten as

$$R^0_{x_2x_1}(\tau) = AR^0_s(\tau) \otimes \delta(t - D), \tag{2.20}$$

where $\otimes$ denotes a convolution operation. Equation (2.20) can be interpreted as the spreading of a delta function at D by the inverse Fourier transform of the signal spectrum. When the signal experiences multiple delays due to a multipath environment, the cross-correlation can be represented as

$$R_{x_2x_1}(0) = R^0_s(\tau) \otimes \sum_i A_i\delta(t - D_i). \tag{2.21}$$

If the delays of the signal are not sufficiently separated, the spreading of the one delta function will overlap another, thereby making the estimation of the peak and TDOA difficult if not impossible. The frequency function $\Psi_G(f)$ can be chosen to ensure a large peak in

Table 2.1: GCC Frequency Functions

Processor Name	**Frequency Function** $\Psi_G(f)$
Cross-correlation	1
Roth Impulse Response	$1/G_{x_1x_1}(f)$ or $1/G_{x_2x_2}(f)$
Smoothed Coherence Transform	$1/\sqrt{G_{x_1x_1}(f)G_{x_2x_2}(f)}$
Eckart	$G_{s_1s_1}(f)/[G_{n_1n_1}(f)G_{n_2n_2}(f)]$
Hannan-Thomson or Maximum Likelihood	$\frac{\lvert\gamma_{x_1x_2}(f)\rvert^2}{\lvert G_{x_1x_2}(f)\rvert[1-\lvert\gamma_{x_1x_2}(f)\rvert^2]}$

the cross-correlation $x_1(t)$ and $x_2(t)$, resulting in a narrower spectra and better TDOA resolution. However, in doing so, the peaks are more sensitive to errors introduced by the finite observation time, especially in cases of low SNR. Thus the choice of $\Psi_G(f)$ is a compromise between good resolution and stability [21]. Following is a survey of some of the frequency functions proposed in the literature.

Cross-Correlation Processors: Several frequency functions, or processors, have been proposed to facilitate the estimate of $\hat{D}$. When the filters $H_1(f) = H_2(f) = 1$, $\forall(f)$, then $\Psi_G(f) = 1$, and the estimate $\hat{G}$ is simply the delay abscissa at which the cross-correlation peaks. This is considered cross-correlation processing. Other processors include the Roth Impulse Response processor [23], the Smoothed Coherence Transform (SCOT) [27], the Eckart filter [21, 24], and the Hannan-Thomson (HT) processor or Maximum Likelihood (ML) estimator [28]. A list of GCC frequency functions is provided in Table 2.1 from [21].

Roth Impulse Response Processor: The Roth Impulse Response processor has the desirable effect of suppressing the frequency regions in which power spectral noise density, $G_{n_1n_1}(f)$ or $G_{n_2n_2}(f)$, is large and the estimate of the cross power spectral signal density, $\hat{G}_{x_1x_2}(f)$, is likely to be in error. However, if the power spectral noise density is not equal to some constant times the power spectral density of the signal, $G_{s_1s_1}(f)$, the Roth processor does not minimize the spreading effect of the delta function [21]. Furthermore, one is uncertain as to whether the errors in $\hat{G}_{x_1x_2}(f)$ are due to frequency bands in which $G_{n_1n_1}(f)$ or $G_{n_2n_2}(f)$ large.

Smoothed Coherence Transform Processor: The uncertainty with the Roth processor led to the development of the proposed Smoothed Coherence Transform (SCOT). The SCOT processor suppresses frequency bands of high noise and assigns zero weight to bands where $G_{s_1 s_1}(f) = 0$. The SCOT frequency function is given as

$$\Psi_S(f) = 1/\sqrt{G_{x_1 x_1}(f) G_{x_2 x_2}(f)}. \tag{2.22}$$

This results in the cross-correlation

$$R^S_{y_2 y_1}(\tau) = \int_{-\infty}^{\infty} \hat{\gamma}_{x_1 x_2}(f) e^{j\pi f \tau} df, \tag{2.23}$$

where

$$\hat{\gamma}_{x_1 x_2}(f) \hat{=} \frac{\hat{G}_{x_1 x_2}(f)}{\sqrt{G_{x_1 x_1}(f) G_{x_2 x_2}(f)}} \tag{2.24}$$

is the coherence estimate [21]. The SCOT processor assigns weighting according to SNR characteristics. In terms of the noise characteristics, [24] realizes the SCOT as

$$|\Psi_S(f)|^2 = 1/N. \tag{2.25}$$

The SCOT frequency function, for which $H_1(f) = 1/\sqrt{G_{x_1 x_1}(f)}$ and $H_2(f) = 1/\sqrt{G_{x_2 x_2}(f)}$, can be interpreted as a prewhitening process. If $G_{x_1 x_1}(f) = G_{x_2 x_2}(f)$, then the SCOT filter is equivalent to the Roth filter. Consequently, the SCOT still produces the same broadening as the Roth function [21].

Eckart Processor: The Eckart processor, similarly to the SCOT processor, suppresses frequency bands of high noise and assigns zero weight to bands where $G_{s_1 s_1}(f) = 0$. The Eckart frequency function maximizes the ratio of the change in mean correlator output to the standard deviation of the correlator output due to the noise alone [21]. For the model given by (2.2) and $n_1(t)$ and $n_2(t)$ having the same spectra, the Eckart frequency function in terms of the SNR characteristics is given by [24] as

$$|\Psi_E(f)|^2 = S/N^2. \tag{2.26}$$

In practice, the Eckart filter requires knowledge of the signal and noise spectra [21].

Hannan-Thomson or Maximum Likelihood Processor: The previously described frequency functions have been shown to be suboptimal by [24]. The HT processor, which is equivalent to a ML estimator, has been shown to be the optimal processor by [24] and [21]. The HT frequency function is given by

$$\Psi_{HT}(f) = \frac{|\gamma_{x_1 x_2}(f)|^2}{|G_{x_1 x_2}(f)|[1 - |\gamma_{x_1 x_2}(f)|^2]}, \tag{2.27}$$

where $|\gamma_{x_1x_2}(f)|^2$ is the magnitude-squared coherence [29]. For the model in (2.2) and $n_1(t)$ and $n_2(t)$ having the same spectra, the HT frequency function in terms of the SNR characteristics is given as

$$|\Psi_{HT}(f)|^2 = \frac{S/N^2}{1 + 2(S/N)}. \tag{2.28}$$

For low SNR, it has been shown in [21] that the Eckart function is equivalent to the HT frequency function.

Conclusions: These GCC TDOA estimation methods have been shown to be effective in reducing the effects of noise and interference [20]. However, if the noise and interference $n_1(t)$ and $n_2(t)$ in (2.2) are both temporally and spectrally coincident with $s(t)$, as in CDMA, there is little that GCC methods can do to reduce the undesirable effects of this interference. In this situation, generalized cross-correlation methods encounter two problems. First, GCC methods experience a resolution problem. These GCC methods require the differences in the TDOAs for each signal to be greater than the widths of the cross-correlation functions so that the peaks can be resolved. Consequently, if the TDOAs are not sufficiently separated, the overlapping of cross correlations can introduce significant errors in the TDOA estimate. Second, if $s(t)$, $n_1(t)$ and $n_2(t)$ are resolvable, conventional GCC methods must still identify which of the multiple peaks is due to the signal of interest and interference. These problems arise because GCC methods are not signal selective and produce TDOA peaks for all signals in the received data, unless they are spectrally disjoint and can be filtered out [19].

Cyclic Cross-Correlation Methods

Most signals encountered in communications and telemetry systems are appropriately modeled as cyclostationary time series rather than as stationary time series. This is a direct result of underlying periodicities in the time series due to periodic sampling, scanning, modulating, multiplexing and coding operations employed in the transmitter. If the cyclic properties of the Signal-Of-Interest (SOI) are different than that of Signals-Not-Of-Interest (SNOI), then these properties can be exploited to selectively find out the TDOA of only the SOI regardless of the extent of temporal, spectral or spatial overlap between the SOI and the interfering signals. The methods that exploit these cyclostationary properties are called Cyclic Cross-Correlation (CCC) methods.

If the SOI has a known (or measurable) analog carrier frequency or digital keying rate that is distinct from those of all interfering signals, then CCC methods clearly outperform GCC methods [20]. Their complexity is also comparable to that of the conventional

GCC algorithms. A number of CCC methods such as Correlated CCC (CCCC), Spectral Correlation Ratio (SPECCORR), Spectral Coherent Alignment (SPECCOA), Spectral Coherence Nulling (SPECCON), Cyclic Linear Phase (CLP) and Cyclic Phase-Difference (CPD) methods have been proposed in [18].

However, in CDMA the interfering signals of the other users exhibit the same periodicities as that of the desired user. Hence, in this case the CCC methods cannot provide any improvement over the GCC methods. Hence, we don't discuss CCC methods in detail here. A detailed mathematical description of different CCC methods, their comparative performance with each other and with GCC methods can be found in [18, 19, 20].

2.3.2 Hyperbolic Equation Solving Algorithms

Once the TDOA estimates have been obtained, they are converted into range difference measurements and these measurements can be converted into nonlinear hyperbolic equations. As these equations are non-linear, solving them is not a trivial operation. Several algorithms have been proposed for this purpose having different complexities and accuracies.

Here, we will first discuss the mathematical model that is used by these algorithms, which is then followed by a survey of the algorithms that can be used for solving hyperbolic equations.

Mathematical Model for Hyperbolic TDOA Equations

A general model for the two dimensional (2-D) PL estimation of a source using M base stations is developed. Referring all TDOAs to the first base station, which is assumed to be the base station controlling the call and the first to receive the transmitted signal, let the index $i = 2, \ldots, M$, unless otherwise specified, (x, y) be the source location and (X_i, Y_i) be the known location of the ith receiver. The squared range distance between the source and the ith receiver is given as

$$\begin{aligned} R_i &= \sqrt{(X_i - x)^2 + (Y_i - y)^2} \\ &= \sqrt{X_i^2 + Y_i^2 - 2X_i x - 2Y_i y + x^2 + y^2}. \end{aligned} \tag{2.29}$$

The range difference between base stations with respect to the base station where the signal arrives first, is

$$\begin{aligned} R_{i,1} &= c\, d_{i,1} = R_i - R_1 \\ &= \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2}, \end{aligned} \tag{2.30}$$

where c is the signal propagation speed, $R_{i,1}$ is the range difference distance between the first base station and the ith base station, R_1 is the distance between the first base station and the source, and $d_{i,1}$ is the estimated TDOA between the first base station and the ith base station. This defines the set of nonlinear hyperbolic equations whose solution gives the 2-D coordinates of the source.

Solving the nonlinear equations of (2.30) is difficult. Consequently, linearizing this set of equations is commonly performed. One way of linearizing these equations is through the use of Taylor-series expansion and retaining the first two terms [30, 31]. A commonly used alternative method to the Taylor-series expansion method, presented in [32, 33, 34, 35], is to first transform the set of nonlinear equations in (2.30) into another set of equations. Rearranging the form of (2.30) into

$$R_i^2 = (R_{i,1} + R_1)^2. \tag{2.31}$$

Equation (2.29) can now be rewritten as

$$R_{i,1}^2 + 2R_{i,1}R_1 + R_1^2 = X_i^2 + Y_i^2 - 2X_i x - 2Y_i y + x^2 + y^2. \tag{2.32}$$

Subtracting (2.29) at i = 1 from (2.32) results in

$$R_{i,1}^2 + 2R_{i,1}R_1 = X_i^2 + Y_i^2 - 2X_{i,1} x - 2Y_{i,1} y + x^2 + y^2, \tag{2.33}$$

where $X_{i,1}$ and $Y_{i,1}$ are equal to $X_i - X_1$ and $Y_i - Y_1$ respectively. The set of equations in (2.33) are now linear with the source location (x, y) and the range of the first receiver to the source R_1 as the unknowns, and are more easily handled.

Algorithms for Linearly Placed Base Stations

When base stations are placed in a linear fashion, the estimation of the PL is simplified. Since base stations in a practical cellular-type system are usually not linearly placed, these algorithms are not of much significance for wireless E-911. Hence, following is a brief discussion of four algorithms proposed in literature for such linear cases.

For receivers arranged in a line, Carter's beam forming method provides an exact solution for the source range and bearing [29]. However, it requires an extensive search over a set of possible source locations which can become computationally intensive. Hahn's method estimates the source range and bearing from the weighted sum of ranges and bearings obtained from the TDOAs of every possible combination. This method is very sensitive to the choice of weights, which can be very complicated in obtaining, and is only valid for distant sources [24, 25]. Abel and Smith provide an explicit solution that can achieve the

Cramér-Rao Lower Bound (CRLB) in the small error region [36]. The CRLB is a measure which defines what is meant by "optimum performance" for an algorithm which solves (2.30) [4] and provides a means of assessing how close any particular position location technique comes to approaching the theoretical minimum mean squared error [37, 38, 39]. Chan's method which works for arbitrarily placed receivers also works for linearly placed receivers with minor modifications [37]. A detailed discussion on this method will follow later in this section.

Algorithms for Arbitrarily Placed Base Stations

When base stations are arbitrarily placed, which is a typical scenario in the infrastructure of a cellular/PCS system, the position fix becomes more complex.

Apart from complexity, another issue that is important here is the consistency of the system of equations. If the set of nonlinear hyperbolic equations equals the number of unknown coordinates of the source, then the system is consistent and a unique solution can be determined from either closed form formulas or iterative algorithms. For example, if we want to determine the position of a mobile handset in a 2-D system and we use three base stations, giving us two TDOA measurements at base stations #2 and #3 relative to base station #1, then we would have a consistent system as there will be two equations to solve for two unknowns. However, if the system is inconsistent, i.e., there are redundant range difference measurements, then the problem of solving for the position location of the source becomes more difficult because no unique solution exists. This may happen if we try to use more than three base stations to have redundant TDOA measurements for a 2-D solution. Although this may not happen very often because of the hearability problems in CDMA (discussed in 2.4), this may occur in some situations such as in microcellular environments. Hence, it is an important issue whether an algorithm is able to optimally solve inconsistent systems of equations or not.

Other issues are computational complexity of the algorithms, their ability to provide exact solutions, the risk of convergence to a local minimum for iterative algorithms if the starting 'seed' is bad, and the requirement of some *a priori* information for the algorithms to work.

Following is a survey of seven algorithms found in literature that are able to deal with situations when the receivers are arbitrarily placed. These algorithms have been examined in the light of the issues mentioned above. Among these, there are three algorithms that have been found to be particularly feasible for wireless E-911 and they are explained in more mathematical detail later.

Friedlander's Method: Friedlander's method utilizes a Least Squares (LS) and a Weighted LS (WLS) error criterion to solve for the position location estimate [32]. It has been shown in [40] that the LS solution provides the Maximum Likelihood (ML) estimate, if the range difference errors are uncorrelated and Gaussian distributed with zero mean and equal variances. If the variances are equal, then the WLS is the ML estimate. However, a problem exists because the variances are either not known *a priori* or are difficult to estimate. Friedlander's simulation results indicated that when using four base stations the LS and WLS solutions were identical. However, for more than four base stations, the WLS PL solution outperformed the LS PL solution. This method assumes that R_1 is independent of x and y in (2.33) and thus is able to eliminate R_1 from those equations. This method does reduce the computational complexity as compared to other solutions but is suboptimal, as compared to some of them, because it eliminates a fundamental relationship.

Spherical-Intersection Method: The spherical-intersection (SX) method [33, 41] is another commonly used approach. It assumes that R_1 is known and solves x and y in terms of R_1 from (2.33). The least squares solution of (2.29) is then used to find the R_1 and hence, x and y. Since R_1 is assumed to be constant in the first step, the degree of freedom to minimize the second norm of the error vector, ψ , used in the solution is reduced [37]. The solution obtained is therefore suboptimal as demonstrated in [34, 35].

Spherical-Interpolation Method: Another approach called the spherical-interpolation (SI) method [34, 35, 41], first solves x and y in terms of R_1, then inserts the intermediate result back into (2.33) to generate equations in the unknown R_1 only. Substituting the computed R_1 values that minimize the LS equation error to the intermediate result produces the final result. One drawback to the SI method is its inability to produce a solution if the number of unknowns is equal to the number of equations based on the TDOA estimates, which may occur in certain situations. The SI method was shown in [34] to provide an order of magnitude greater noise immunity than the SX method. Although the SI performs better than the SX method, it assumes the three variables x, y and R_1 in (2.33) to be independent and eliminates R_1 from those equations. Consequently, the solution is suboptimal because this relationship is ignored. The method proposed by Friedlander and the SI method have been shown in [32] to be mathematically equivalent.

Divide-and-Conquer Method: A Divide and Conquer (DAC) method, proposed by Abel [42], consists of dividing the TDOA measurements into groups, each having a size equal to the number of unknowns. Solution of the unknowns is calculated for each group, then appropriately combined to provide a final solution. Although this method can achieve optimum performance, the solution uses stochastic approximation and requires that the Fisher information be sufficiently large. The Fisher information matrix (FIM) is the inverse of the Cramér-Rao Matrix Bound (CRMB)(i.e.(FIM)=$(CRMB)^{-1}$) [25]. The estimator provides optimum performance when the errors are small, thus implying a low-noise threshold in which the method deviates from the CRLB. This method requires an equal number of range difference measurements in each group, and as a result, the TDOA estimates from the remaining sensors cannot be used to improve accuracy.

Taylor-Series Method: Another method to obtain precise estimate at reasonable noise levels is the Taylor-series method [30, 31]. The Taylor-series method linearizes the set of equations in (2.30) by Taylor-series expansion, then uses an iterative method to solve the system of linear equations. The iterative method begins with an initial guess and improves the estimate at each iteration by determining the local linear least-square (LS) solution. The Taylor-series can provide accurate results and is robust. It can also make use of redundant measurements to improve the PL solution. However, it requires a good initial guess and can be computationally intensive. For most situations, linearization of the nonlinear equations does not introduce undue errors in the position location estimate. However, linearization can introduce significant errors when determining a PL solution in bad geometric dilution of precision (GDOP) situations. GDOP describes a situation in which a relatively small ranging error can result in a large position location error because the mobile is located on a portion of hyperbola far away from both receivers. It has been shown by Bancroft [43] that eliminating the second order terms can lead to significant errors in this situation. The effect of linearization of hyperbolic equations on the position location solution is also explored by Nicholson in [44, 45].

Fang's Method: For arbitrarily placed base stations and a consistent system of equations in which the number of equations equals the number of unknown source coordinates to be solved, Fang [46] provides an exact solution to the equations of (2.33). However, his solution does not make use of redundant measurements made at additional receivers to improve position location accuracy. Furthermore, his method experiences an ambiguity problem due to the inherent squaring operation. These ambiguities can be resolved using *a priori* information or through the use of symmetry properties. Unlike the algorithms mentioned previously, this method provides a closed form and exact solution and it is also computationally less intensive than the Taylor-series method.

Chan's Method: A non-iterative solution to the hyperbolic position estimation problem which is capable of achieving optimum performance for arbitrarily placed sensors was proposed by Chan [37]. The solution is in closed-form and valid for both distant and close sources. When TDOA estimation errors are small, this method is an approximation to the maximum likelihood (ML) estimator. Chan's method performs significantly better than the SI method and has a higher noise threshold than the DAC method before the performance deviates from the Cramér-Rao lower bound. Furthermore, it provides an explicit solution form that is not available in the Taylor-series method. It is also better than Fang's method as it can take advantage of redundant measurements like the Taylor-series method. However, it needs *a priori* information to resolve an ambiguity in its calculations like the Fang's method.

Conclusions: In the light of the above discussion, it is concluded that the methods that can be practically used for solving hyperbolic equations are the Taylor-series method, Fang's method and Chan's method. Among these, Fang's and Chan's methods provide a closed form exact solution which is not available with the Taylor-series method and also are computationally less intensive. The Taylor-series method also carries the risk of converging to a local minimum if given a bad starting 'seed'. On the other hand, the Taylor-series and Chan's method can make use of any redundant measurements, if occasionally available. It will be shown later in this section that the ambiguities in Fang's and Chan's algorithms are not a problem in cellular-type systems. The mathematical procedures for these three algorithms follow.

Mathematical Procedure for the Taylor-Series Method

The iterative Taylor-series method begins with an initial guess and improves the estimate at each iteration by determining the local linear least-square (LS) solution. With a set of TDOA estimates, the method starts with an initial guess (x_0, y_0) and computes the deviations of the position location estimation

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = (\mathbf{G}_t^T \mathbf{Q}^{-1} \mathbf{G}_t)^{-1} \mathbf{G}_t^T \mathbf{Q}^{-1} \mathbf{h}_t, \tag{2.34}$$

where

$$\mathbf{h}_t = \begin{bmatrix} R_{2,1} - (R_2 - R_1) \\ R_{3,1} - (R_3 - R_1) \\ \vdots \\ R_{M,1} - (R_M - R_1) \end{bmatrix}$$

$$\mathbf{G}_t = \begin{bmatrix} [(X_1 - x)/R_1] - [(X_2 - x)/R_2] & [(Y_1 - y)/R_1] - [(Y_2 - y)/R_2] \\ [(X_1 - x)/R_1] - [(X_3 - x)/R_3] & [(Y_1 - y)/R_1] - [(Y_3 - y)/R_3] \\ \vdots & \vdots \\ [(X_1 - x)/R_1] - [(X_M - x)/R_M] & [(Y_1 - y)/R_1] - [(Y_M - y)/R_M] \end{bmatrix}$$

and $\mathbf{Q}$ is the covariance matrix of the estimated TDOAs. The values R_i for $i = 1, 2, \ldots, M$ are computed from (2.29) with $x = x_0$ and $y = y_0$. In the next iteration, x_0 and y_0 are set to $x_0 + \Delta x$ and $y_0 + \Delta y$. The whole process is repeated until Δx and Δy are sufficiently small, resulting in the estimated PL of the source (x, y). The Taylor-series method can provide accurate results, however, it requires a close initial guess (x_0, y_0) to guarantee convergence and can be computationally intensive.

Mathematical Procedure for Fang's Method

For a 2-D hyperbolic PL system using three base stations to estimate the source location (x, y), Fang establishes a coordinate system so that the first base station (BS) is located at $(0, 0)$, the second BS at $(x_2, 0)$ and the third BS at (x_3, y_3). Realizing that for the first BS, where $i = 1$, $X_1 = Y_1 = 0$, and for the second BS, where $i = 2$, $Y_2 = 0$, the following relationships are simplified

$$\begin{aligned} R_1 &= \sqrt{(X_1 - x)^2 + (Y_1 - y)^2} = \sqrt{x^2 + y^2} \\ X_{i,1} &= X_i - X_1 = X_i \\ Y_{i,1} &= Y_i - Y_1 = Y_i. \end{aligned}$$

Using these relationships, the equation of (2.33) can be rewritten as

$$\begin{aligned} 2R_{2,1}R_1 &= R_{2,1}^2 - X_i^2 + 2X_{i,1}x \\ 2R_{3,1}R_1 &= R_{3,1}^2 - (X_3^2 + Y_3^2) + 2X_{3,1}x + 2Y_{3,1}y. \end{aligned} \tag{2.35}$$

Equating the two equations (2.35) and simplifying results in

$$y = g * x + h, \tag{2.36}$$

where

$$\begin{aligned} g &= \{R_{3,1} - (X_2/R_{2,1}) - X_3\}/Y_3 \\ h &= \{X_3^2 + Y_3^2 - R_{3,1}^2 + R_{3,1} * R_{2,1}(1 - (X_2/R_{2,1})^2)\}/2Y_3. \end{aligned}$$

Substituting equation (2.36) into the first equation in (2.35) results in

$$d * x^2 + e * x + f = 0, \tag{2.37}$$

where

$$\begin{aligned} d &= -\{(1 - (X_2/R_{2,1})^2) + g^2\} \\ e &= X_2 * \{(1 - (X_2/R_{2,1})^2)\} - 2g * h \\ f &= (R_{2,1}^2/4) * \{(1 - (X_2/R_{2,1})^2)\}^2 - h^2. \end{aligned}$$

Solving the quadratic equation (2.37), we get two values for x. Using *a priori* information, one of the values is chosen and is used to find out y from (2.36).

However, it turns out that this ambiguity is not a problem in cellular-type systems. It has been found by simulations in this research that one of the roots of (2.37) which is $\frac{-e+\sqrt{e^2-4df}}{2d}$ always results in x values which give mobile's position estimates that are well beyond the cell coverage area. Hence for position location in cellular/PCS systems we only need to evaluate the following root from (2.37)

$$x = \frac{-e - \sqrt{e^2 - 4df}}{2d}. \tag{2.38}$$

As stated earlier, putting this value of x in (2.36) will give us the other coordinate of the mobile's position estimate.

Mathematical Procedure for Chan's Method

Following Chan's method [37], for a three base station system (M=3), producing two TDOA's, x and y can be solved in terms of R_1 from (2.33). The solution is in the form of

$$\begin{bmatrix} x \\ y \end{bmatrix} = - \begin{bmatrix} X_{2,1} & Y_{2,1} \\ X_{3,1} & Y_{3,1} \end{bmatrix}^{-1} \times \left\{ \begin{bmatrix} R_{2,1} \\ R_{3,1} \end{bmatrix} R_1 + \frac{1}{2} \begin{bmatrix} R_{2,1}^2 - K_2 + K_1 \\ R_{3,1}^2 - K_3 + K_1 \end{bmatrix} \right\}, \tag{2.39}$$

where

$$\begin{aligned} K_1 &= X_1^2 + Y_1^2 \\ K_2 &= X_2^2 + Y_2^2 \\ K_3 &= X_3^2 + Y_3^2. \end{aligned}$$

When (2.39) is inserted into (2.29), with $i = 1$, a quadratic equation in terms of R_1 is produced. Substituting the positive root back into (2.39) results in the final solution. There may exist two positive roots from the quadratic equation that can produce two different solutions, resulting in an ambiguity. This problem has to be resolved by using *a priori* information.

As was seen for Fang's algorithm, simulations in this work have shown that one of the roots of the quadratic equation in R_1 almost always gives negative values for R_1, which is not possible. In some rare cases when that root does give positive numbers, the numbers are too large and are well above the cell radius, which is again not possible. Hence, when the quadratic equation in R_1 is obtained in the form

$$aR_1^2 + bR_1 + c = 0, \tag{2.40}$$

only the following root should be considered for cellular PL.

$$R_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}. \tag{2.41}$$

An interesting observation that was made while studying the ambiguities in the Fang's and Chan's algorithms was that both these ambiguities are essentially the same. It was seen that if we make wrong choices in both algorithms for a given case then the wrong results given by both algorithms are identical.

In [37], Chan and Ho present a version of their algorithm that can take advantage of redundant measurements (four or more sensors for a 2-D system). The simulation results in [37] show that this method clearly either outperforms or performs at least as well as other algorithms in all cases and approaches the CRLB. Chang and Ho also give another version of their algorithm for the case when the receivers are arranged in a linear fashion and show that it is mathematically equivalent to Carter's beam forming method [29].

When Chan's method is compared with other two algorithms considered, it is seen that it is the best choice for solving the hyperbolic equations. It is an exact solution and is better than the Taylor-series method which is iterative and has the risk of convergence to local minima. When compared with Fang's method, we see that it can take advantage of redundant measurements, if available, whereas Fang's method cannot. Hence, it is concluded that Chan's method is the best available option for solving hyperbolic equations for wireless E-911.

2.4 TDOA Techniques in CDMA Systems

Different wireless systems offer different advantages and trade-offs for TDOA position location method. CDMA is advantageous for TDOA PL in some aspects but also has some drawbacks to it. Study of the application and different issues faced by TDOA techniques in CDMA is important because CDMA seems set to become the dominant multiple access technology for wireless personal communications systems within the foreseeable future.

2.4.1 Advantages in CDMA

The most obvious advantage of CDMA for TDOA techniques is that CDMA Interim Standard-95 (IS-95) [47] is a wideband system when compared with other standards like Advanced Mobile Phone Service (AMPS), IS-136 or Global System for Mobile communications (GSM). This is because a key limitation of conventional cross-correlation is that the time resolution of the TDOA estimate, in the presence of multipath, is limited to approximately $1/B$, where B is the bandwidth of the received signal [48]. For example, when receiving a 1 MHz signal, the time delays can only be resolved to within 1μs or within 300 meters. In this respect, IS-95 is the most well suited standard among all the standards in use nowadays, as it is the most wideband of all.

However, it will be shown in section 4.4, that the accuracy can be further increased by increasing the sampling rate of the incoming signal. This happens because as the sampling rate increases, the quantization error in timing estimates decreases [8], which results in more accurate TDOA measurements.

Another advantage of CDMA standard is its inherent multipath rejection capability. For any PL system to be practical, it must be able to resolve different multipath components. If we use only the earliest arriving signal components for cross-correlation, we can minimize the timing errors due to multiple signal reflections. Hence, CDMA is most suitable here as it not only resolves but takes advantage of different multipath components by employing a rake receiver on both links.

2.4.2 Disadvantages in CDMA

The single biggest problem that the TDOA method faces in CDMA is the power control operation of the IS-95 standard. To achieve maximum capacity, it is crucial for the CDMA systems that all the signals must be received at approximately the same power levels [49]. Hence the IS-95 standard uses open loop and closed loop power control mechanisms to keep the power levels from the mobiles constant at the base station. In practice the power levels are distributed with a variance of 1 to 2 dB around the desired mean [50].

Hence, when a mobile is closer to its controlling base station, it transmits at a lower transmit power than a mobile farther away from the base station. As a result, for the mobile that is closer to the base station, its signal is received at a very low power at the other two base stations participating in the TDOA PL. This happens because of the simultaneous effects of increased path loss and reduced transmit power. Hence, the Signal to Noise Ratio (SNR) at the other base stations drops rapidly as the mobile comes closer to its home cell site. This results in poor PL accuracy when the mobile is close to the controlling base station. This effect will be explored in detail in section 4.5.

Another problem that the TDOA method faces in CDMA systems is that the signals of all users are spectrally and temporally overlapping. Hence, it is not possible to use generalized or cyclic cross-correlation techniques to find the desired user's peak at the cross-correlation output among the peaks of other users. The method proposed in this work to solve this problem is discussed in 3.7.1.

2.5 Measures of Position Location Accuracy

The most commonly used measure of PL accuracy is the comparison of the mean square error (MSE) of the position location solution to the theoretical MSE based on the Cramér-Rao Lower Bound (CRLB). Another commonly used measure of PL accuracy is the Circle of Error Probability (CEP). The effect of the geometric configuration of the base stations on the accuracy of the position location estimate is measured by the Geometric Dilution of Precision (GDOP). A simple relationship exists between the GDOP and CEP measures.

In this work we also propose a new measure of accuracy which is more suitable for CDMA systems. It is explained in 2.5.4.

2.5.1 Comparison of MSE with CRLB

A commonly used measure of accuracy of a PL estimator is the comparison of the mean squared error (MSE) of the PL solution to the theoretical MSE based on the Cramér-Rao Lower Bound on the variance of unbiased estimators. The classical method for computing the MSE of a 2-D position location estimate is

$$MSE = \varepsilon = \mathbf{E}[(x-\hat{x})^2 + (y-\hat{y})^2], \tag{2.42}$$

where (x, y) are the coordinates of the source and $(\hat{x}, \hat{y})$ is the estimated position of the source. The Root-Mean Square (RMS) position location error, which can also be used as a measure of PL accuracy, is calculated as the square root of the MSE

$$RMS = \sqrt{\varepsilon} = \sqrt{\mathbf{E}[(x-\hat{x})^2 + (y-\hat{y})^2]}. \tag{2.43}$$

To gauge the accuracy of the PL estimator, the calculated MSE or RMS PL error is compared to the theoretical MSE based on the Cramér-Rao Lower Bound (CRLB). The conventional CRLB sets a lower bound for the variance of any unbiased parameter estimator and is typically used for a stationary Gaussian signal in the presence of stationary Gaussian noise [20]. For non-Gaussian and nonstationary (cyclostationary) signals and noise, alternate methods have been used to evaluate the performance of the estimators [20]. The derivation of the CRLB for Gaussian noise is provided in [21, 24, 25, 37]. The CRLB on the PL covariance is given by Chan [37] as

$$\mathbf{\Phi} = c^2(\mathbf{G}_t^T\mathbf{Q}^{-1}\mathbf{G}_t)^{-1}, \tag{2.44}$$

where $\mathbf{G}_t$ is defined in (2.34) with $(x, y, R_i) = (x^0, y^0, R_i^0)$, which are the actual coordinates of the source and the range of the first base station to the source, and matrix $\mathbf{Q}$ is the TDOA covariance matrix. The sum of the diagonal elements of $\mathbf{\Phi}$ defines the theoretical lower bound on the MSE of the PL estimator. Matrix $\mathbf{Q}$ may not be known in practice; however, if the noise power spectral densities are similar at the receivers, it can be replaced by a theoretical TDOA covariance matrix with diagonal elements of σ_d^2 and $0.5\sigma_d^2$ for all other elements, where σ_d^2 is the variance of the TDOA estimate [37].

2.5.2 Circular Error Probability

A crude but simple measure of accuracy of position location estimates that is commonly used is the circular error probability (CEP) [30, 31]. The CEP is a measure of the uncertainty in the location estimator relative to its mean. For a 2-D system, the CEP is defined as the radius of a circle which contains half of the realizations of the random vector with the mean as its center. If the position location estimator is unbiased, the CEP is a measure of the uncertainty relative to the true transmitter position. If the estimator is biased and bound by bias B, then with a probability of one-half, a particular estimate is within a distance B + CEP from the true transmitter position. Figure 2.2 illustrates the 2-D geometrical relations.

The CEP is a complicated function and is usually approximated. Details of its computation can be found in [30, 31]. For hyperbolic position location estimator, the CEP is approximated with an accuracy within approximately 10 % as

$$CEP \approx 0.75\sqrt{\sigma_x^2 + \sigma_y^2}, \tag{2.45}$$

where σ_x^2 and σ_y^2 are the variances in the estimated position [31].

2.5.3 Geometric Dilution of Precision

The accuracy of range-based PL systems depends to a large extent on the geometric relationship between the base stations and the source to be located. One measure that quantifies

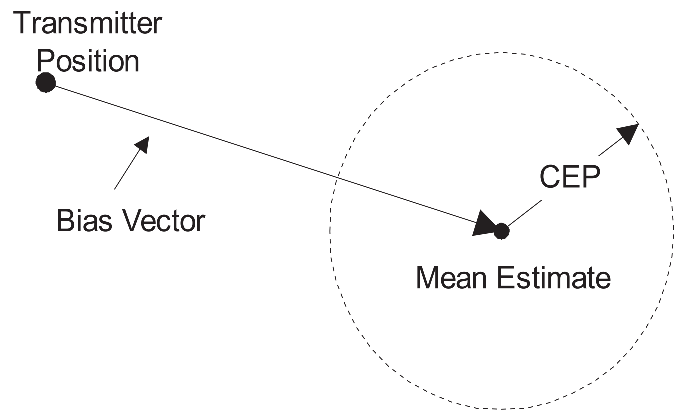

Figure 2.2: Circle of Error Probability

the accuracy based on this geometric configuration is called the geometric dilution of precision (GDOP) [31, 43, 51, 52, 53, 54]. The GDOP is defined as the ratio of the RMS position error to the RMS ranging error. The GDOP for an unbiased estimator and a 2-D hyperbolic system is given by [31, 52] as

$$\begin{aligned} GDOP &= \left(\sqrt{(c\sigma_x)^2 + (c\sigma_y)^2}\right) \Big/ \sqrt{(c\sigma_s)^2} \\ &= \left(\sqrt{\sigma_x^2 + \sigma_y^2}\right) \Big/ \sigma_s, \end{aligned} \tag{2.46}$$

where $(c\sigma_s)^2$ is the mean squared ranging error and $(c\sigma_x)^2$ and $(c\sigma_y)^2$ are the mean square position errors in the x and y estimates. The GDOP is related to the CEP by

$$CEP \approx (0.75\sigma_s)GDOP. \tag{2.47}$$

The GDOP can be used as a criterion for selecting a set of base stations from a large set whose measurements produce minimum PL estimation error or for designing base station locations within new systems.

2.5.4 The New Proposed Measure of Accuracy

The most commonly used measure of position location accuracy is Root-Mean-Square (RMS) error. This is because of the fact that this measure makes it easy to visualize the amount of inaccuracy in PL and also because it is straight forward to compare it with the CRLB. In most of the position location applications this works quite well. The reason is that the error in the TDOA estimates grows steadily with the increase in the levels of background noise and interference and with the diminishing power of the received signal.

However, we encounter quite a different situation in Direct-Sequence CDMA (DS CDMA) systems. The main problem encountered here is that if we use the composite received signals to determine the TDOAs by simple cross-correlation, then there is no way to find out the cross-correlation peak belonging to the desired user. Hence, the method adopted in this work is to first find the placement and polarity of the bits of the desired user in the snap shots of the incoming composite signal and then to replace those portions of the composite received signal with the respread bits having appropriate polarity. When we cross-correlate versions of received signals in this way, we only get one peak belonging to the desired user. This method is explained in more detail in 3.7.1. However, it is clear that the correct estimation of TDOA in this procedure depends on correct estimation of the transmitted bits. Any wrong bit decisions produce bad respread replacement in the composite signal. As a result, the TDOA estimates are off by huge amounts whenever enough bits go wrong. Hence, errors in TDOAs don't increase gradually with increasing noise and interference but increase dramatically whenever enough bits go bad. Hence, PL estimates may be off by as much as a few kms, whenever, there are errors in TDOA estimation. Therefore, any PL accuracy measure that is based on mathematical mean would portray a very dismal picture of the performance, although, the system might be very accurate most of the time.

Hence, for DS-CDMA systems, this measure of quality is not suitable. Therefore, we propose another simple measure of accuracy which shows the percentage of times the error is less than any particular threshold. This type of accuracy measure is not affected by occasional big errors. It is also very suitable for accuracy measurement of wireless E-911, because the FCC requirement is also stated in terms of the percentage of times the error has to be less than a particular figure.

Figures 2.3 and 2.4 demonstrate this point. Both these figures present the same result of a simulation which shows increased PL error with increased levels of thermal noise. This simulation measured the accuracy of position fixes at different levels of E_b/N_0. However, Fig 2.3 uses RMS PL error whereas Figure 2.4 uses the new measure of accuracy using the FCC error threshold of 125 m. The RMS error representation gives a pathetic impression of the results, as the RMS error is in tens of kms. However, the new measure shows that the performance is actually quite reasonable and meets the FCC requirement for E_b/N_0 values above about 11 dBs.

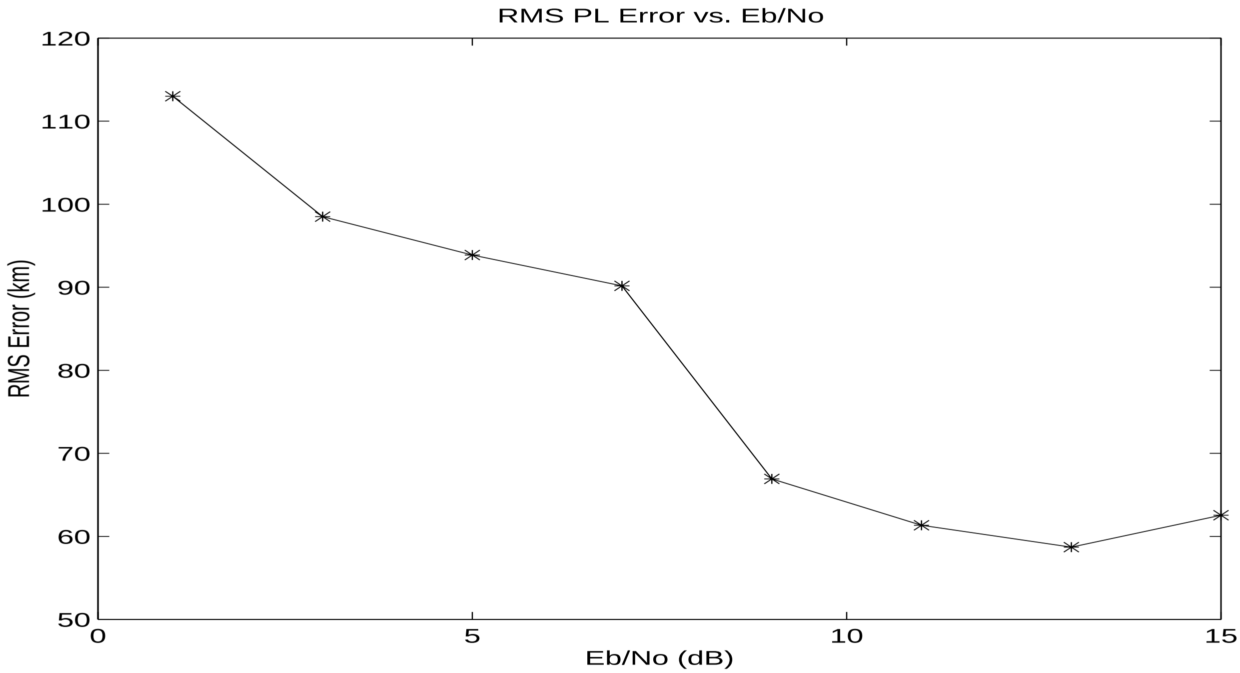

Figure 2.3: Performance Measure in terms of RMS Error

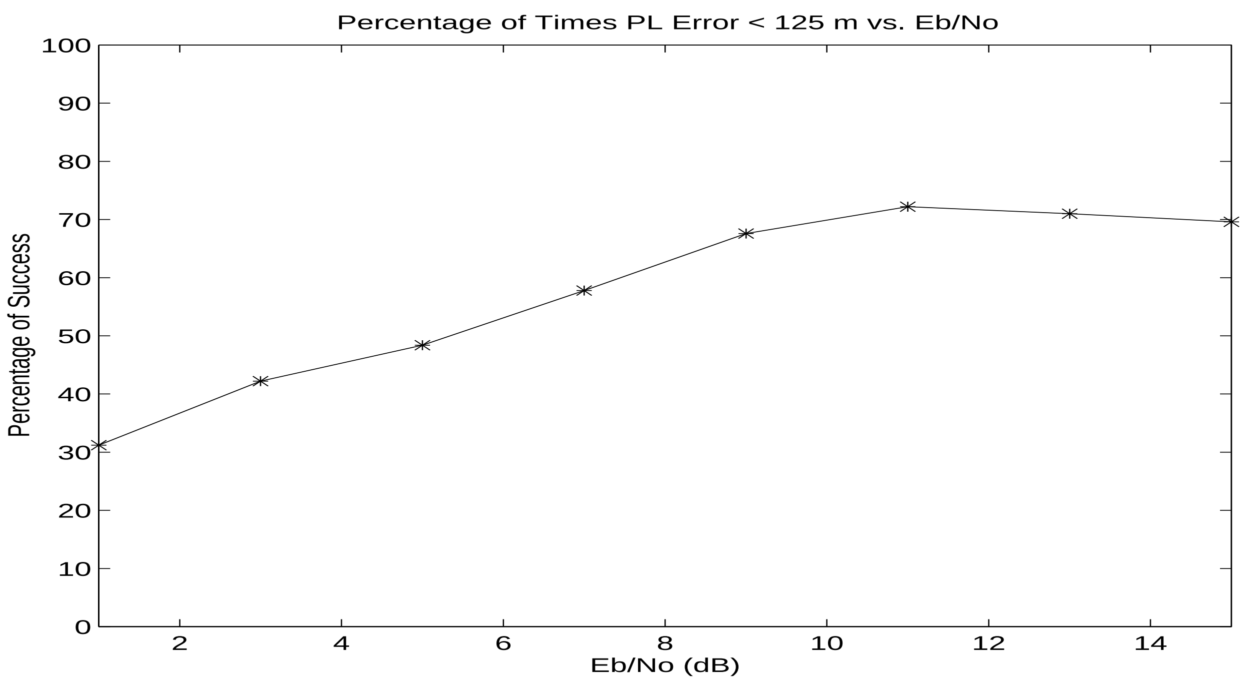

Figure 2.4: Performance Measure in terms of Percentage of Success

2.6 Chapter Summary

In this chapter, we have extensively covered different aspects of the TDOA technique for position location. We first made a comparison of this technique with other PL techniques for application in wireless E-911 and concluded that it is the most suitable method for implementing E-911.

Later, the two stages involved in the TDOA PL procedure were studied in detail. Different methods of cross-correlation for finding TDOAs were presented. Advanced cross-correlation techniques such as generalized cross-correlation and cyclic cross-correlation methods were discussed. Different types of filters proposed for generalized cross-correlation were surveyed. After that, we looked at the techniques that are used to solve the hyperbolic equations resulting from the TDOA estimates. A comparison of all the methods with each other was made and algorithms that appeared most practical were studied in more detail. It was shown that the method presented by Chan is the most suitable for implementation in wireless E-911.

Then, we discussed the relative merits and demerits of TDOA PL when used in CDMA systems. After that, we presented different measures of accuracy used for judging the performance of PL systems. In the end, we proposed a measure of accuracy which is very suitable for TDOA PL accuracy measurement in CDMA systems and is consistent with FCC requirement.

Chapter 3

Simulation Models

3.1 Introduction

In this Chapter, we describe the simulation modeling used for the results generated in this work. We first discuss the general structure of the control flow in the simulation programs. Then, we look at different aspects of the CDMA reverse link simulation and the simplifying assumptions. This includes the spreading codes used for spreading the users' signals and the power control assumptions. Then, we discuss the ways in which we have simulated different channel environments including the large-scale and small-scale fading simulations. We also discuss the interference cancellation techniques which have been used in some of the simulations.

After that, we discuss the position location method of this work and the way it has been implemented. This consists of a discussion of the cross-correlation technique and the algorithm used for solving the hyperbolic equations. We introduce in detail the cross-correlation method that we are proposing for use in CDMA systems and also an improved version of that technique.

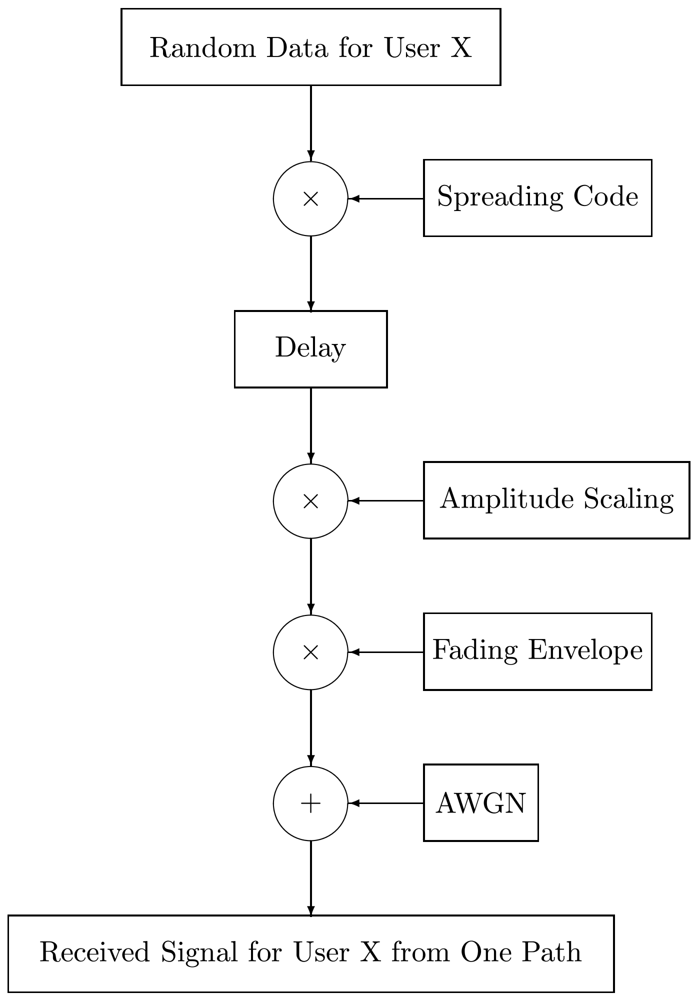

Figure 3.1: Simulation Flow for the Signal of a Single User

3.2 General Structure of the Simulations

In what follows, we describe the general flow of the control in the simulation programs. At first, random binary data is generated for different users and is spread using the spreading codes of respective users. The length of the data is set according to the desired length of the snap shot for TDOA PL. This is done for all users in all of the cells.

We then calculate the signal delays and attenuations experienced by each user's signal for each base station, depending on the distance of the user and the path loss model being used. The spread and sampled signals of the users are accordingly delayed and scaled. Additive White Gaussian Noise (AWGN) is added to the signals depending on the desired E_b/N_0. If the simulation assumes a frequency selective fading channel, then the multipath components are created and are scaled according to the Doppler spectra depending on the velocity of the user. Figure 3.1 shows this procedure for a single user resulting in the received signal estimate for one of the multipath components. Then, we compose the received signal at each base station by incoherently adding the versions of all the components of signals from all the users, for that base station, as shown in Figure 3.2.

After all the received signals have been computed, we begin the process of identifying the data of the desired 911 user. Since that signal is very weak at the neighboring base stations, we employ interference cancellation at those base stations in some of the simulations discussed in 5.6. This is done to study the improvement obtained, when we subtract the signals belonging to the own-users of any neighboring cell which is participating in the PL process, to receive a better version of the 911 user's signal from the cell containing that user.

Once the data bits for the desired user are identified, they are respread to form the snap shot so that the snap shot now consists of only the desired user's spread signal. Then, we perform the cross correlation and subsequently get the hyperbolic equations. Using the hyperbolic equation solving algorithms, we get the PL estimate of the 911 user. This process is shown in Figure 3.3. In the figure, the controlling base station is referred to as BS#1 and the other two as BS#2 and BS#3.

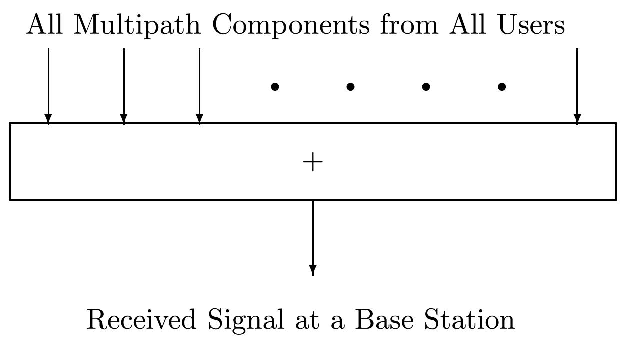

Figure 3.2: Composition of Received Signal at Base Stations

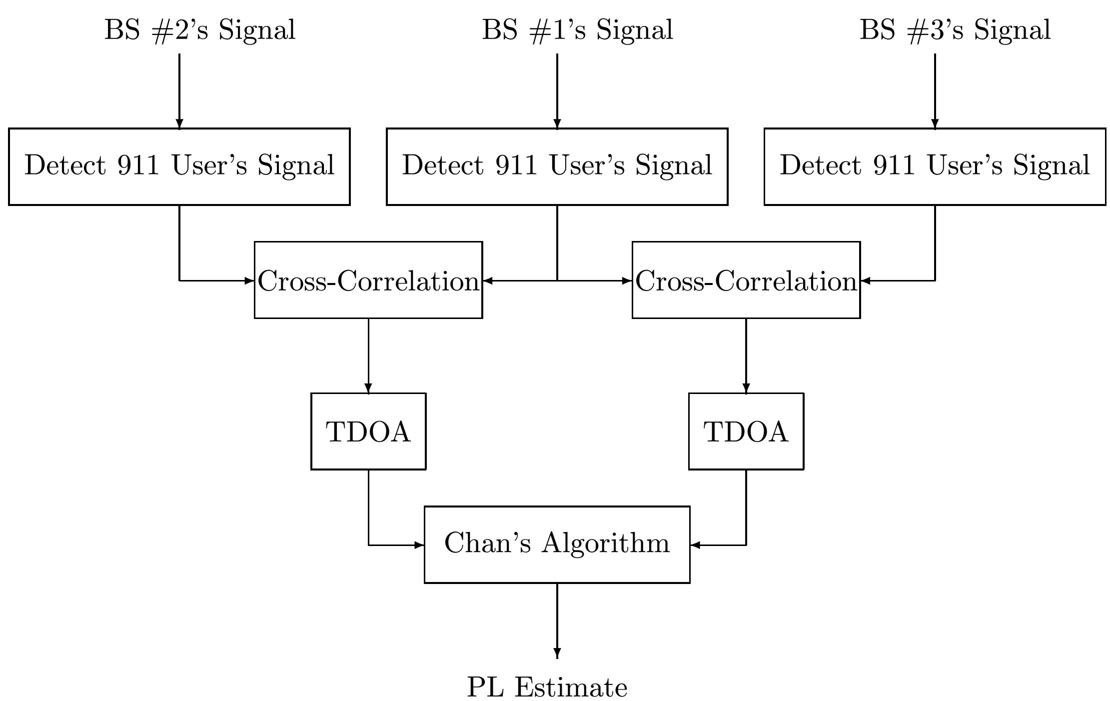

Figure 3.3: The Position Location Calculation Process

3.3 Reverse Link System Model

In this section, we describe the way we have modeled the reverse link for the PL process. Since, the TDOA method does not require any information from the forward link, we are only concerned with the reverse link. Most of the parameters used conform with the IS-95 CDMA cellular standard [47].

The base station configuration used for the simulation is based on a hexagonal cellular layout as shown in Figure 3.4.

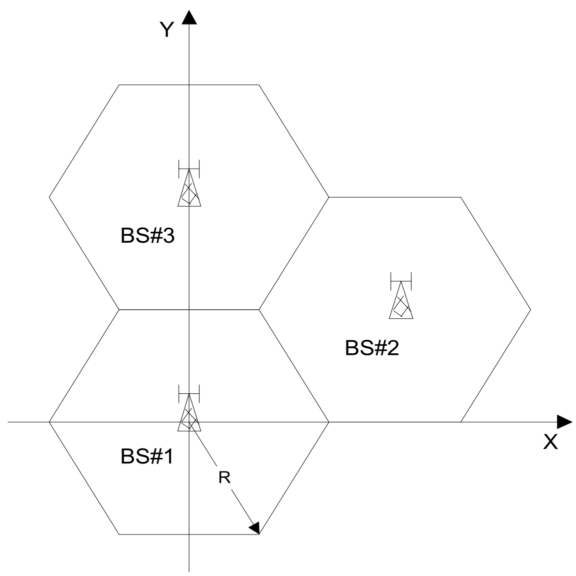

Figure 3.4: Three Base Station Configuration

A major radius of 5 km is used for all simulations which is typical of macrocellular environments. The base stations and mobile unit are assumed to be coplanar. It is assumed that the controlling base station is the one having the shortest distance from the mobile unit. The mobile unit transmitter is modeled as a DS/SS transmitter. It is assumed that the mobile unit uses a half-wave dipole antenna with unity gain. The center frequency of the reverse link channel is assumed to be at 900 MHz and a bandwidth of 1.2288 MHz is used.

The base station receiver model used is the DS/SS receiver model and it is assumed that each base station is utilizing an omni-directional isotropic antenna with unity gain. Throughout, it is assumed that all base station clocks are perfectly synchronized using a common reference. Consequently, relative clock drift and bias is assumed to be zero. This is a realistic assumption as the CDMA cellular systems use the GPS signals for synchronization and clocks used in GPS are extremely accurate as the main application of GPS is itself highly accurate position location. Perfect acquisition and synchronization of the users' PN code is also assumed along with assuming a perfect phase tracking.

3.3.1 Spreading Codes

The long PN spreading sequence used in IS-95 CDMA cellular standard introduces a processing gain of N = 4 chips/symbol after the 1/3 rate convolutional encoder and the 64-ary orthogonal modulator introduces a processing gain of N = 32. As a result, the IS-95 system introduces a total processing gain of N = 128. Hence, in all the simulations we have used a processing gain of N = 128.

However, we haven't used any specific type of code generating scheme and have simply used random spreading codes. It has been found [55] that codes which have been randomly generated perform almost as well as many other types of pseudo-random codes that have elaborate generating schemes such as gold codes or small and large Kasami codes. Hence, it was concluded that the use of random spreading codes would be a good approximation of the spreading codes actually used in IS-95.

3.3.2 Power Control

In some of the simulations, the effect of using higher transmit power for the 911 user is studied. In those cases, we have given a gain of some desired value to the 911 user's signal, while all other users' signals have been kept at the same level. In some other simulations, we have simulated imperfect power control and the method used for simulating that is described along with the results in 5.2. Apart from these cases, perfect power control is assumed in all other cases so that the total received power of each user on the receiving antenna at the base station is the same, thus eliminating the near-far effect. However, the power control only compensated for the path loss and not for the Rayleigh fading effects.

3.3.3 Rake Receiver

The IS-95 CDMA cellular standard uses a four-finger rake receiver at the base station for exploiting the multipath diversity. Rake receivers make use of the signal energy in the multipath components and are able to maximize the Signal-to-Noise Ratio (SNR) of the signal by coherently combining signal energies from the LOS and multipath components. Figure 3.5 shows the general structure of a rake receiver used in CDMA systems.

In accordance with the IS-95 standard, the rake receiver simulated in this work had four fingers and maximal ratio combining was used to form the decision statistic.

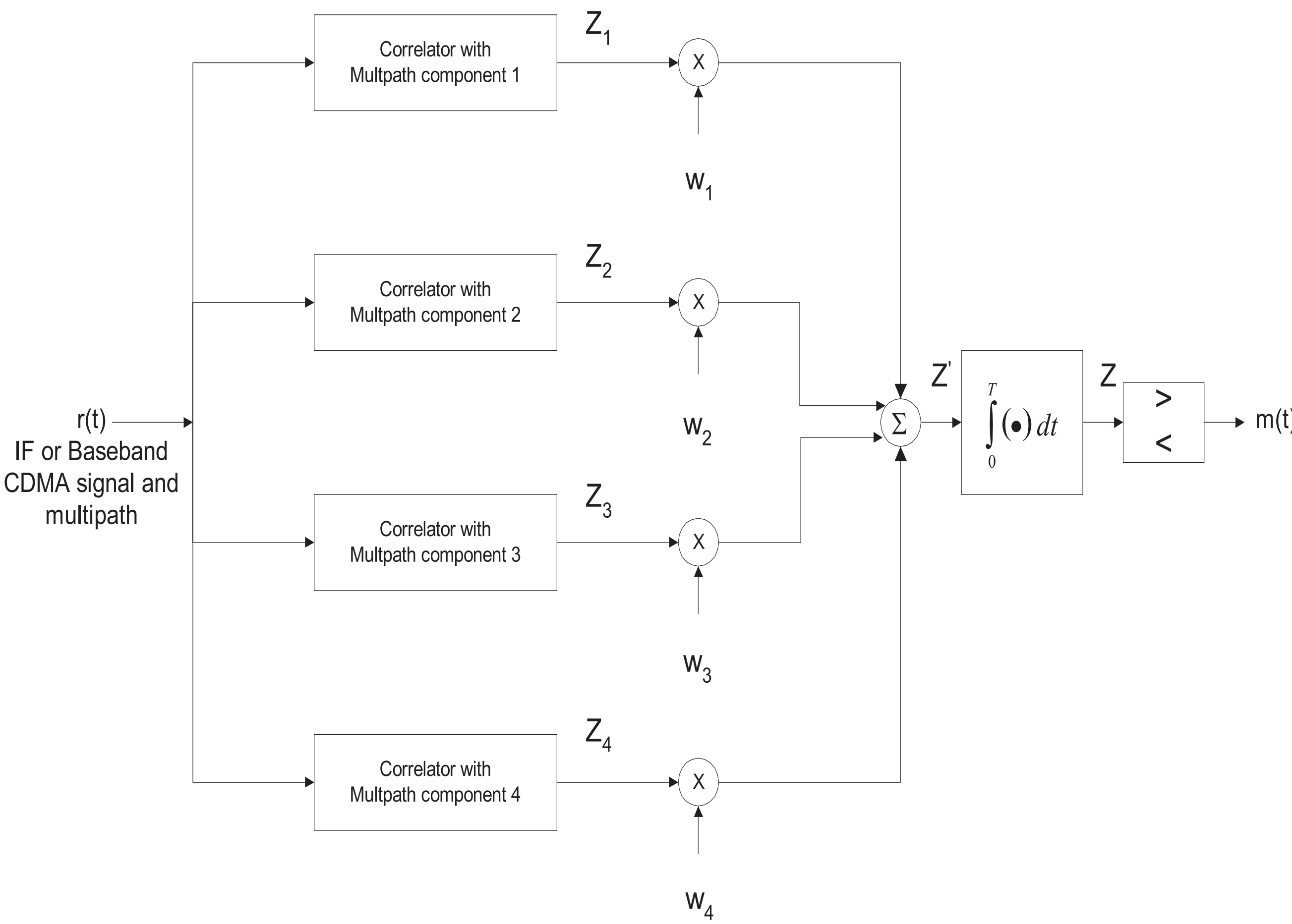

Figure 3.5: General Implementation of a Rake Receiver

3.4 Selection of Mobile Positions

It has been assumed that the RF channel is symmetrical in all directions. Because of this assumption, mobile positions used in the simulations have only been generated in a particular zone of the cell which is shown in Figure 3.6. The figure shows that the area of the controlling base station can be divided into twelve zones. Assuming hexagonal cell layout and a symmetrical channel, any one of these zones can be used to represent the performance in the entire cell. This would result in reduced redundancy in measurements and the simulations would converge to the results with less number of points.

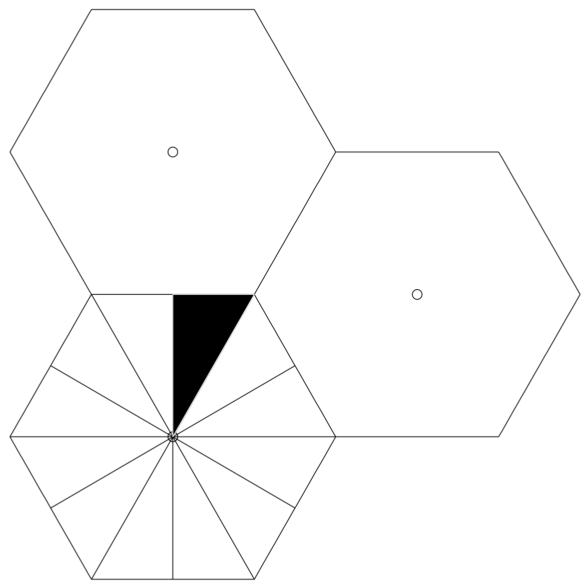

Figure 3.6: The Area of the Main Cell Used for Mobile Positions in the Simulations

This is done in simulations, where results averaged over the entire area of the cell were needed. Hence, for such cases, we need to generate random positions for the mobile which are uniformly distributed in the zone shown in figure 3.6. Hence, following equations were derived to generate X and Y coordinates so that the density of mobile positions generated is uniform throughout the zone of interest. Equation (3.1) was used to generate the X-coordinate of the mobile position:

$$x = \frac{R}{2}(1 - \sqrt{U}), \tag{3.1}$$

where R is the major radius of the cell and U is a random variable uniformly distributed in the interval $0 < U < 1$. The other coordinate is calculated using the following equation:

$$y = \sqrt{3}x + V, \tag{3.2}$$

where x is the value of X-coordinate as calculated from (3.1) and V is a random variable uniformly distributed in the range

$$0 < V < \sqrt{3}\left(\frac{R}{2} - x\right),$$

where as before, x is the X-coordinate from (3.1) and R is the major radius of the cell.

Other than the simulations which measured performance as a function of mobile position, all other simulations used equations (3.1) and (3.2) to generate uniformly distributed mobile positions.

One exception was the study of the effects of linear cellular arrangement in 4.6. Figure 3.7 shows the geometry and the area used to generate the mobile positions for such a cellular layout. This type of layout is of interest because many cellular systems are designed to provide coverage along highways.

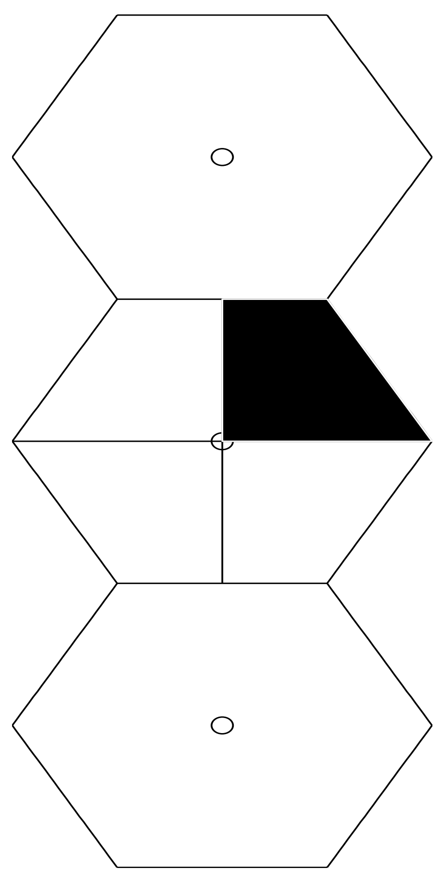

Figure 3.7: The Area of the Main Cell Used in the Linear Cellular Pattern

The same basic principle was used in this case also. It can be shown that the four sections of the main cell can each be individually representative of the entire cell performance, if the RF channel is spatially symmetric.

3.5 Channel Modeling

In this section, we explain the method used to simulate the path loss effect, the generation of AWGN, and the simulation of frequency selective fading.

3.5.1 Path Loss Model

For calculating the path loss values in this work, we have used the well-known Hata model. The Hata model [56] is an empirical formulation of the graphical data provided by Okumara [57], and is valid from 150 MHz to 1500 MHz. Hata presented the urban area propagation loss as a standard formula and supplied correction equations for application to other situations. The standard formula for median path loss in urban areas is given by:

$$L_{50}(urban)(dB) = 69.55+26.16log_{10}(f_c)-13.82log_{10}(h_t)-a(h_r)+\left[44.9 - 6.55log_{10}(h_t)\right] log_{10}(d), \tag{3.3}$$

where f_c is the frequency in MHz, h_t is the height of the base station antenna in m, h_r is the height of the mobile antenna in m, d is the T-R separation distance in km and $a(h_r)$ is the correction factor for effective mobile antenna height:

$$a(h_r) = (1.1log_{10}(f_c) - 0.7)h_r - (1.56log_{10}(f_c) - 0.8). \tag{3.4}$$

To obtain the path loss in a suburban area, the standard Hata formula in (3.3) is modified as:

$$L_{50}(dB) = L_{50}(urban) - 2\left[log_{10}(f_c/28)\right]^2 - 5.4. \tag{3.5}$$

As mentioned previously, our value for f_c is 900 MHz. We are assuming the base station antenna height, h_t, to be 10 m and the mobile antenna height, h_r, to be 1 m.

3.5.2 Generating AWGN

In all of the simulations, zero-mean additive white Gaussian noise is added to the users' signal to simulate the effect of thermal and background noise and the noise in the receivers. To add noise according to the desired level of E_b/N_0, we have used the method described in [58], a brief description of which follows.

In the simulation of digital communications systems, the SNR is commonly evaluated as E_b/N_0, where E_b is the transmit energy per bit and N_0 is a function of the noise power spectral density. The energy per bit in terms of the transmit signal power is given as

$$E_b = P_s T_{bit}, \tag{3.6}$$

where T_{bit} is the duration of a bit and P_s is the signal power at the receiver input. Because of the coding gain, N, provided by the Pseudo-Noise (PN) spreading sequence and the sampling of the signal by N_s, the energy is spread over many more symbols. The noise power, assuming a AWGN channel with two-sided power spectral density of $N_0/2$, is given by

$$\sigma_n^2 = \frac{N_0}{2}. \tag{3.7}$$

Based on these assumptions, we get the variance of each noise sample to be

$$\sigma_n^2 = \frac{A^2 N N_s}{2E_b/N_0}, \tag{3.8}$$

where A is the amplitude of the user's signal. In our simulations, we have used unity signal power which results in $A = 1$. Therefore, the noise power for a given E_b/N_0 is calculated using

$$\sigma_n^2 = \frac{N N_s}{2E_b/N_0}. \tag{3.9}$$

Hence, zero-mean Gaussian noise samples with variance given by (3.9) are added to the signals of all the users.

3.5.3 Frequency Selective Fading Model

For wideband signals, such as in CDMA, the channel bandwidth is usually considerably smaller than the signal bandwidth. This leads to frequency selective fading which introduces inter symbol interference (ISI) in the time domain. As a result, the received signal will consist of multiple copies of the original signal, which are attenuated and time delayed. Each component of the signal is itself composed of many specular components which add together with different phases. In the absence of a powerful LOS carrier, it can be shown that the envelope of this fading for any component follows a Rayleigh distribution [59]. Additionally, the rate at which a signal varies (known as the coherence time of the channel) is inversely related to the Doppler spread of the channel.

The method used to generate the fading envelopes for the multipath components is taken from [60]. This method exploits Gan's model for the Doppler power spectrum [61]. Gans showed that for an omni-directional antenna with a gain of 1.5, the Doppler spectrum of the received signal can be modeled by:

$$S_{E_Z}(f) = \frac{1.5}{\pi f_m \sqrt{1 - \left(\frac{f - f_c}{f_m}\right)}}, \tag{3.10}$$

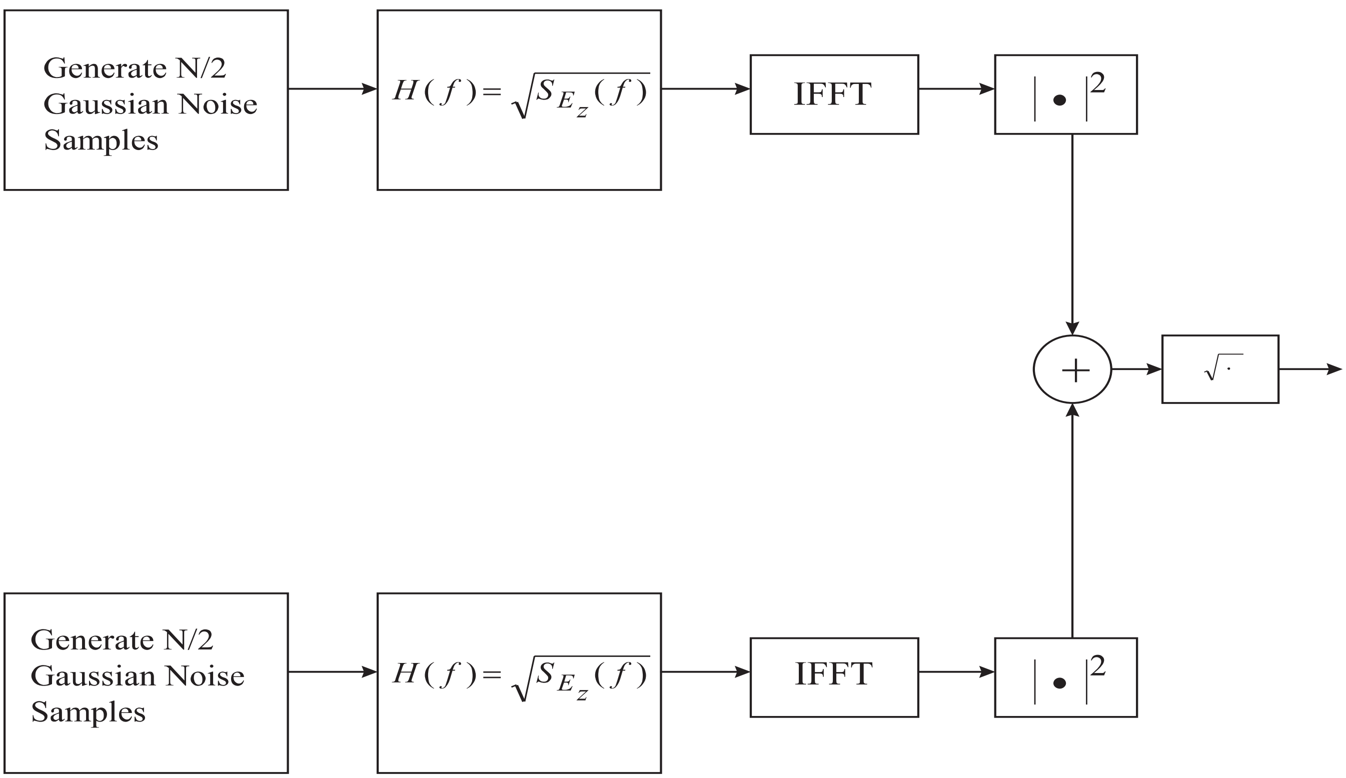

Figure 3.8: Rayleigh Fading Simulator

where f_c is the center frequency and f_m is the maximum Doppler spread. The maximum Doppler spread can be found by:

$$f_m = \frac{v}{\lambda}, \tag{3.11}$$

where v is the velocity of the transmitter and λ is the wavelength of the center frequency f_c. Using the model in (3.10) for the Doppler spectrum, we can simulate a Rayleigh fading envelope by first generating independent complex Gaussian noise samples and filtering them using a Doppler shaped filter defined by $H(f) = \sqrt{S_{E_Z}(f)}$ as shown in Figure 3.8. The filter outputs are then inverse Fourier transformed. After taking the absolute value, each stream is squared and summed to provide the Rayleigh fading envelope. This envelope is then applied to the simulated signal. This method is done for all the components of the signals from all the users.

3.6 Interference Cancellation

The foremost problem facing reliable TDOA position location is the hearability of the 911 user's signal at the neighboring base stations. One feasible method to solve this problem is to use multiuser receivers that have the ability to reduce the Multiple Access Interference (MAI) to increase the SNR of the required signal at those base stations.

In some of the results in 5.6, we have studied the effect of using and not using the interference cancellation at the neighboring base stations. In those simulations, we have used one stage of parallel interference cancellation to reduce MAI for the desired user's signal at the base stations other than the controlling one.

Different methods for implementing parallel interference are available. In this work, we have simulated the use of matched filters at the first stage for the estimation. This allows a single estimate (the matched filter output) to be used for both the data symbol and the channel gain and alleviates the need for any outside estimates. While more robust receivers could be used in the first stage to improve performance, this approach is the most straightforward and allows reasonable complexity.

Mathematically, we can represent the decision metric for an S-stage parallel cancellation scheme as

$$\hat{\mathbf{b}} = \mathrm{sgn}\left[\mathbf{y}_{\mathrm{I}}^{(\mathrm{S})}\cos(\boldsymbol{\Theta}) + \mathbf{y}_{\mathrm{Q}}^{(\mathrm{S})}\sin(\boldsymbol{\Theta})\right], \tag{3.12}$$

where

$$y_{I_j}^{(s)} = \frac{1}{T}\int_{(i-1)T+\tau_k}^{iT+\tau_k} \hat{r}_{I_k}^{s}(t)a_k(t-\tau_k)dt \tag{3.13}$$

$$y_{Q_j}^{(s)} = \frac{1}{T}\int_{(i-1)T+\tau_k}^{iT+\tau_k} \hat{r}_{Q_k}^{s}(t)a_k(t-\tau_k)dt \tag{3.14}$$

and

$$\hat{r}^s_{I_k}(t) = r_I(t) - \sum_{j \neq k} y_j^{s-1} a_j(t-\tau_j)\cos(\theta_j) \tag{3.15}$$

$$\hat{r}^s_{Q_k}(t) = r_Q(t) - \sum_{j \neq k} y_j^{s-1} a_j(t-\tau_j)\sin(\theta_j) \tag{3.16}$$

with $j = (i-1)K + k$ for the ith bit of the kth user and $\hat{r}^s_{I_k}(t)$ is the kth user's signal after $s-1$ stage of cancellation. This implementation requires the estimation, regeneration, and cancellation of each interferer from each of the desired users.

The analytical performance of this multistage parallel cancellation approach was derived in [62]. It was shown that in an AWGN channel the bit error rate of the receiver employing the standard Gaussian approximation for MAI at stage s is:

$$P_k^s(E) = Q\left(\left[\frac{1}{2E_b/N_o}\left(\frac{1-\left(\frac{K-1}{3N}\right)^s}{1-\frac{K-1}{3N}}\right) + \frac{1}{(3N)^s}\left(\frac{(K-1)^s-(-1)^s}{K}\frac{\sum_j P_j}{P_k} + (-1)^s\right)\right]^{-1/2}\right),$$

where K is the number of users and N is the processing gain.

The development of this equation assumes that $Z_{k,i}^{(s)}$ is an unbiased estimate of the $\sqrt{P_k}b$ at each stage. However, it was found that this is not the case [58]. Rather, $Z_{k,i}^{(s)}$ is biased particularly after the first stage of cancellation with the bias increasing with system loading. One method of alleviating this problem is to multiply the estimate by a back-off factor with a value in the range $[0, 1)$. This factor significantly reduces the bias at stage 2 and improves performance dramatically in heavily loaded systems. This back-off factor varies with both the stage of cancellation and the system loading. It is found that a factor of 0.5 in the first stage of cancellation is a good trade-off and results in performance improvements of an order of magnitude for loadings above $0.6N$ [63].

An expression that approximately gives us the optimal value for this Interference Reduction Factor (IRF), depending on the number of users and the spreading gain which is:

$$IRF = 0.95 - 0.48 \times \frac{k}{N}, \tag{3.17}$$

where k is the number of users and N is the spreading gain of the CDMA system. In most of our simulations, we are assuming up to 15 users in each cell and the IS-95 spreading gain is 128. Hence, from (3.17) we get a value of 0.86 for the interference reduction factor.

Another case, where interference cancellation has been applied is presented in 5.5. The reason is that one of the ways to enhance the reception of the 911 user's signal at neighboring base stations is to instruct the 911 mobile to transmit at a higher power level as it comes closer to the home cell site. Although, this will result in good reception at the neighboring cell sites, it will increase interference for other mobiles operating in the home cell and thus will cause performance degradation. In 5.5, we have studied the use of series interference cancellation to cancel out the strong 911 user in the case described, to salvage the performance of the system.

3.7 Position Location Method

The TDOA PL technique utilized in the simulations consisted of a cross-correlation TDOA estimator and the Chan's Algorithm for solving the hyperbolic equations.

3.7.1 Cross Correlation Method

As discussed in detail in 2.3.1, we cannot use specialized processors for generalized cross-correlation or cyclic cross-correlation techniques for finding the TDOA of the desired user in CDMA systems because the signals of all the users are temporally and spectrally overlapping and exhibit the same periodic frequencies.

Hence, we cannot simply cross-correlate the received composite CDMA signals at any two base stations as it would give us multiple peaks for different paths of different users.

The method adopted in this work uses the information obtained from the detected data bits of the desired user. At first, snap shots are taken at all the base stations at a synchronized time period like any ordinary cross correlation mechanism. Once the snap shots are taken, bit periods belonging to the 911 user are identified in the snap shot using the timing information of the earliest arriving component. This can be accomplished by using the information from the rake receiver finger which leads in time from the other two fingers. This should not be a problem because the position location process starts when a call is identified as being a 911 call and since the call is already in progress, the receiver is already synchronized with the incoming signal. However, we would use the information from the other fingers of the rake receiver to improve our bit estimate, as is the usual detection process of maximal ratio combining.

Once the sign of a bit and its location within the snap shot is identified, we replace that portion of the snap shot by the respread version of that bit. This is done with all the bits. Incomplete bits in the beginning and the end of the snap shot can also be appropriately worked on by using the continuous information from the received bit stream from the receiver. After this process, the snap shot consists only of the spread signal of the desired user and the cross-correlation yields the TDOA of only that user.

However, in real systems, there may be small estimation errors, even in the absence of interference and thermal noise which are due to the uncertainty in the peak correlation estimation by the cross-correlation estimator. To simulate this effect we add TDOA estimation error to the TDOA output from the cross-correlator. These errors are modeled as zero-mean Gaussian noise added to the TDOA estimate. The standard deviation of this error has been kept at 10 ns in all the simulations in this work [37].

It is obvious that if our bit estimates are incorrect, then we would compose a bad snap shot and thus would increase the chance of having a wrong TDOA estimate. Hence, in this method, the performance of the TDOA PL method ties directly with the Bit Error Rate (BER) of the system. Any improvement in the received BER would result in a higher percentage of accurate TDOA estimates and accurate PL estimates.

Improved Cross Correlation Technique

One of the main characteristics of the cross-correlation method discussed above is that whenever errors occur in the TDOA estimates they occur in big amounts. In fact, it has been observed in this work that the magnitude of error in TDOA estimates is always in multiples of bit duration. The reason behind this is that we reconstruct the snap shot for the desired user using the decoded bits of that user from the original snap shot. If a wrong bit decision is made, then a whole portion of snap shot equal to one bit duration which has a number of chips equal to the spreading gain, is replaced with the wrong polarity. As a result, if such wrong replacements cause a cross-correlation error, the wrong peak occurs exactly at multiples of bit times away from where it should have been.

This will be true in almost every case when there is a TDOA estimation error. The only case when this may not happen will be when there are so many bits in error that there is absolutely no similarity between a pair of snap shots and the cross-correlation would yield a peak at any random place. However, this case will be very rare and can only happen for very short snap short lengths. Another reason is that the snap shot formed at the controlling base station will be good most of the time. This is because voice communication cellular systems usually operate at a typical BER of 10^{-3} and a snap shot has a maximum length of a few tens of bits. As a result, it is highly unlikely that there will be more than a couple of bits in error in a snap shot of length equal to a few tens of bits. As an example, if we assume a snap shot length of 12 bits which is equal to 1536 chips in length and assume the BER to be 10^{-3}, then the probability of more than one bit being in error is very low as can be found out using discrete Poisson distribution. If B is the number of bits in error, then the probability that more than one bit is in error is:

$$P(B > 1) \quad = \quad 1 - [P(B = 0) + P(B = 1)] \tag{3.18}$$

$$P(B > 1) = 1 - [C_{12}^{0}(1 - BER)^{12} + C_{12}^{1} BER \times (1 - BER)^{11}]. \quad (3.19)$$

Solving the above equation for a BER of 10^{-3}, yields a probability of 0.000065 which means that 99.99% of the time there will either be no error or just one bit in error in a snap shot of 12 bits. However, a lot of bits may go wrong for the snap shots at the neighboring base stations as the signal quality there, would be much poorer. But in almost all cases, there would exist enough correlation between the pairs of snap shots, so that the error in the TDOA estimates will follow the rule mentioned above.

Hence, we conclude that in an overwhelming majority of cases, the nature of error in TDOA estimates is predictable and thus we can devise a method to add corrections to eliminate those errors.

Correction Procedure: In the IS-95 CDMA system, the chip rate is 1.2288 Mcps and the spreading gain is 128, hence, the bit duration is about 104.16 μs. On the other hand the maximum possible value for a TDOA measurement between any two base stations (BS) is equal to the time it takes for the radio signal to travel between those two base stations. This TDOA estimate may occur when a mobile unit is very close to the controlling base station. In our case, the base stations are separated by a distance of 8.66 km (assuming a hexagonal layout with a major radius of 5 km). Hence the propagation time between any two BS which is also the maximum possible TDOA is 28.86 μs. This is much less than a bit duration which is 104.16 μs.

Hence, if we find a TDOA estimate that is higher than the maximum possible TDOA, then we can assume that there is an error in the TDOA estimate and can correct it by subtracting from it an appropriate multiple of the bit duration and reducing it to an amount within the maximum possible TDOA.

This method has been applied and the results have been presented in Chapter 6. It has been found that this correction gives us highly accurate results and manages to correct an overwhelming majority of TDOA measurements that were originally estimated incorrectly. The performance of TDOA technique with this enhancement is way above the FCC requirement for wireless E-911, as evidenced by the results given in Chapter 6.

3.7.2 Algorithm for Solving Hyperbolic Equations

Among the methods available for solving the hyperbolic equations obtained from the cross-correlation process, Chan's method was found to be the most suitable as discussed in 2.3.2. Hence, for our simulations we have used that method.

3.7.3 Measure of Position Location Accuracy

For most of our results, we have used the new measure of accuracy that we discussed in 2.5.4.

For any simulation, we count the number of times the PL error is within 125 meters and divide it by the total number of runs to get the percentage of times the error was below this threshold.

3.8 Chapter Summary

In this chapter, we described the simulation models for this work. We presented the general flow of control for the simulations and showed the relationship between different parts of the PL process. The reverse link simulation of IS-95 was discussed in detail and we mentioned different simplifying assumptions that were made and justified some of them in relation to the real situations. This included the discussion of spreading codes and the power control aspects of the reverse link. The simulation of rake receiver was described and the method used to simulate the mobile positions was discussed. The channel modeling strategy used in this work was explained which consisted of the method of generating AWGN, path loss model and frequency selective fading. It was mentioned that in some simulations, the system uses a single stage of parallel interference cancellation to enhance received signal at the neighboring base stations, whereas in some other simulations, we have used series interference cancellation to cancel out the 911 user when it is transmitting at a higher power.

Finally, we discussed the position location process simulation, including a detailed description of the new method proposed in this work for TDOA cross-correlation in CDMA and the possible improvement in this method for improved performance.

Chapter 4

General Results

4.1 Introduction

In this chapter, we present the results of the simulations to study some of the important issues that affect the position location accuracy in CDMA systems.

In section 4.2, we present the PL accuracies observed at typical E_b/N_0 values encountered in cellular environments. Later, we look at the effect of varying snap shot lengths on the PL accuracy and the dependence of PL error on the sampling rate of the system. With the help of the results obtained, we will try to suggest optimal value for the snap shot length. In section 4.5, we study the effect of decreasing distance from the home cell site on the PL performance. We also consider an atypical cellular layout and observe the performance degradation in section 4.6 and compare it with the performance in the typical layout patterns. Finally, we study the performance in flat fading and frequency selective fading channels and compare it to the performance in simple AWGN channels.

4.2 Effect of AWGN

To study the effects of AWGN level on the position location accuracy, simulations were performed at different noise levels. In these results, three base stations were used. Fifteen users were assumed to be active in each cell. A sampling rate of 8 samples per chip was used. Frequency of operation was 900 MHz. The snap shot for cross-correlations had a length of 12 bits which is equal to 1536 chips in IS-95. The bandwidth and chip rate also corresponded with that of IS-95. The TDOA estimation noise was kept at a standard deviation of 10 ns. The calculations were made at eight different values of E_b/N_0 from 1 dB to 15 dB. This range is around the typical values of operation for a CDMA system. At each value of E_b/N_0, position fixes were obtained while placing the mobile randomly at different locations within the cell. From the measurements, the PL error was calculated using the known original position of the mobile. To average out the difference in performance at different positions within the cell, 1000 random measurements were taken for each value of E_b/N_0. The results are presented in Figure 4.1.

As expected, the graph shows that the accuracy improves as the E_b/N_0 increases. The performance reaches the FCC requirement, once the E_b/N_0 goes above approximately 9 dB. This simulation does not include channel coding and hence the coding gain has not been accounted for. Hence, it is expected that the performance should be better in real systems and the requirement may be met at lower levels of E_b/N_0.

We also see that the improvement is much sharp at lower levels of E_b/N_0 and then becomes slower at higher values. The reason is that when the AWGN levels become insignificant the system performance becomes dependent only on the interference from other users. Since number of interferers for the 911 user is kept constant, hence, after a certain level the improvement in E_b/N_0 does not provide much gain in position location accuracy.

Based on the results of this simulation, the E_b/N_0 in many other simulations has been maintained at 10 dB.

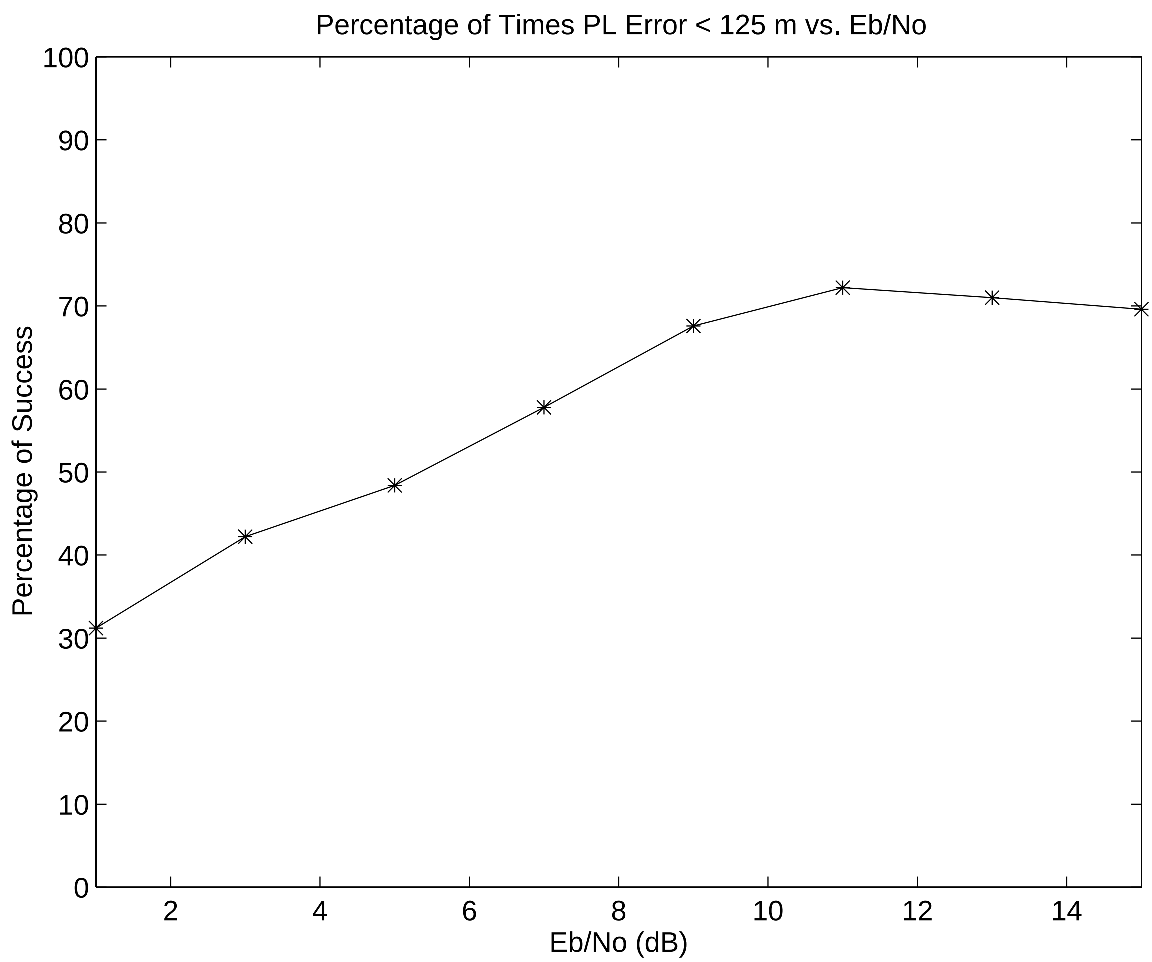

Figure 4.1: Position Location Performance at Different AWGN Levels (Sampling Rate = 8 samples per chip, Snap Shot Length = 12 bits, σ_d = 10 ns, 15 users per cell)

4.3 Length of the Signal Snap Shot

It is obvious that the length of the signal snap shot for TDOA PL process plays a very important role in determining the accuracy of the position fix. This is because as the snap shot lengths increase the cross correlation properties of the spreading codes become more strong and the effect of noise and interference becomes lesser. Hence, it is attractive to go for longer snap shot lengths. However, long observation windows would require more computational time and complexity for the cross-correlation process. Hence, the appropriate length would be a trade-off between these two factors. The right length should be short enough so that a number of position fixes may be obtained in little time and should be long enough to be able to smooth out the effects of noise and interference.

Another important factor is that we may not be able to get observation windows of arbitrary lengths in real systems. The reason is that the vocoder in IS-95 takes advantage of the gaps in voice activity to minimize interference and power consumption and transmits in bursts of data. One frame in IS-95 consists of 16 power control groups. Each frame has 192 bits and each power control group consists of 12 bits. However, as the voice activity is usually much less than 100 percent, fewer than full 16 power control groups are transmitted in any frame. For example, if the voice activity is 50%, then eight alternate groups will be transmitted instead of full sixteen power control groups. The relevance of this mechanism to position location becomes obvious when we consider the scenario that if we start snap shot at any power control group, then there is a substantial probability that the next groups may not be transmitted because of low voice activity. Hence, in the worst case we might get a snap shot of just 12 bits. However, in some cases we may be able to get a bigger multiple of 12.

To study the effect of different window lengths, we have simulated the process of position location for snap shots of different lengths. Like the previous simulation, we have used a three-cell configuration with fifteen users in each cell. Three curves have been drawn at different values of E_b/N_0 which are 5, 10 and 15 dB. A sampling rate of 8 samples per chip was used. For each point, 400 position location processes were executed at randomly selected mobile positions to average out the effect of mobile positions. The TDOA estimation error was set at a standard deviation of 10 ns. Snap shots of lengths 2, 4, 8, 16 and 32 were considered. These numbers correspond to 256, 512, 1024, 2048 and 4096 chips respectively. The reason for using exponentially increasing lengths will become obvious later when we will discuss the results which are presented in Figures 4.2 and 4.3.

We see in Figure 4.2 that initially as we increase the window length from 2 bits to 4 bits, we get substantial gain in the position location accuracy. However, as we go to further higher values of observation window lengths such as 16 bits or 32 bits, the gain in accuracy decreases. Hence, a window length of around 10 bits appears sufficient for PL accuracy and we do not gain much as we go to higher snap shot lengths. In the light of the previous discussion about frames and power control groups in IS-95, it is safe to say that a length of 12 bits for the observation window will be good enough for the TDOA position location. This corresponds to a window length of one power control group.

It is also observed that the accuracy increases linearly with an exponential increase in the observation window lengths. This becomes obvious in Figure 4.3 where we have drawn horizontal axis in logarithmic form.

The difference in the three curves for E_b/N_0 values of 5 dB, 10 dB and 15 dB confirms the results of the Figure 4.1, as the difference in performance is not so much when going from 10 dB to 15 dB as compared to the difference in performance between 5 dB and 10 dB.

In the light of the above observations, we have used an observation window length of 12 bits i.e. 1536 chips in all the other simulations.

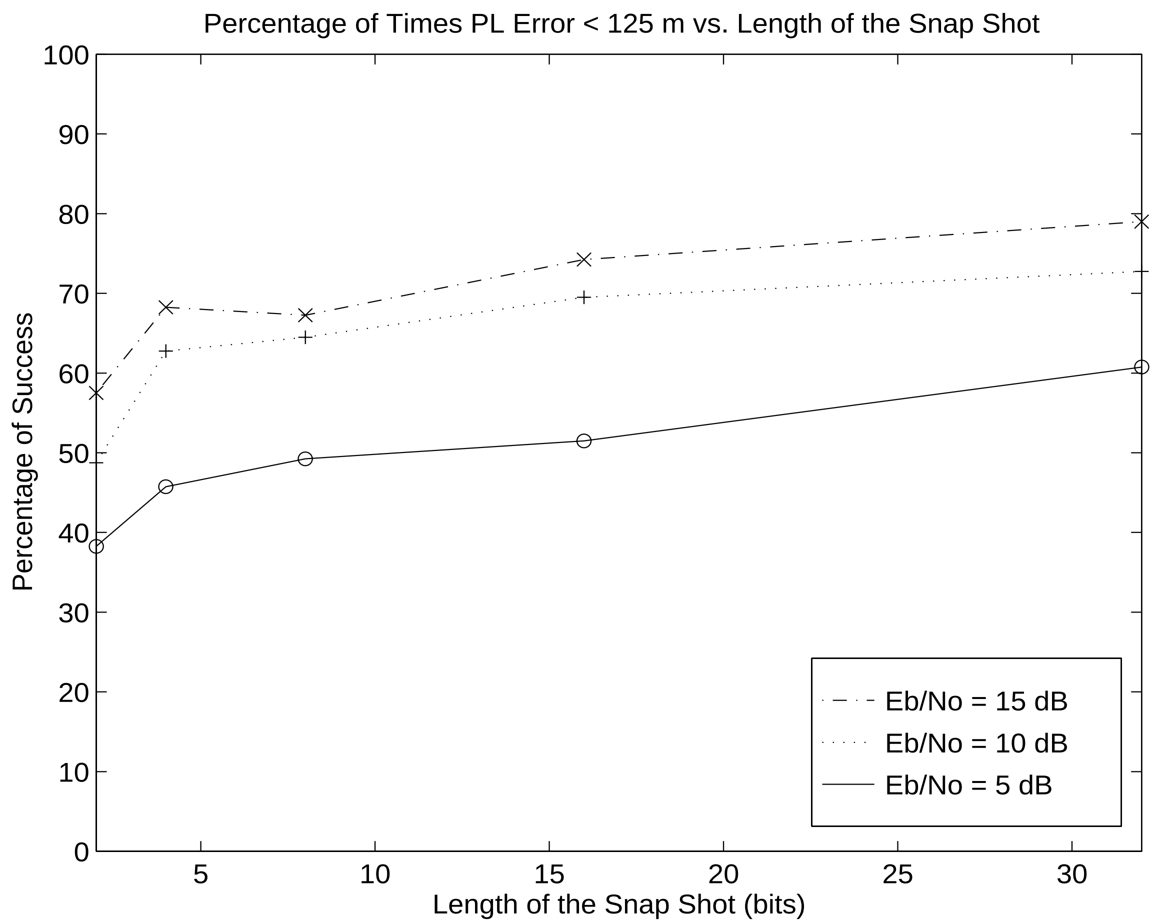

Figure 4.2: Position Location Performance with Different Snap Shot Lengths (Sampling Rate = 8 samples per chip, $\sigma_d = 10$ ns, 15 users per cell)

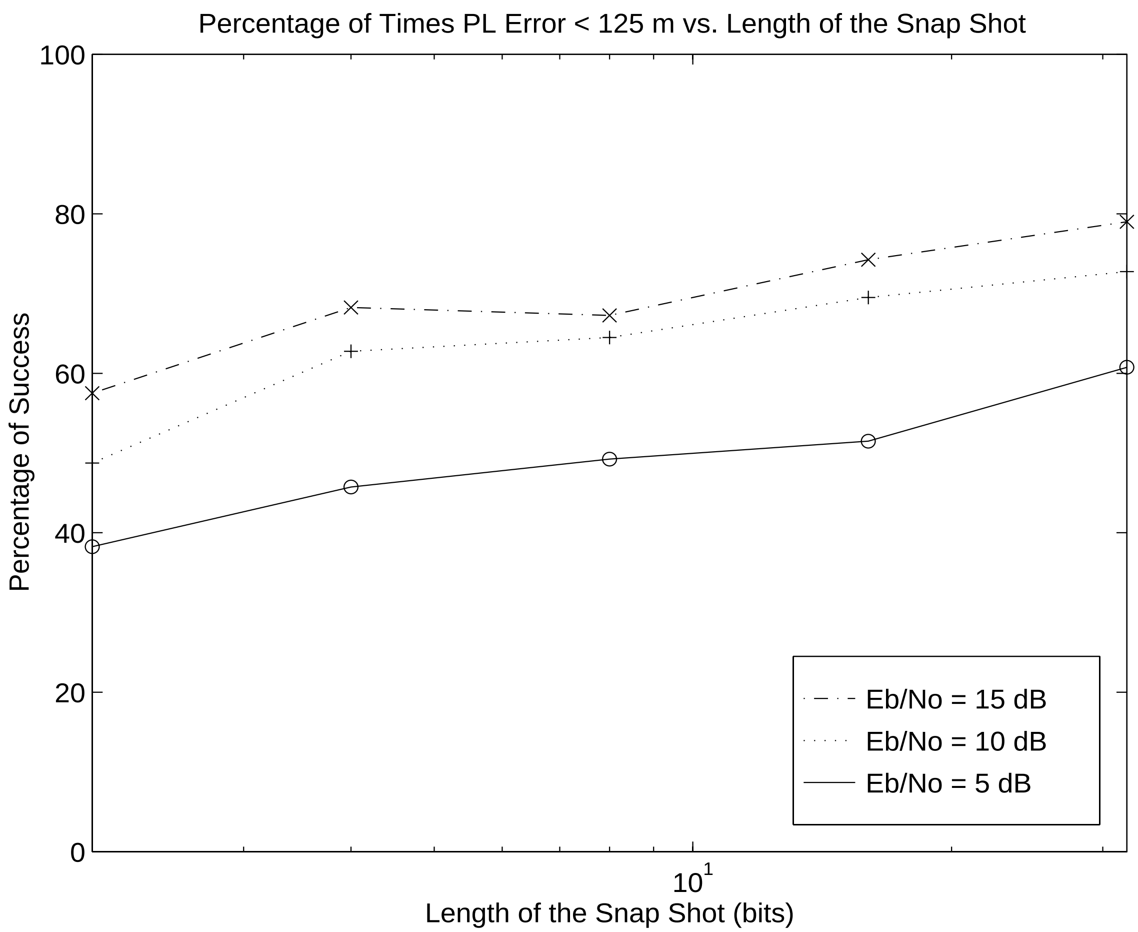

Figure 4.3: Position Location Performance with Different Snap Shot Lengths Shown with Logarithmic Axis (Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell)

4.4 Effect of the Sampling rate on TDOA Accuracy

In this section, we study the effect of the sampling rate of the receiver on the position location accuracy. The accuracy of the TDOA estimates which are calculated by cross-correlation procedures, depends on the sampling rate of the signals. Usually, the higher the bandwidth of the incoming signals the higher is the sampling rate of the system. However, even a signal with a comparatively narrow bandwidth can give more accurate TDOA estimates, if its sampling rate is increased. The reason is that as we increase the sampling rate of the system, the time quantization error in TDOA estimates decreases. Hence, wide-band systems such as CDMA that have a naturally higher sampling rate give more accurate position location results than systems with narrower bandwidths.

To get accuracy measurements at different sampling rates, simulations were performed at three different E_b/N_0 levels of 5, 10 and 15 dB. A window length of 12 bits was used in all cases. Like previous examples, a three-cell configuration with fifteen users in each cell is used. For each point in the results, 500 position location processes were executed at uniformly distributed random mobile positions to eliminate the effect of difference in performance at different mobile positions within the cell. Eight different sampling rates were considered ranging from 2 samples per chip to 16 samples per chip, in multiples of two. Results are presented in Figures 4.4 and 4.5.

Figure 4.4 shows the relationship of RMS PL error with the sampling rate. As we had discussed earlier in 2.5.4, the use of RMS PL error may not be a suitable criteria in the type of simulations performed in this work. However, to demonstrate the effect of increased sampling rate on the PL accuracy we have used that criteria in Figure 4.4. To avoid misleading results such as the ones shown in figure 2.3 as an example, here we have only considered "successful" position fixes by discarding extraordinarily large errors which place the mobile to be outside the cell area.

Figure 4.4 shows that if a successful fix is made, the RMS error of that fix depends on the sampling rate of the system with all other factors kept constant. As the sampling rate is increased, the RMS error decreases. As the sampling rate increases from 2 samples per chip to 16 samples per chip, the RMS error decreased from about 41 meters to 6 meters. We also see that the curves of all the three E_b/N_0 values are concurrent. This shows that provided the fix is obtained, the error is independent of the noise level. However, we see later in Figure 4.5, that the effect that increasing noise does produce, is to decrease the ratio of successful position fixes. Figure 4.5 also shows that the percentage of success is independent of sampling rate as long as the sampling rate is high enough to produce errors less than the threshold in the specified requirements. For example, these results show that even a sampling rate of 2 samples per chip for IS-95 is high enough to produce errors less than 125 m FCC requirement, provided that a "successful" position fix is made.

Summarizing the above discussion, we can say that to increase the percentage of success for a given threshold, we need to increase the SNR, provided that the sampling rate is high enough. And to decrease the error in the PL fix, we need to increase the sampling rate of the system.

In almost all of our simulations, we have used a sampling rate of 8 samples per chip. This rate is currently being used by the manufacturers producing the equipment used in the systems based on IS-95 [47].

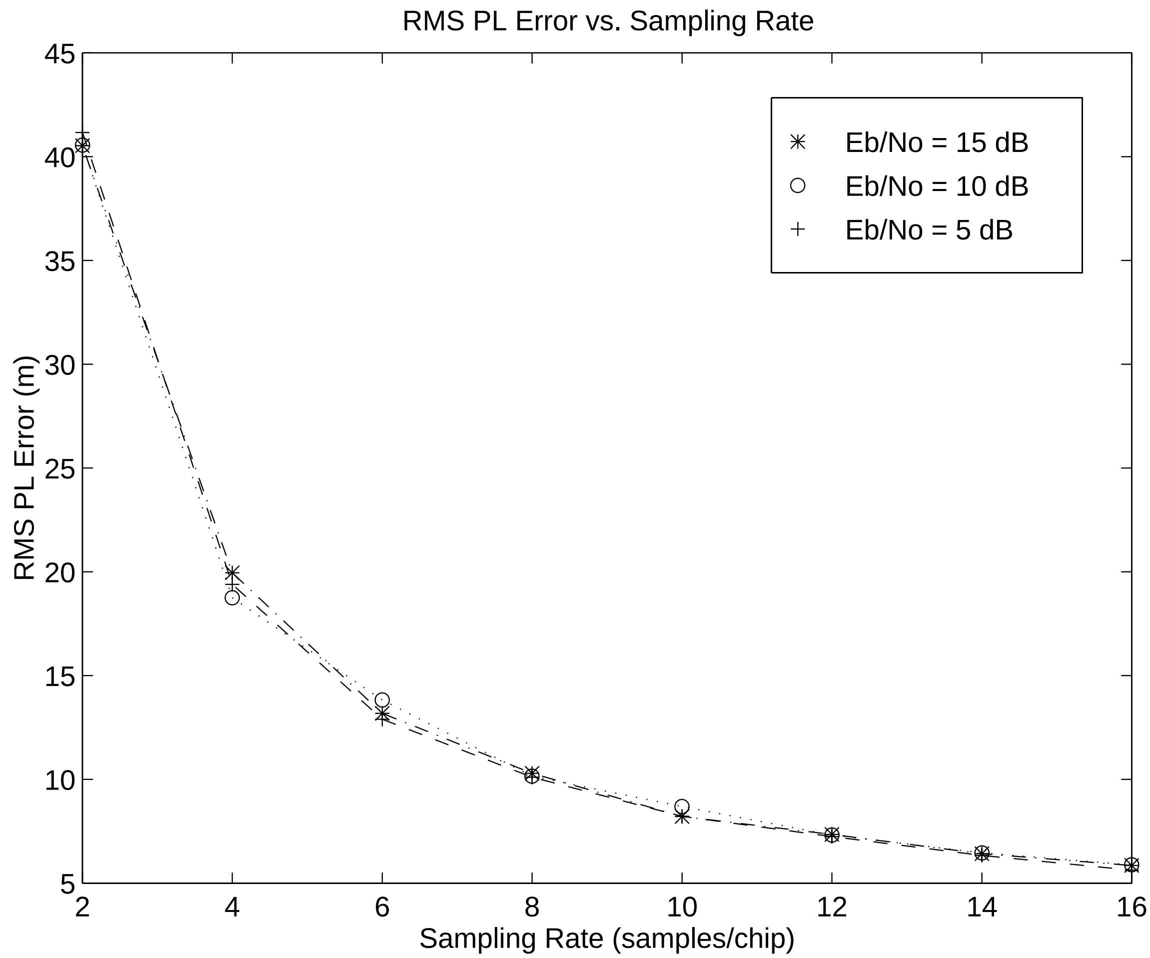

Figure 4.4: Dependence of RMS Error in Position Location on the Sampling Rate of the Receiver (PL errors above 1000 m have been discarded, Snap Shot Length = 12 bits, σ_d = 10 ns, 15 users per cell)

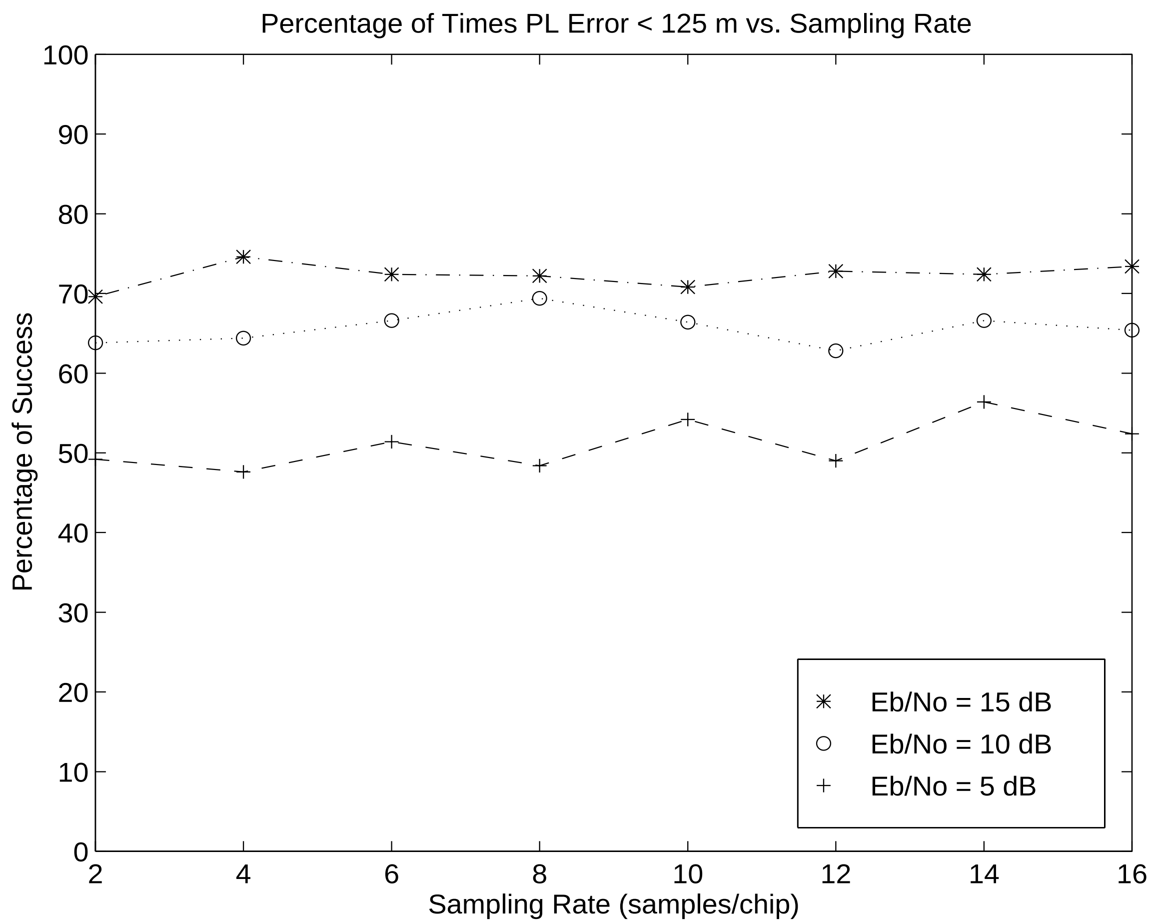

Figure 4.5: Position Location Performance at Different Sampling Rates in Terms of Percentage of Success (Snap Shot Length = 12 bits, σ_d = 10 ns, 15 users per cell)

4.5 Distance from the Base Station

In this section, we study the effect of the distance of the 911 mobile from the controlling base station. For this purpose, accuracy curves were plotted for distances ranging from the edge of the cell to a distance of 1 km from the cell site. Three curves were plotted at E_b/N_0 values of 5, 10 and 15 dB. A sampling rate of 8 samples per chip was used and a three base station configuration with 15 users per cell was used. An observation window length of 12 bits was used. At each point, 200 position location processes were executed. This simulation does not need as much averaging as the previous simulations because the distance from the cell site is being kept constant for a given point. Figure 4.6 shows the mobile positions for the simulation. Figure 4.7 shows the results of the simulation.

As seen previously, increased SNR results in better performance. However, the main feature of these results is that the performance degrades sharply as the mobile comes closer than about 60-70% the cell radius. As the mobile moves closer the ratio of successful fixes drops to a very low percentage. At very close locations, even an increase in the E_b/N_0 does not buy us much and the system performance drops to an unusable level. In other words, although the overall performance over the entire cell area may be satisfactory as we saw in figure 4.1 for an E_b/N_0 of 10 dB, the distribution of success percentage is highly non-uniform. The success percentage is near 100% at the cell boundary, whereas, it is below 10% at positions close to the cell site.

The main reason behind this phenomenon is the CDMA power control operation. As the mobile moves closer to the controlling base station, the base station instructs the mobile to decrease its transmit power gradually to keep its received power level at the base station to be equal with the other users' signal powers. This results in poor signal quality at the neighboring base stations which are also participating in the PL process. This affect is further aggravated by the fact that as the mobile moves closer to its home cell site, its distance from the other two base stations increases on the average, which translates to increased path loss. Hence, increased path loss and decreased transmit power act synergestically and result in poor performance for mobile positions close in to the home cell site.

This is one of the foremost problems faced by TDOA position location in CDMA systems as power control operation is one of the fundamental requirements for the success of CDMA cellular systems. A solution to this problem is vital for the applicability of this technique to CDMA. In the coming chapters, we'll propose methods to combat this affect. As we'll discuss in detail in 5.4, one of the obvious methods is to make the 911 mobile transmit at higher power levels than the other mobiles. In chapter 6, we'll see that this problem can also be solved by improved TDOA estimation.

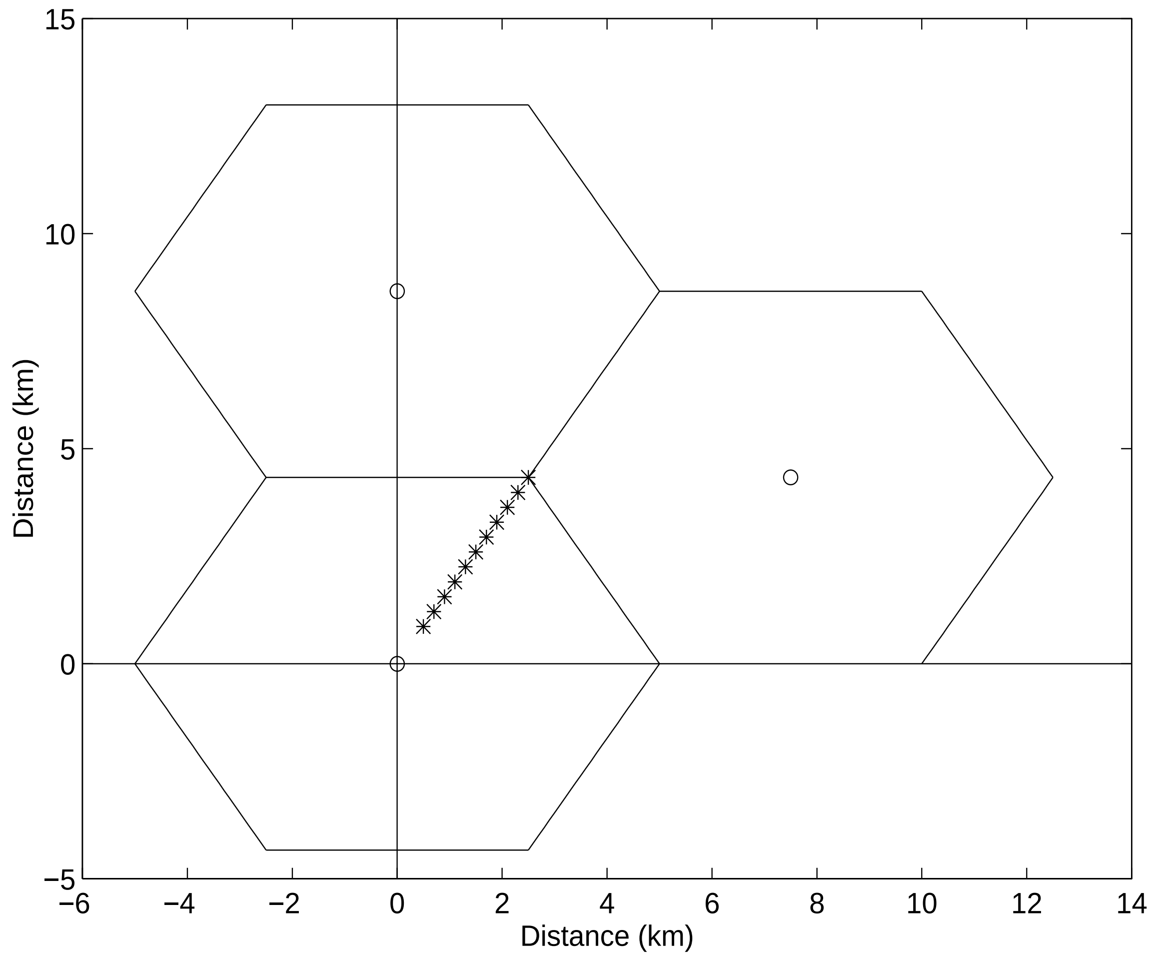

Figure 4.6: Mobile Positions Within the Home Cell Considered for Studying the Effect of Distance from Base Station on PL

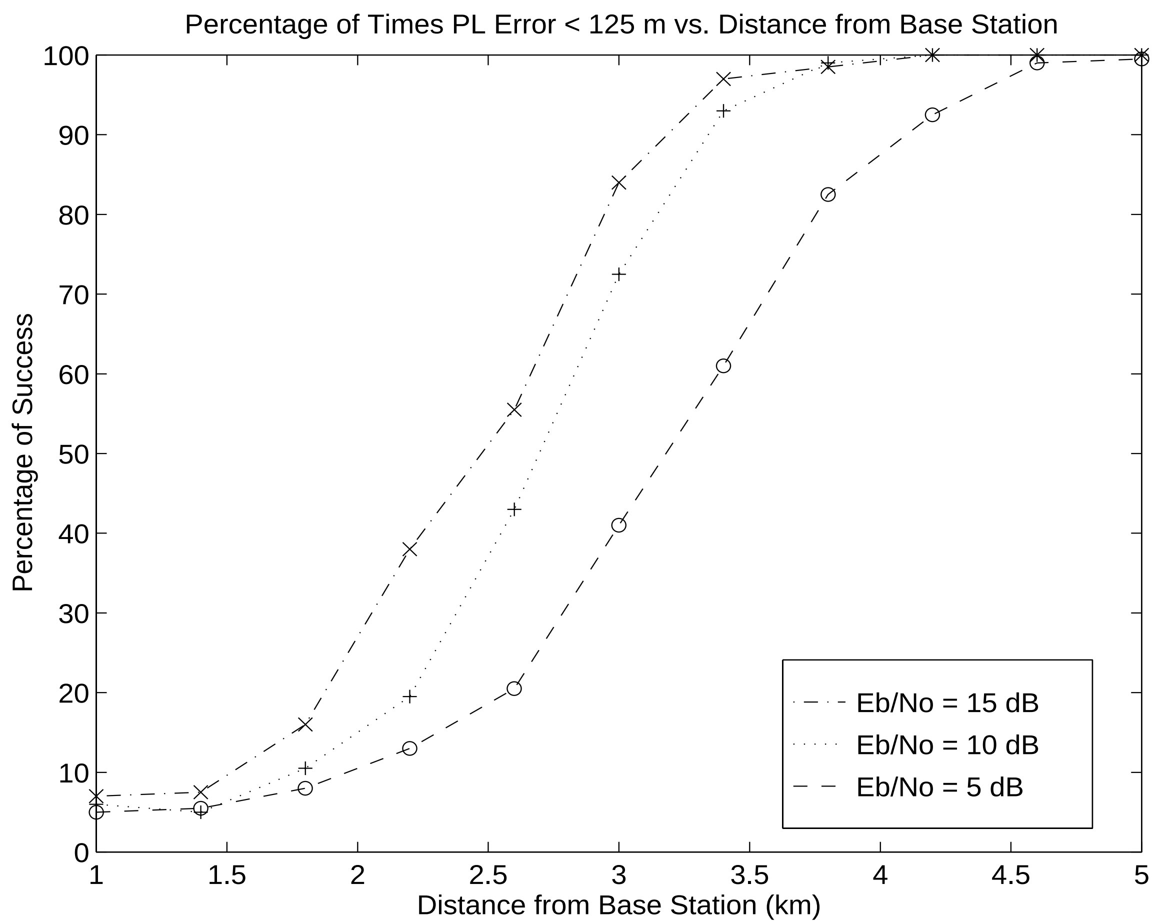

Figure 4.7: Position Location Performance at Different Distances from the Home Cell Site (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell)

4.6 Non-Ideal Arrangement of Base Stations

In previous simulations, we had been assuming an ideal hexagonal cell layout for the cellular systems. However, this is not always true in real systems and most systems usually don't strictly follow such a layout. This is relevant to position location performance because the Geometric Dilution Of Precision (GDOP) of the system may be seriously affected, if the the base stations are at such positions relative to the handset which are not suitable for the hyperbolic procedure.

To study the effect of non-ideal arrangement of base stations, we have compared the performance of the position location procedure in two different layout patterns. Figure 4.8 shows an ideal hexagonal cell layout which is usually used in the simulations of cellular systems. For the non-ideal case, we have chosen the cell pattern shown in Figure 4.9. This type of layout may be found in practice along highways to provide cellular coverage to passengers. Randomly distributed positions for the 911 user and other users have also been shown. Such unique positions are generated for every position fix. Both simulations were performed under identical conditions. An observation window length of 12 bits was used. The sampling rate was 8 samples per chip. In both cases, there were fifteen active users in each cell. The performance comparison is shown in Figure 4.10.

The figure shows a significant degradation in performance for the case when the three base stations lying in a line are used for the TDOA position location. The reason behind this effect is that in such a case the hyperbolic curves formed by TDOA estimates approach a straight line as the mobile moves more and more towards positions between any two of the base stations. Therefore, both hyperbolas intersect each other at very small angles. In such a case, even a small error in TDOA estimation can cause a large position location error. This is quite opposite to the ideal case shown in Figure 4.8. In that case, when the 911 mobile is between the three base stations, both hyperbolas intersect each other at right angles and the GDOP in that case is minimum. Also in that case, even unsymmetrical positions are not as bad as the ones in the non-ideal linear cellular layout.

However, it must be understood that the case shown in Figure 4.9 is a worst case arrangement and in most cases, we can find base stations which are lying in quite a non-linear fashion. In practical systems, other strategies can also be used to combat this problem. In future system designs, the GDOP can be used as a criterion for selecting a set of base station locations from a large set, whose measurements produce minimum PL estimation error, provided that we have the option to select cell sites from a given pool of locations. Hence, in the future, position location accuracy may also become a factor in choosing cell sites like other factors, such as the cost of real estate and coverage requirements.

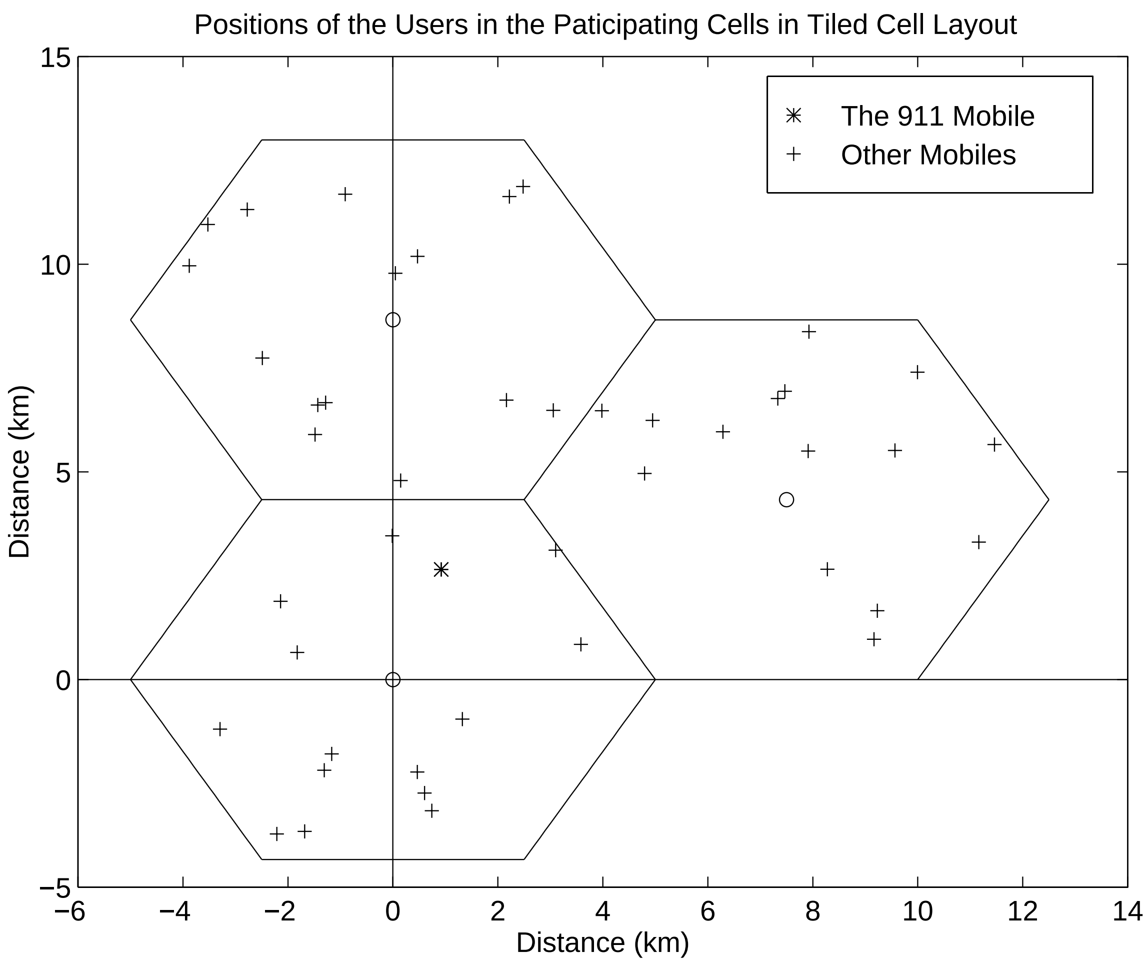

Figure 4.8: The Ideal Hexagonal Cellular Layout with Randomly Placed Mobiles

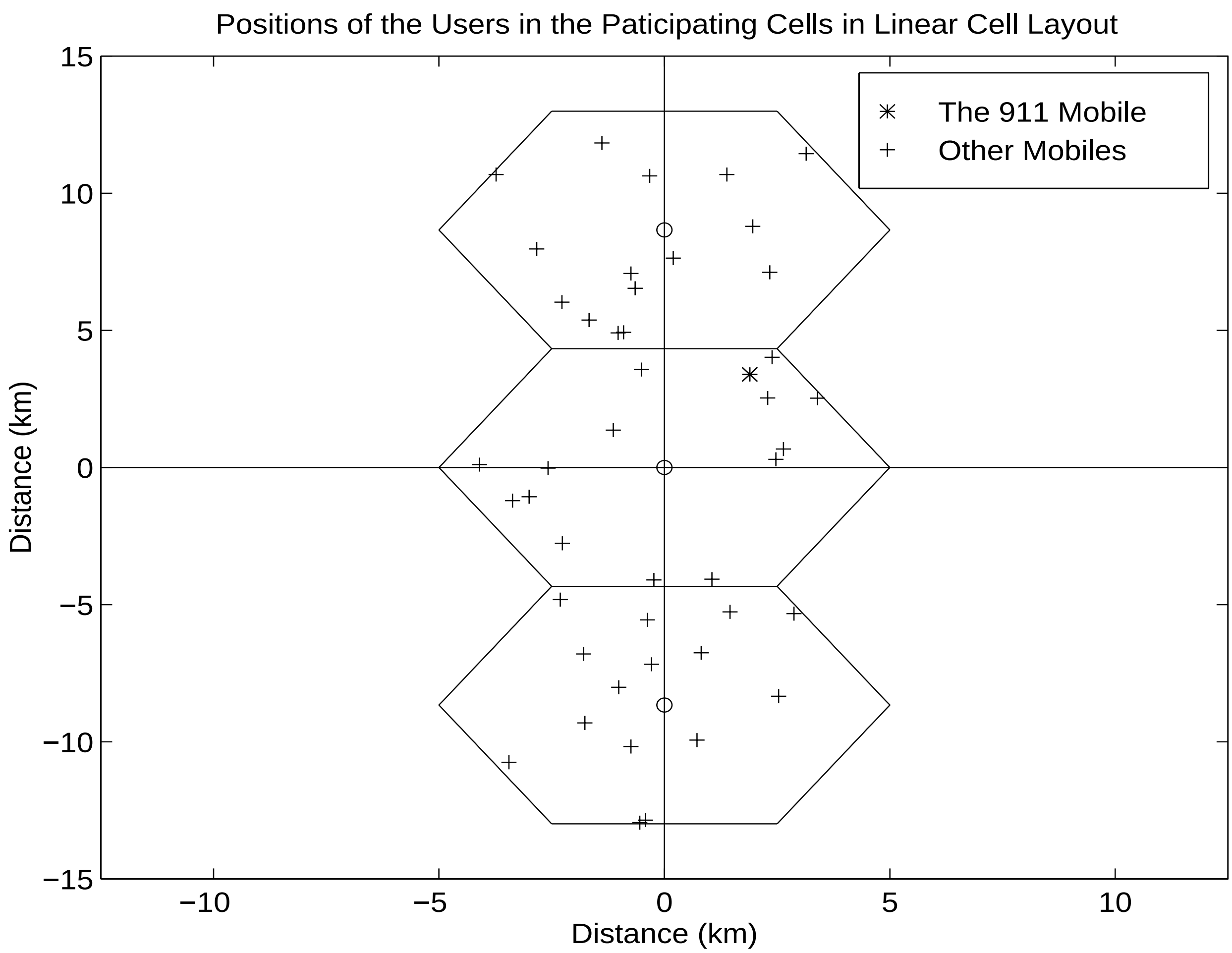

Figure 4.9: A Linear Non-Ideal Hexagonal Cellular Layout with Randomly Placed Mobiles

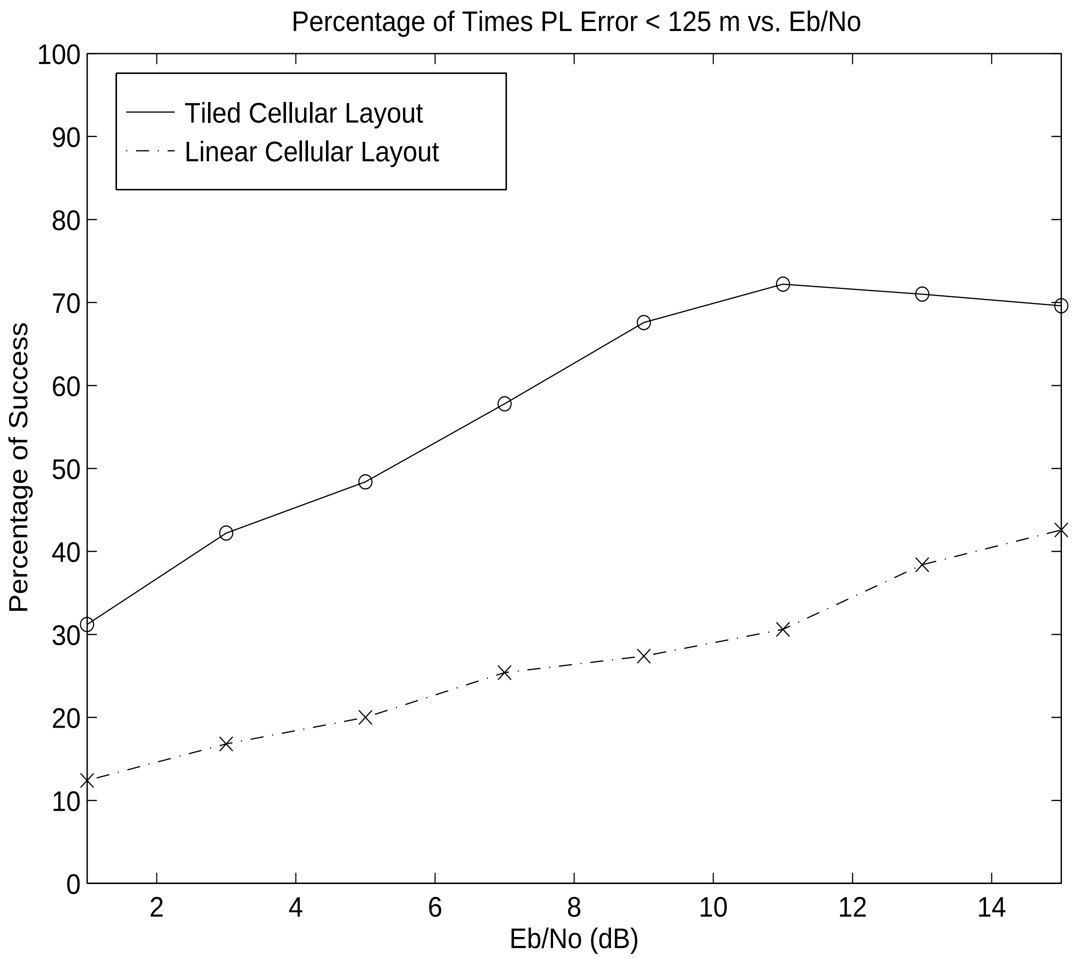

Figure 4.10: Position Location Performance in a Non-Ideal Base Station Layout (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell)

4.7 Performance in Rayleigh Fading Channels

In this section, we compare the performance differences in a simple AWGN channel and the Rayleigh fading channels. To compare the performance accuracy, measurements were made for mobile positions at different lengths from the home cell site. Apart from the AWGN channel, curves were drawn for the flat fading and frequency selective fading channel environments. Thermal noise level in all three simulations was kept at an E_b/N_0 of 10 dB. It is known that the wideband CDMA systems usually undergo frequency selective fading in the RF channel and hence, that case is more important for study here.

For the flat fading case, the velocity of the mobile was simulated to be 5 km/hr. This can approximate the case when a person is walking inside a building and because of short power delay profiles in the in-building atmosphere the signal is undergoing flat fading.

To simulate frequency selective fading channel, a second component was simulated which had half the amplitude of the LOS component and was delayed by about 5 μs. This represents a typical delay encountered in urban environments [5]. A vehicle speed of 100 km/hr was used for this case. Figure 4.11 shows the performance plots for the three channel types.

The figure shows that at positions close to the base station, the performance in the three channel models does not differ significantly. However, as we go away from the home cell site, the performance in AWGN channel improves more rapidly than the other channel types. The results also indicate that the performance in frequency selective fading channel is slightly better than the flat fading case. The probable reason is that we have more than one multipath component in the frequency selective fading environment and the IS-95 rake receiver takes advantage of the multipath diversity to enhance the accuracy of the bit estimations.

Hence, we conclude that the position location procedure used in this research is applicable in flat and frequency selective fading channels as well.

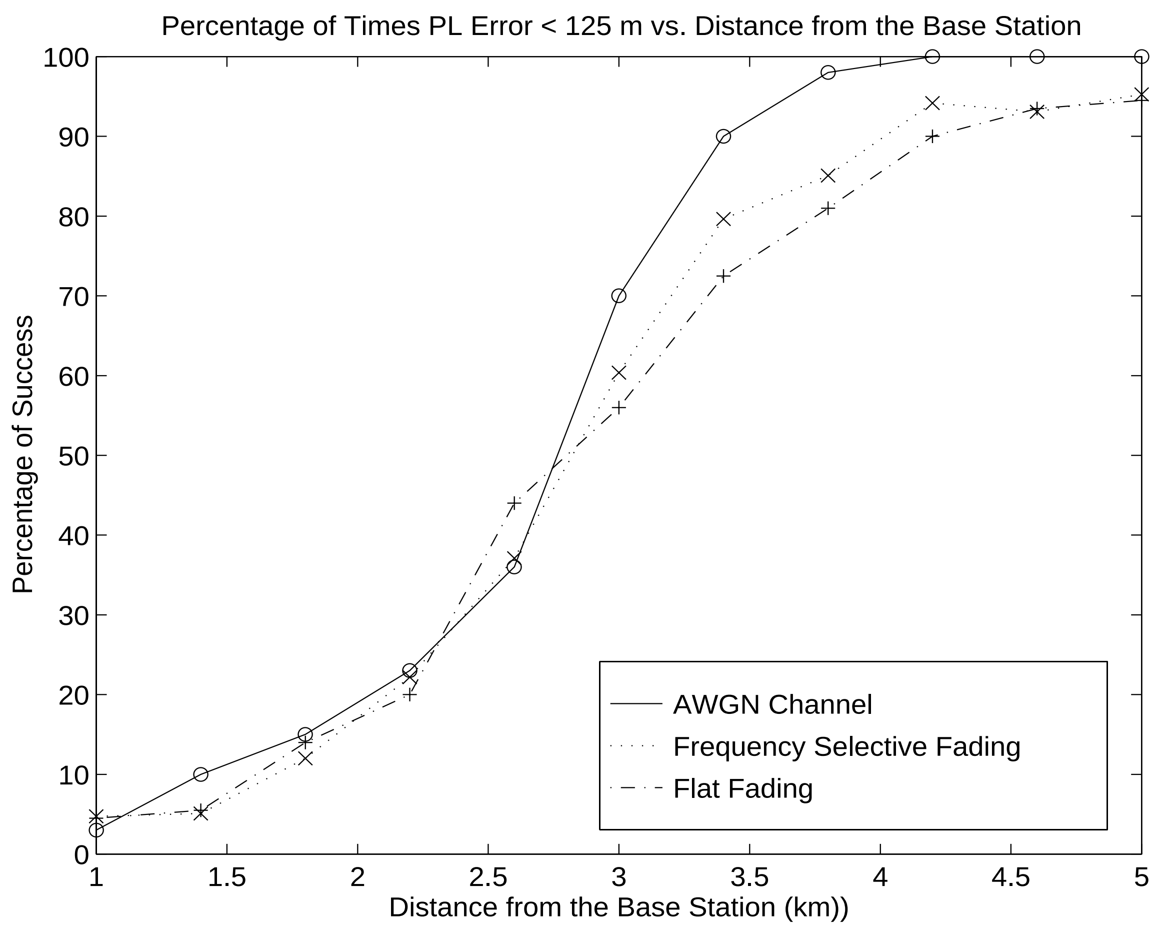

Figure 4.11: Performance Comparison in Different Types of Channel Environments (E_b/N_0 = 10 dB, Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell, Mobile Velocity in Frequency Selective Fading Case = 100 km/hr, Mobile Velocity in Flat Fading Case = 5 km/hr)

4.8 Chapter Summary

In this chapter, we looked at some of the basic issues regarding the TDOA position location procedure. In the beginning, we looked at the effect of AWGN levels, sampling rate and window lengths in sections 4.2, 4.3 and 4.4. It was shown that increase in the sampling rate or the observation window length results in better performance. Optimal values for TDOA PL were identified and were used in the subsequent simulations.

The effect of distance from the home cell site to the mobile was studied and the dismal system performance when the mobile is close to the cell site, was identified as one of the foremost problems facing the TDOA techniques in CDMA systems. It was shown in 4.6 that non-ideal arrangement of cell sites results in decreased performance levels because of increased GDOP. Finally, we studied the performance of the position location procedures in flat fading and frequency selective fading channels and compared it to that in AWGN channel. It was concluded that although the performance degrades in those environments as compared to the simple AWGN channel, however, the degradation in not severe and the PL method appears to be viable in Rayleigh fading channels also.

Chapter 5

Performance in Non-Ideal Multiuser Environments

5.1 Introduction

This chapter is devoted to the study of problems faced in a multiuser environment. For the results in the previous chapter, we had assumed an ideal multiaccess situation, in which all users' signals are received with equal powers. Throughout, we assumed that the number of users in each cell is constant at fifteen users per cell. We also did not investigate the effect of using higher transmit power level for the 911 user.

In this chapter, we'll look into the above mentioned issues. We'll first discuss the effect of non-ideal power control on position location accuracy in 5.2. We'll investigate the effect of using interference cancellation at participating neighboring base stations to improve desired user's signal reception. We'll also see the effect of different system loading levels on position location process.

As we have seen earlier, the hearability of the 911 user's signal at neighboring base stations is a problem when the mobile is close to the controlling base station. One approach to solve this problem is to instruct the mobile to transmit at higher power levels. We have studied this approach in 5.4 and have presented the results for accuracy improvements. We also look into the use of interference cancellation to cancel that increased power signal, to avoid a toll on system capacity.

5.2 Effects of Imperfect Power Control

The CDMA system depends heavily on the use of power control so that all signals arrive at the receiver with approximately the same power. However, if this condition is violated and the disparity between the received power levels increases, this results in significant capacity loss [49]. Under normal circumstances, power control limits received power levels to approximately 1-2 dB of variance [50]. However, it has been shown in [49] that even a variance of just 2 dB in received power levels can cause a capacity loss of more than 50%. Hence, the issue of power control is extremely important for the performance of CDMA systems.

Therefore, we have tried to study the effect of disparity in received powers on the performance of PL process. To study this problem we have used the same approach as in [49]. Ideal power control performance was compared with that in the cases when the received power levels have a standard deviation of 1, 1.4 and 2 dB. Performance was measured at a range of E_b/N_0 values from 1 dB to 15 dB. Observation window length was 12 bits and there were fifteen users in each cell. Figure 5.1 shows the results of the simulation.

From the figure, we notice that imperfect power control does not introduce any significant performance degradation as far as position location performance is concerned, although the average BER of the system may decrease. One probable reason for this may be that at different instances, the 911 user may have higher than average and lower than average power levels with equal probability and hence the net effect becomes zero. This will happen in practice, if the received power levels with a given variance are randomly distributed between mobiles differently at different times. It is also clear from the figures that increasing the power level variance from 1 dB to 1.4 dB and then to 2 dB does not produce any significant effect. Although some significant results may be observed, if the power variance is increased further, however, this would not be realistic, because as we mentioned earlier [50] shows that power control mechanisms are able to keep the power variance to these levels.

Hence, we conclude that the issue of slightly imperfect power control is not significant for the performance of TDOA position location in CDMA systems, although it may still be important for the overall performance of CDMA systems.

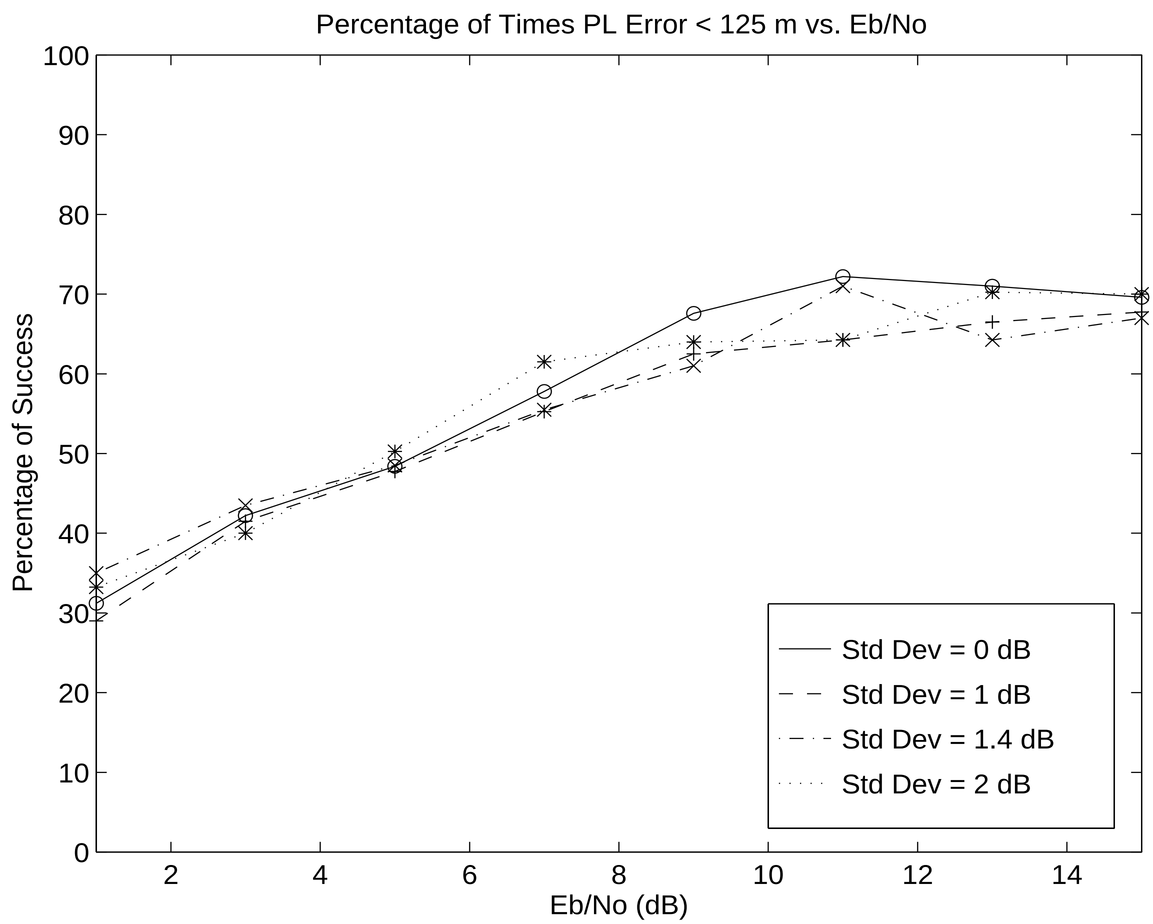

Figure 5.1: Position Location Performance at Different Standard Deviations of Received Power Levels (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, $\sigma_d = 10$ ns, 15 users per cell)

5.3 Performance at Different Loading Levels

In this section we study the effects of increasing system load on the performance of the PL system. In this simulation, we have drawn three curves at E_b/N_0 values of 5, 10 and 15 dB. The system activity was increased from just one user per cell up to fifteen users per cell and the performance was plotted. Results are shown in Figure 5.2.

We see that as the system loading increases, the success percentage of the PL process slowly decreases. This is expected as an increase in the number of active users means that the Multiple Access Interference (MAI) will increase and consequently diminish the quality of the 911 user's signal.

However, it is noticeable that the performance degradation is not very sharp in the plotted range of number of users per cell. The reason behind this observation is that theoretically a CDMA system with parameters used in this simulation is able to support many more users than just fifteen. It is well known that a CDMA system without channel coding can support a number of users equal to roughly about 20% of the length of spreading code. This number increases to 50%-60% for a CDMA system with channel coding. Hence, our system that has a spreading gain of 128 should be able to support about 20-30 users. Since we do not fully exhaust this range, hence, we do not experience any significant performance impairment.

However, for many practical reasons, the new IS-95 CDMA systems being deployed are not holding up to the initial capacity promises and many are limited to values which are just about fifteen users per cell. This is the main reason that we have considered position location performance up to this figure.

Another thing worth noticing is that the curve for E_b/N_0 value of 15 dB approaches that of 10 dB as the number of users increase. This is typical of CDMA capacity curves, as with low AWGN and increasing number of users the system basically becomes interference limited.

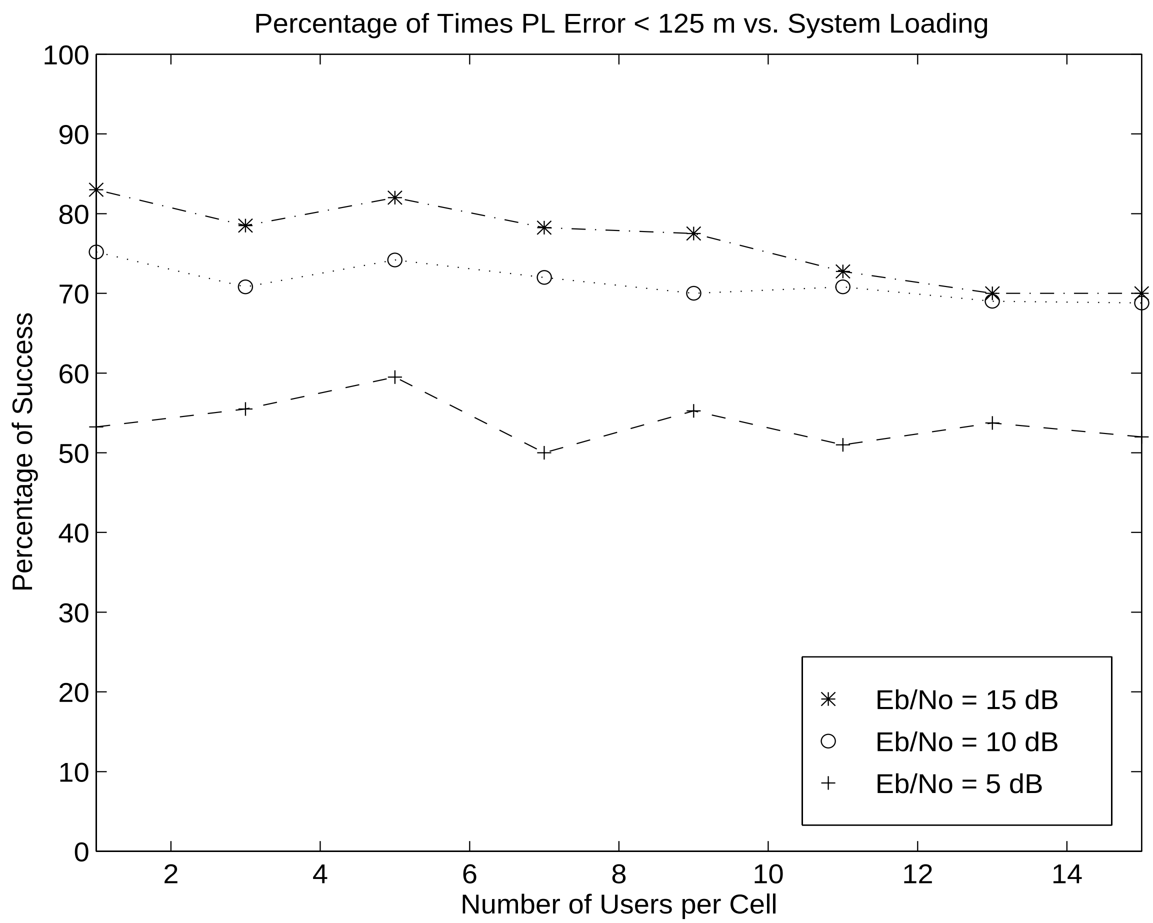

Figure 5.2: Position Location Performance at Different System Loading Levels (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns)

5.4 Using High Power Level for the 911 User

As we have discussed earlier, one of the biggest problems for TDOA PL technique in CDMA systems is the power control operation of CDMA. As the 911 mobile comes closer to the home cell site, the decreased transmit power and increasing path loss for other base stations, makes the mobile signal very weak at the neighboring base stations participating in the PL process. In Figure 4.7, we saw that for an E_b/N_0 value of 10 dB, about 65% of the total cell area satisfied the FCC criteria of PL errors less than 125 m for 67% of the time. This corresponded to points more then 3 km away from the cell site for a cell of major radius 5 km. Hence, we see that a big portion of the cell is not adequately covered.

One of the ways to solve this problem is to instruct the 911 mobile to transmit at a higher power to increase signal quality at other base stations. It has been proposed [17] that if the mobile is instructed to transmit at maximum power, then the coverage area for position location can be considerably increased. However, initially we see two interference related problems with this solution.

The first problem will be with the home cell. If the 911 mobile's signal is received at the base station at a power higher than other mobiles, then it will degrade the overall performance of the reverse link because the BER at the receiver for other mobiles in the cell will be affected. This happens because of increased MAI as seen by the mobiles other than the 911 mobile.

The second problem may occur with the neighboring cells when the 911 mobile is near the cell boundary. If the mobile is almost at the same distance from its home cell site and a neighboring base station, then its received power at the neighboring base station will be almost equal to the own-users of that cell. Hence, if at that point the 911 mobile starts transmitting at maximum power, then apart from hurting the performance of its own cell, it will also affect the system performance in the neighboring cell.

The solution to the first problem seems to be the use of interference rejection techniques to cancel out the powerful 911 user to improve the signal reception of other users in the home cell. We'll explore this possibility in the next section.

Although the second problem may also be solved in the same way, we can use a simpler solution. The way around the problem is to increase the power gradually instead of just switching to maximum power when a mobile needs to be located. As we know that on the cell boundary a mobile can be traced accurately even at normal transmit power, hence, at that position we don't need it to transmit at maximum power. The correct procedure may be to gradually increase the transmit power until the neighboring base stations receive the 911 mobile's signal at adequate strength. Hence, we might not need any power enhancement for a mobile at the cell boundary and may need a few power increasing steps for mobiles closer to their home cell site. Another advantage of this approach is that the mobile will always increase its power gradually in steps and cannot be instructed to go to maximum power suddenly. This is because the closed loop power control mechanism makes power corrections in fixed sized steps of typically 1 dB and does not have the capability to make the mobile transmit at maximum power in a single step.

Hence, we have plotted curves at different power increases for the 911 mobile. Figure 5.3 shows the plots. All of the simulations were performed at an E_b/N_0 of 10 dB. We have considered the normal operation, 3 dB, 6 dB, 9 dB and 12 dB power increases. It is clear from the curves that at the cell edge, even normal operation keeps the position location error below 125 m almost 100% of the time. So, we don't need any power enhancement there. This corroborates the point made in the preceding discussion.

We see a clear gain in the coverage area as the mobile power is increased further and further. Increments of 3 dB in transmit power for the 911 mobile result in an average increase of roughly 0.5 km of more inward gain in the coverage area in terms of the distance from the base station. As we stated earlier, without any power increase about 65% of the cell area satisfies the FCC requirement of PL error less then 125 m for 67% of the time. With a power increase of the 3 dB, the coverage area increases to about 72% of the total area. With a 6 dB gain, the coverage area becomes 81%. With a 9 dB gain, about 87% of the total area satisfies the FCC criteria. And with a 12 dB increase, we extend the coverage to about 89% of the total cell area. However, it is evident that as we keep on increasing the power gain for the 911 user, we get diminishing returns as the gain in the coverage area keeps on decreasing. It is quite obvious that although we can probably cover more than 90% of the cell area, some area just around the base station might still not be feasible for reliable PL. Another reason may be that for macrocells, the Fraunhoffer region may extend to as much as 1 km from the antenna and hence, it is possible that even with increased power we may not be able to get reliable results in that region.

Hence, we conclude that it is possible to extend coverage of the position location methods by instructing the mobile to transmit at higher power. We have also seen that its a better approach to increase mobile power gradually in many steps rather than to have it transmit at maximum power in a single step. We have also found that some area around the base station might still remain outside position location coverage because of its long distance from the other cell sites and because of it not being in the far zone.

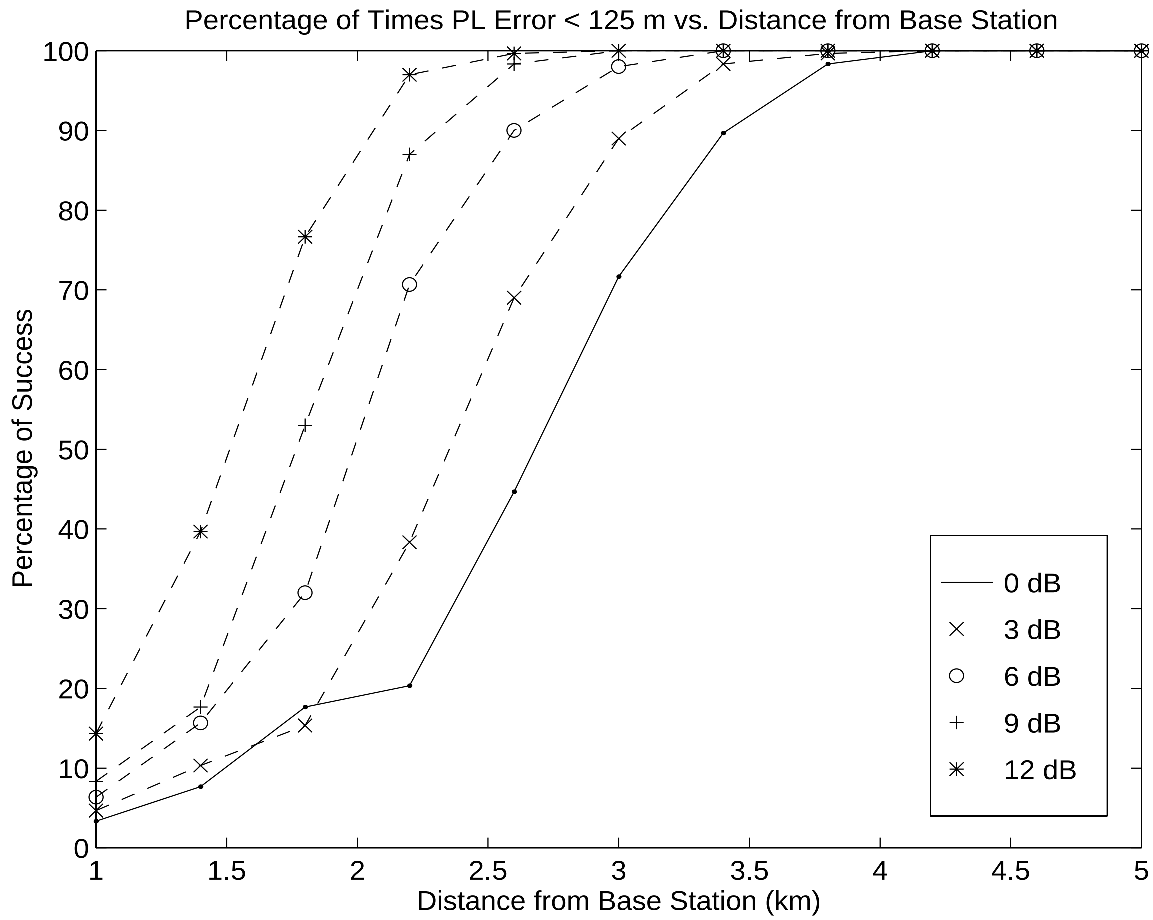

Figure 5.3: Increase in PL Coverage by Using Increased Transmit Power for the 911 User (911 mobile's power increases in 3 dB steps, $E_b/N_0 = 10$ dB, Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, $\sigma_d = 10$ ns, 15 users per cell)

5.5 Bit Error Rate with the Cancellation of the High Power 911 User

In the previous section, we saw that by increasing the 911 mobile's transmit power in a controlled fashion, we can increase the PL coverage to a great extent. However, the negative effect of this would be the increase of MAI for the mobiles in the cell containing the 911 mobile.

In this section, we have considered the use of interference rejection techniques to mitigate that effect. Since the 911 user's signal with increased power level will be the most strong signal in that cell, it will be easy to detect and cancel it out. In these simulations we have taken Bit Error Rate (BER) to be the cumulative BER of all the users in the home cell including the 911 user. Simulations were performed with fifteen users in each cell and at a range of E_b/N_0 values from 1 dB to 13 dB. To plot each point in the curves, at least 25 errors were counted. Simulations were run in blocks of 12 bits, which is the length of one power control group in IS-95 and is also the observation window length used throughout this work. Figure 5.4 shows the results obtained.

We see that for a power increase of 3 dB in the 911 mobile's power, there is not much degradation in the performance, even without cancelling that signal. As we go to higher power gains for the 911 user's signal, we see an increase in the BER when cancellation is not in effect, which is considerable at an increase of 6 dB, becomes significant for a power increase of 9 dB and renders the system unusable at 12 dB increase. It is also clear from the results that the cancellation restores the system performance and brings the BER back down to the level of normal BER experienced when all mobiles are being received with equal powers.

Another interesting observation is that with the 911 signal cancellation in effect, the performance actually improves slightly as we increase the power gain for the signal of the 911 user. The reason is that since that user is detected almost without error because of higher power and cancelled out perfectly, the BER for other users remains unaffected. In fact, BER for other users may slightly improve in cases of cancellation because of the slight reduction in MAI for other users. But since the reception of 911 user's signal improves considerably because of higher received power, the BER for that user keeps on improving, which has a slight positive effect on the overall system BER.

Hence, from these observations we conclude that the use of higher transmit power for the 911 mobile is a very feasible option, with the application of interference cancellation for that signal and can be applied to extend the coverage of reliable position location.

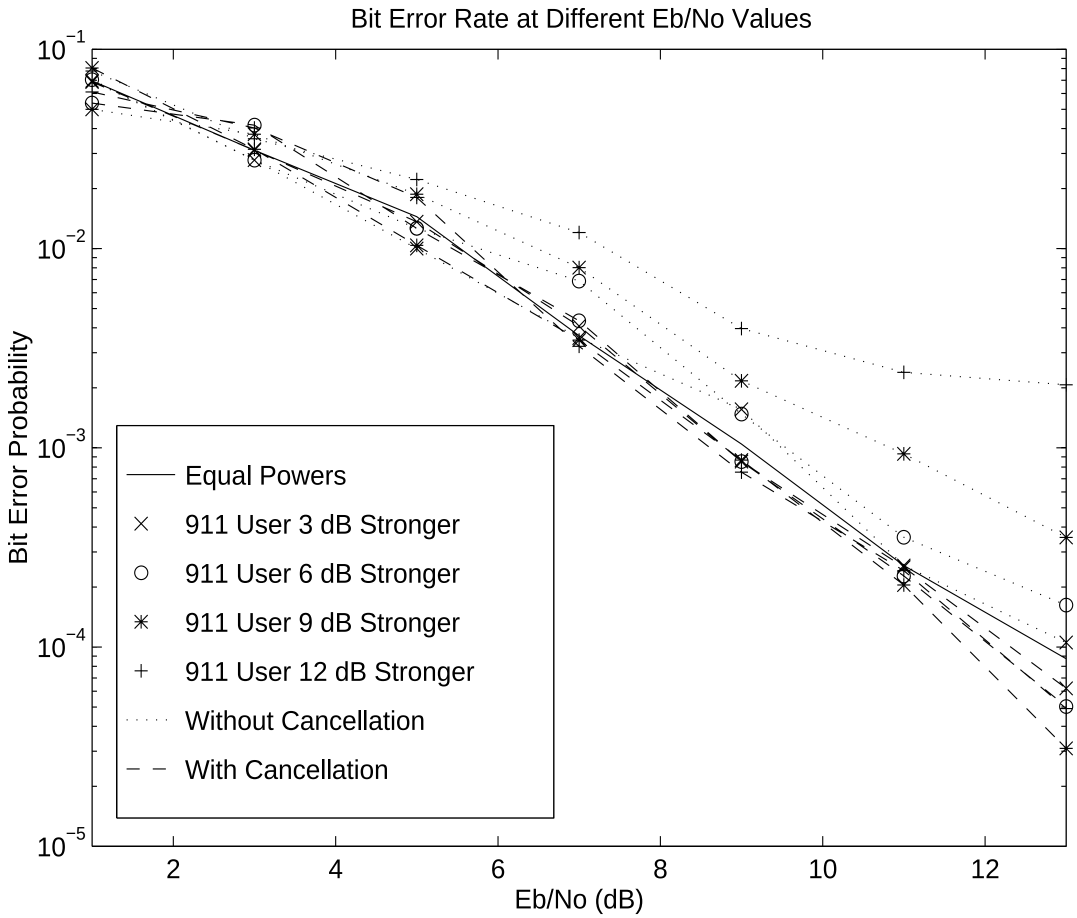

Figure 5.4: System Performance with Increased Transmit Power for the 911 User with and without 911 User Cancellation (15 users in the home cell)

5.6 Interference Cancellation at other Base Stations

Apart from the approach discussed in the last two sections, another way for improved reception of 911 user's signal at the neighboring base stations is the application of interference rejection at the neighboring base stations to reduce MAI for the desired signal. When the 911 mobile is closer to its home cell site, its signal at the neighboring cell sites is very weak as compared to the signals from the users of those cells. This causes bit errors in the received version of 911 user's signal at those base stations. Hence, if at those cell sites, we cancel their own users' signals and then detect the desired user's signal, this results in improved reception for the signal of interest.

In this section we have studied this approach. We have applied one stage of parallel interference cancellation at both participating neighboring base stations to cancel their own users before detecting the 911 user's signal. We have used matched filters to estimate the amplitudes of all the signals, the way it was described in 3.6. The method of using interference reduction factor has also been described in 3.6. In an approach similar to other simulations, we have plotted three graphs at E_b/N_0 values of 5dB, 10 dB and 15 dB. Performance was measured at points of different distances from the base station. Figure 5.5 shows the results of the simulation.

We see from the plots that MAI cancellation at the neighboring base stations does give us gain in performance and increases the coverage area, however, the gain in performance seems to be highly dependent on the E_b/N_0 value of the system operation. At 5 dB, there is not any significant improvement. Without cancellation, about 51% of the area satisfies the FCC requirement. With cancellation in effect, this increases just to 54%. The main reason for this small improvement is that a good first stage estimation of user data is necessary for parallel interference cancellation to work. With an E_b/N_0 of just 5 dB, our first stage estimates are not very good, resulting in ineffective cancellation. However, this changes as the signal power relative to noise power increases. For E_b/N_0 of 10 dB, the coverage area increases from 66% to 72% and at 15 dB, it increases from 70% to approximately 80% of the total cell area.

It is interesting to compare the performance observed by employing interference cancellation at neighboring base stations with the case discussed in the previous section, when we instruct the mobile to transmit at higher power and then cancel it out. Comparing the performance at E_b/N_0 of 10 dB, we observe that a power increase of just 3 dB for mobile power matches the performance improvement with the application of cancellation at other base stations. At higher power gains, the former method clearly outperforms the parallel cancellation approach.

Besides the performance advantage, the former method is also computationally less intensive than this method. In the previous method, we just have to cancel one strong user, whereas, in this approach each neighboring base station cancels all its users in the first stage. Since the number of users can be very high at times, this is much more time consuming than cancelling just a single user.

Hence, we conclude that although parallel cancellation at neighboring base stations does improve performance, it is not as efficient a method as is the one in which we cancel just the 911 user after having it transmit at a higher power.

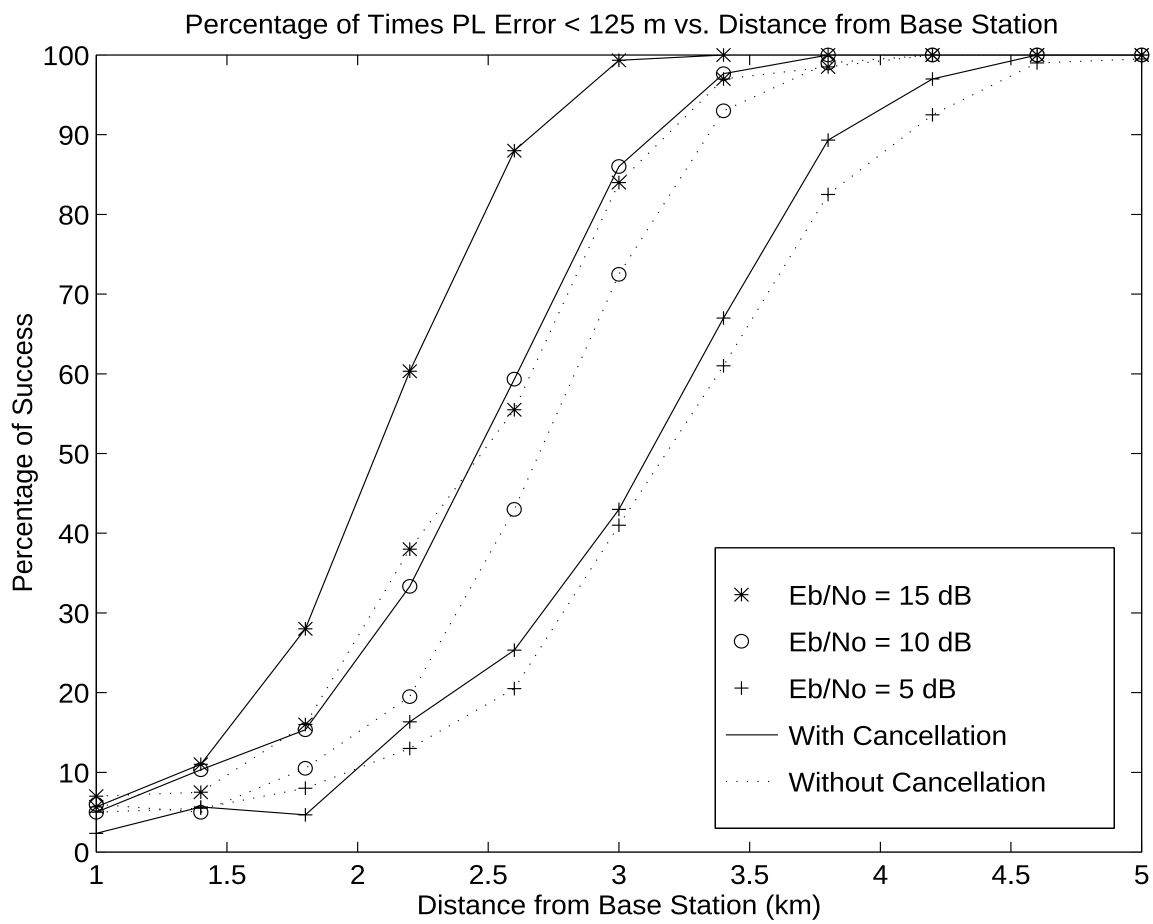

Figure 5.5: Measurement of Performance Improvement with the Use of Parallel Interference Cancellation at the Neighboring Base Stations (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell)

5.7 Chapter Summary

In this chapter, we looked at the aspects of the position location problem related to multiuser environments. We first looked at cases of non-ideal power control and found out that the performance is not very different from that of ideal power control, in cases where, standard deviation of received power levels is within the range usually experienced in practice.

Effect of increased system loading was examined and it was found that although, there is a performance degradation with increasing number of users, however, it is not significant in the range of system loading used in practice with the current CDMA systems.

The feasibility of using higher power levels for the 911 user to facilitate reliable PL was studied. It was found that increasing the desired user's power level does effectively increase the PL coverage area up a great deal. The effect of this practice on system BER was examined and it was learned that the cancellation of the strong 911 signal can restore the system BER to its normal levels.

We also looked at the effect of using parallel interference at the neighboring base stations to improve the received signal quality of the 911 user. We found that this procedure gives some improvement, however, the gain is less than the high-mobile-power method and is also computationally more intensive.

Chapter 6

The Improved TDOA Estimation

6.1 Introduction

In this chapter, we discuss the performance results with improved TDOA estimation. As we mentioned earlier in 3.7.1, the nature of errors in TDOA estimation seems to follow a pattern, when we cross-correlate the spread-spectrum signal versions of any user. We can use the specific properties of those errors to detect and subsequently correct them. Hence, we'll see in this chapter that we can obtain highly accurate results when we improve TDOA estimation by incorporating those changes.

We will first discuss the method of doing the proposed corrections. To compare the performance with unmodified TDOA estimation, we have measured PL performance with similar conditions as in Chapter 4. This includes effects of varying levels of AWGN, distance from the cell site, length of observation window, effect of linear arrangement of base stations and performance in Rayleigh fading channels.

6.2 Proposed Improvement in TDOA Estimation

As explained earlier in 3.7.1, we first replace the snap shot of the composite CDMA signal by detected spread-spectrum signal of the desired user and then perform the actual cross-correlation. This is done to avoid having multiple peaks at the cross-correlator output and thus we find the TDOA estimate of the desired user only.

One of the main characteristics of the cross-correlation method discussed above, is that whenever errors occur in the TDOA estimates they occur in amounts which are greater than the whole expected value of TDOA itself. In fact, it has been observed in this work that the magnitude of error in TDOA estimates is always in multiples of bit duration. The reason behind this is that we reconstruct the snap shot for the desired user using the decoded bits of that user from the original snap shot. If a wrong bit decision is made, then a whole portion of snap shot equal to one bit duration which has a number of chips equal to the spreading gain, is replaced with the wrong polarity. As a result, if such wrong replacements cause a cross-correlation error, the wrong peak occurs exactly at multiples of bit times away from where it should have been.

This will be true in almost every case when there is a TDOA estimation error. The only case when this may not happen will be when there are so many bits in error that there is absolutely no similarity between a pair of two snap shots and the cross-correlation would yield a peak at any random place. However, this case will be very rare as the snap shot formed at the controlling base station will be good most of the time. This is because voice communication cellular systems operate at a typical BER of 10^{-3} and a typical snap shot length would be at least 12 bits. As we calculated in 3.7.1, the probability of more than one bit in error in a snap shot is less than 0.01%. Hence, even though lot of bits may be detected wrong for the snap shots at the neighboring base stations, there would still be enough similarity in pairs of snap shots in most cases so that the TDOA errors will follow the pattern mentioned above and occur only in multiples of bit duration. Hence, we conclude that the nature of error in TDOA estimates is predictable in most cases and we can use that information to correct the errors.

As we described in 3.7.1, the maximum possible TDOA is equal to the propagation delay between two base stations. This case may occur if the 911 mobile is very near to its home cell site. If the TDOA estimate comes out greater than the maximum possible TDOA, then because of the reasons discussed before, it most probably would have a time error equal to some multiple of bit duration. Hence, after identifying a TDOA as being faulty, we can subtract an appropriate multiple of bit duration to correct it in an overwhelming majority of cases. We have implemented this correction mechanism and the results are presented in the next section.

The main reason for this type of error pattern is the use of signal spreading in a Direct Sequence-CDMA (DS-CDMA) because this type of TDOA error pattern is not obtained if we use a digital system with the same channel transmission rate but without direct sequence spreading. In such a system we will not be making a bit decision based on a lot of samples from the channel like a CDMA system. Instead, we will be basing it on fewer samples depending on coding diversity. Hence, the errors would be multiples of smaller durations and it will not be possible to detect TDOA errors if the maximum possible TDOA is more than the duration of one bit. Another condition for this type of error pattern is that the CDMA system should have a code-on-pulse type spreading code.

Correction Procedure: In the IS-95 CDMA system, the chip rate is 1.2288 Mcps and the spreading gain is 128, hence, the bit duration is about 104.16 μs. On the other hand the maximum possible value for a TDOA measurement between any two base stations (BS) is equal to the time it takes for the radio signal to travel between those two base stations. This TDOA estimate may occur when a mobile unit is very close to the controlling base station. In our case, the base stations are separated by a distance of 8.66 km (assuming a hexagonal layout with a major radius of 5 km). Hence the propagation time between any two BS which is also the maximum possible TDOA is 28.86 μs. This is much less than a bit duration which is 104.16 μs.

Hence, if we find a TDOA estimate that is higher than the maximum possible TDOA, then we can assume that there is an error in the TDOA estimate and we can most probably correct it by subtracting from it an appropriate multiple of the bit duration and thus reducing it to an amount within the maximum possible TDOA.

Conditions for the Application of Improved TDOA Estimation: In summary, the improved TDOA estimation described above is applicable, if the following conditions are satisfied:

- A CDMA code-on-pulse system is used.
- Snap Shots that have been composed by respreading the decoded data are used for cross-correlations.
- The bit duration and the base station separations are such that the maximum possible TDOA is less than a bit duration.

6.3 Results with Improved TDOA Estimation

6.3.1 Performance against Increasing AWGN

At first we have compared performance in a simple AWGN channel, averaging over the entire area of the cell. Figure 6.1 shows the comparative performance of the two methods.

Both simulations were performed under identical conditions. Both used a snap shot length of 12 bits. A sampling rate of 8 samples per chip was used. For the modified TDOA technique, for each point 400 randomly generated mobile positions, uniformly distributed throughout the cell area, were used and position location accuracy was measured. Similarly 500 such runs were executed for each point of the other curve.

We see that there is a remarkable improvement in the performance after the modification in the TDOA estimation. In fact, the success percentage of PL estimation is higher than 95% at all the E_b/N_o values, even as low as 1 dB. Whereas, the unmodified TDOA estimation goes below to 30% success at the same value. Hence, we can safely conclude that with this modification, the PL systems can operate at E_b/N_0 values much below than what is usually used for voice communication.

6.3.2 Accuracy versus the Length of Snap Shot

As we did in 4.3, in this section we have measured the performance of the improved TDOA estimation at observation windows of different lengths and have compared that with that of the unmodified method shown in figure 4.2. Figure 6.2 shows both results.

Like the previous case, both these simulations were run under identical conditions. For both of them, we have plotted three graphs at E_b/N_0 values of 5dB, 10 dB and 15 dB. Both used a sampling rate of 8 samples per chip. Like the previous case, we again see a remarkable gain for the improved TDOA estimation method. It almost stays above the 67% threshold for all three curves for all values of snap shot lengths considered. In this graph, the shortest observation window length used is of 2 bits. The success percentage reaches 100% for a window length of about 16 bits. As we had seen in Figure 6.1, there is not much difference in the performance at the three values of E_b/N_0 used in this plot, for the improved TDOA estimation method.

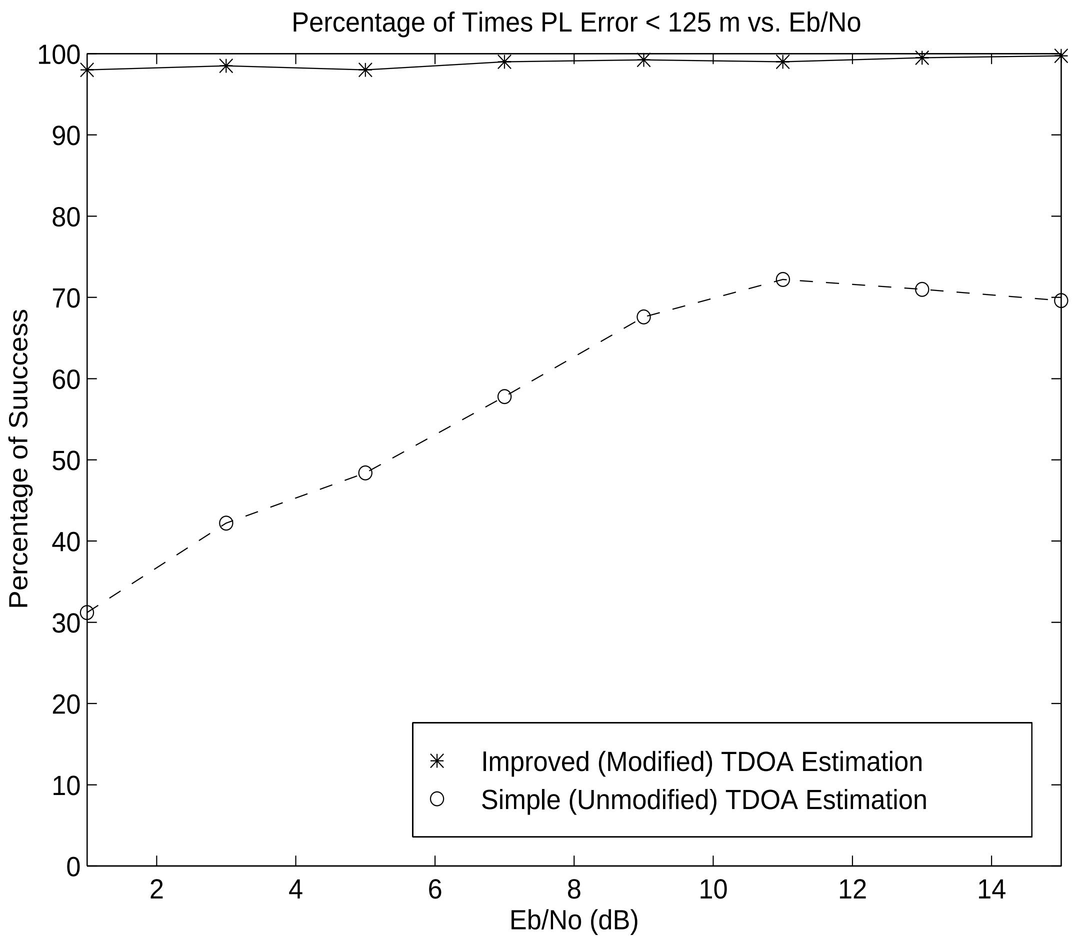

Figure 6.1: Comparison of Improved and Simple TDOA Estimation Methods against Increasing AWGN (Sampling Rate = 8 samples per chip, Snap Shot Length = 12 bits, σ_d = 10 ns, 15 users per cell)

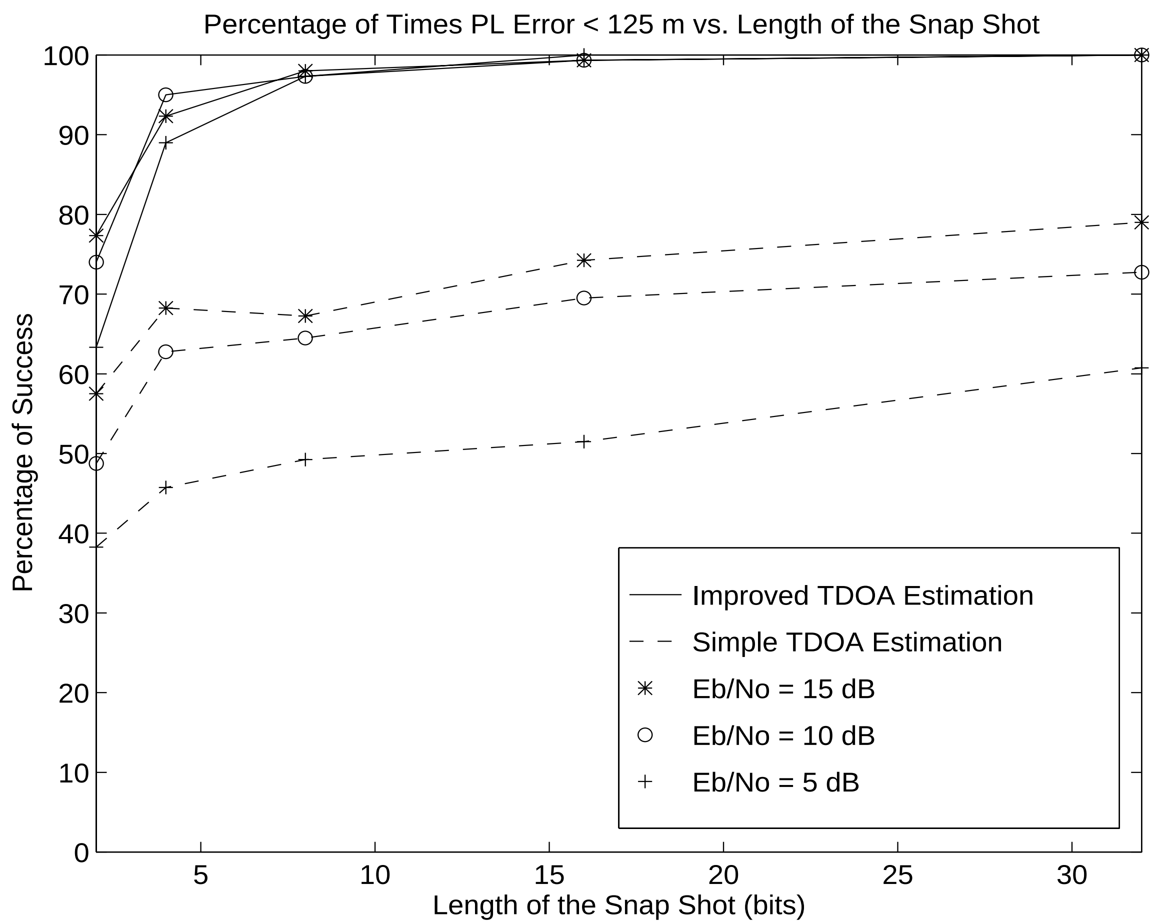

Figure 6.2: Improved and Simple TDOA Estimation Performances with Different Observation Window Lengths (Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell)

6.3.3 Distance from the Home Cell Site

We have seen that without any improvement, decreasing distance from the base station severely affects the performance of the position location system. Hence, in figure 6.3, we have compared the new TDOA method with the simple TDOA estimation method against varying distances from the home cell site. Like previous simulations, we executed the programs at three E_b/N_0 values of 5 dB, 10 dB and 15 dB. We varied the distance from the cell boundary to a distance of 1 km from the base station.

Like the other cases, here again we see tremendous gain with the improved and modified TDOA estimation. The PL error remains below 125 m for 100% of the times at larger distances and the percentage decreases a little at closer distances. Because the error is almost always within the 125 m threshold, there is not much difference in performance at the three different values of E_b/N_0 that we considered.

6.3.4 Effects of Non-Ideal Base Stations

We had seen in 4.6 that if we use irregular arrangement for the participating base stations, then the mobile location accuracy will degrade. We considered a worst-case arrangement and observed significant degradation in performance.

We applied the improved TDOA estimation method for position location in the same cellular arrangement of linearly placed cell sites as shown in figure 4.9. The comparative results are presented in figure 6.3. As seen previously, there is a significant gain in the percentage of times we get a location fix with PL error less than 125 m. However, it is noticeable that the performance does degrade a little from that in the case of tiled cellular layout as shown in figure 6.1, where it was almost perfect. However, even with that slight degradation, the percentage of successful fixes is still above 90%, even at low values of E_b/N_0. Another observation that can be made is that for this type of cellular layout, there is not much gain in success percentage as we go to higher values of SNR. Whereas, for the normal layout case, we see a slow gain as we increase the E_b/N_0.

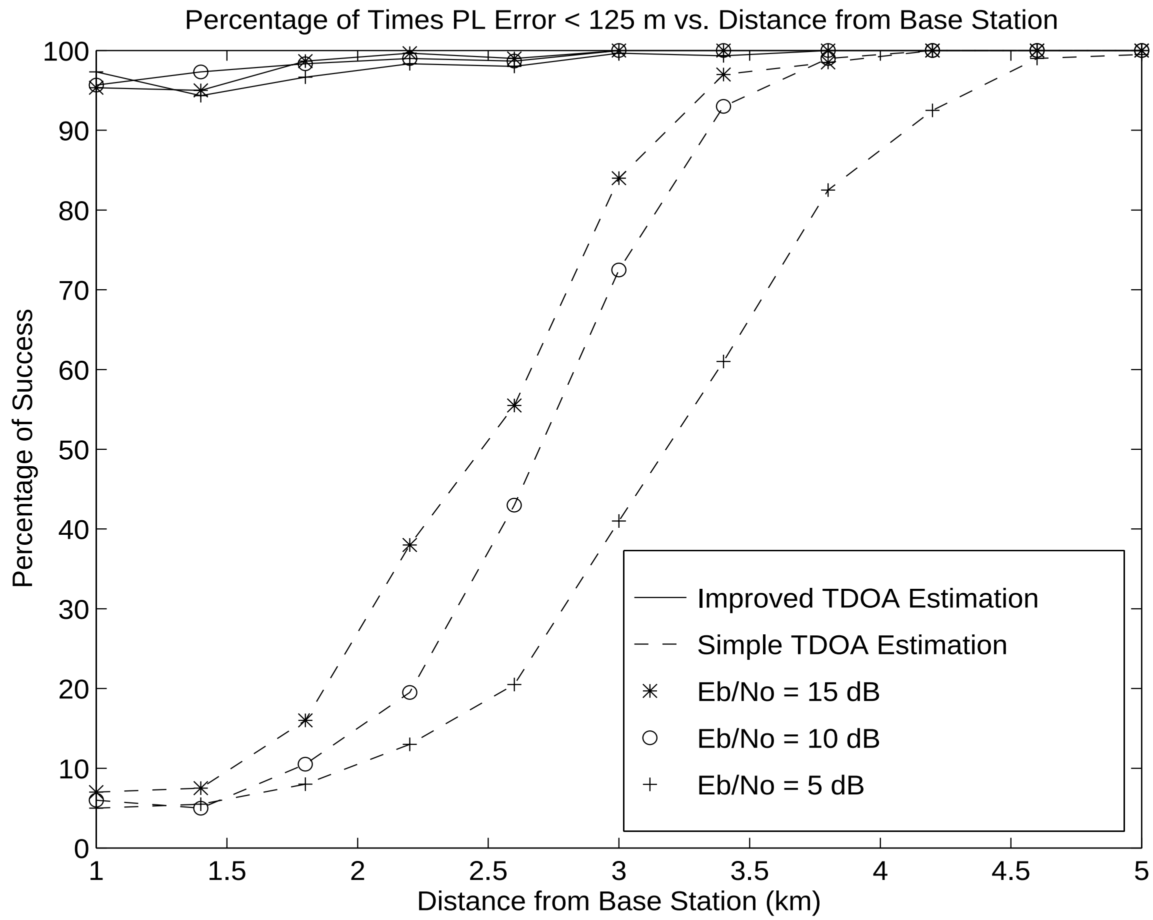

Figure 6.3: Comparison of Improved and Simple TDOA Estimation at Different Distances from the Base Station (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, $\sigma_d = 10$ ns, 15 users per cell)

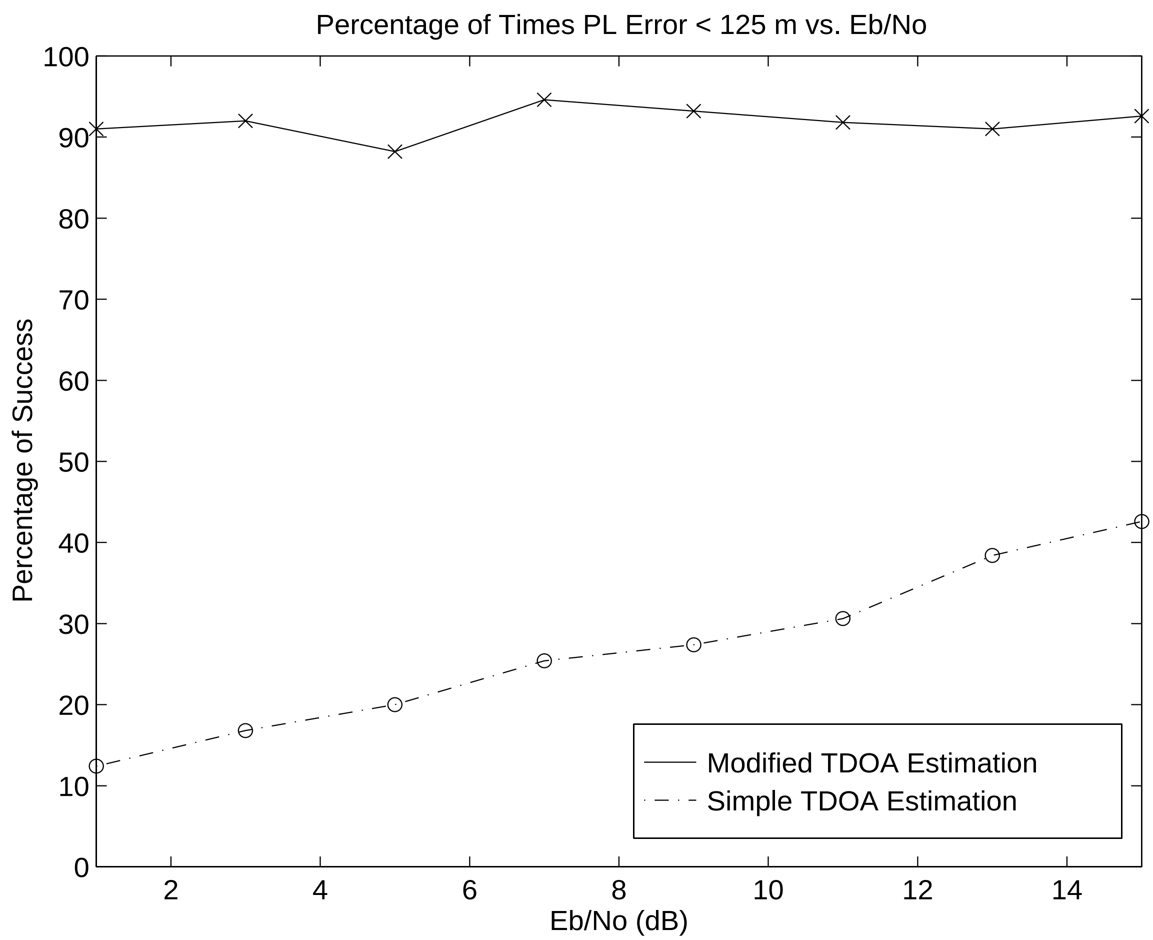

Figure 6.4: Improved and Simple TDOA Estimation Performance with Linear Cell Arrangement (Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell)

6.3.5 Performance in Rayleigh Fading Channels

We have also tested the improved TDOA estimation in the a frequency selective fading channel model. For the sake of comparison, we have used the same model which we used in the case of simple TDOA estimation in Chapter 4. A two-ray model is simulated with the second component having about 70% power as compared to the first arriving component. The time delay of the second component is also kept the same at 5 μs, which is a typical delay in urban cellular environment. E_b/N_0 is 10 dB and mobile velocity is 100 km/hr.

Figure 6.5 shows the results. Like we saw before, there is a very remarkable improvement in the performance with the improved TDOA estimation. Like other cases, at any value of the considered distances, the error was less than 125 m for 90% of the time, even at a close distance of 1 km.

6.4 Conclusions and Chapter Summary

In this chapter, we discussed the particular TDOA error pattern which occurs as a result of performing the cross-correlation on the decoded and respread versions of the signal snap shots. We observed that with this type of an error pattern, we can correct the TDOA errors in most of the cases. This improved TDOA estimation method was developed and applied to some of the cases that we had studied earlier with the simple TDOA estimation. We saw that there is a tremendous gain in performance using the improved TDOA estimation technique. We were able to correct an overwhelming majority of errors and the results in almost all the cases showed the percentage of the errors below the threshold to be above 90%. It can be safely assumed that this method will perform the same way, if we consider some of the other cases that we considered in the previous chapters. It should also be noticed that with this improvement, we did not use any type of interference cancellation at either the home cell site or any of the neighboring base stations.

The performance of the improved TDOA estimation, on the surface, seems unrealistic. However, the high success percentages do not mean perfect estimation with zero error. There was some finite error in every measurement that was made through either of the modified or the unmodified methods. What modified method does is to keep the PL error below a certain threshold for most of the cases. In other words, the improved TDOA estimation method does not eliminate the error, instead, it increases the ratio of the instances when the error is very low, to a great deal. This point would become more obvious if we study and compare the simple and the improved TDOA estimation in terms of RMS PL error, instead of looking at the percentages of the times the error remains below a certain threshold.

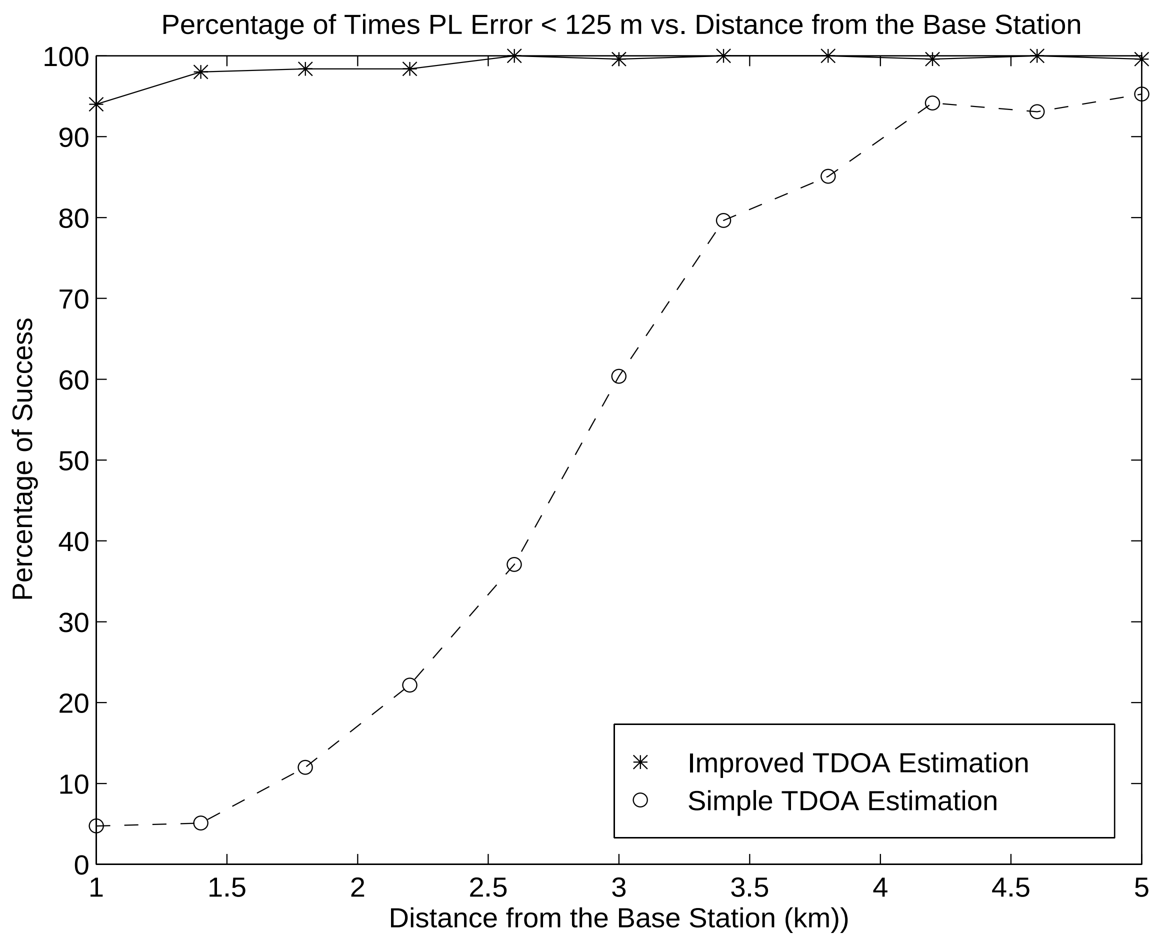

Figure 6.5: Performance Improvement from Modified TDOA Estimation in Rayleigh Fading Channel (E_b/N_0 = 10 dB, Snap Shot Length = 12 bits, Sampling Rate = 8 samples per chip, σ_d = 10 ns, 15 users per cell, Mobile Velocity = 100 km/hr)

Chapter 7

Conclusions

7.1 Methods and Algorithms for TDOA Position Location

The hyperbolic position location method which is also called the Time-Difference-Of-Arrival (TDOA) method finds out the position estimation in two steps. In the first step we estimate the time difference of arrival of the signal between at least two pairs of base stations and in the second step we solve the hyperbolic equations obtained as a result of those TDOA measurements.

For the estimation of TDOA, the method most commonly used is cross-correlation of received signals at any pair of base stations. There exist a lot of methods and algorithms to improve the estimation accuracy of the cross-correlation method. They can be broadly classified into two categories. Generalized Cross-Correlation (GCC) methods try pre-filtering the signals before cross-correlation to suppress the portions of spectrum that have a concentration of noise and interference and to enhance the spectral parts where SNR is higher. Another class of methods is called the Cyclic Cross-Correlation (CCC) methods. These methods exploit the difference in the statistical periodicities of the Signal-Of-Interest (SOI) and the Signals-Not-Of-Interest (SNOI) to increase the accuracy of TDOA estimation.

However, these methods are not applicable to CDMA as the signals of all the users are spectrally and temporally overlapping and also exhibit the same cyclostationary properties. In this work, we have proposed a method in which we first detect the data from the SOI, and then recompose the observed interval of the signal with only the spread-spectrum signal of the desired user. This works well as long as we are able to detect the data of the desired user with sufficient accuracy.

Among the methods available for solving the non-linear hyperbolic equations, formed from the TDOA estimates, it is found that the most suitable for cellular CDMA are Taylor-Series Method, Fang's Method and the Chan's Method. Chan's method is the most suitable as it offers a closed form and exact solution and can take advantage of redundant measurements, if available, to further reduce the position location error.

7.2 Important Factors for the Performance of TDOA Position Location in CDMA

It has been found that some factors are very important in determining the expected accuracy of the PL process. From the implementation point of view, the two most important factors are the length of the observation interval and the sampling rate of the system.

It has been found that increasing the length of the snap shot improves performance. This happens because with longer sequences the cross-correlation properties of the Pseudo-Noise Spreading codes become stronger. However, it may be enough to use a length of 12 bits as there is not much to gain with longer lengths and this number is also suitable keeping in view the operation of IS-95 reverse link.

It has been observed that increasing the sampling rate of the system has a direct impact on the PL error. This happens because with increased sampling, the time quantization error in TDOA estimates decreases, resulting in more accurate PL estimation. Hence, we expect the PL performance to improve further in the future as more high speed hardware replaces slower devices. Because of this relationship, broadband digital communication systems are more suited for TDOA PL as they naturally have a high sampling rate and bandwidth because of having a higher data rate than the narrowband digital systems.

7.3 Issues Effecting the Performance

We have looked at a number of issues that are relevant for the performance of the PL process. We first looked at the PL performance in a simple AWGN channel and observed that at the typical E_b/N_0 levels used in cellular systems, the performance of the PL system was satisfactory, although, it was measured without any of the improvements in the method, which have been proposed in this work.

It was observed that the power control mechanism of CDMA systems makes it difficult to get reliable PL as the mobile handset goes closer to the home cell site. We see a considerable decrease in accuracy and percentage success as the distance decreases.

In real systems, the base station layout does not follow any strict pattern. We observed that this has a negative effect on the performance. We considered a worst case situation and observed that it resulted in severe degradation of performance.

We also looked at the performance in more realistic channel models of Rayleigh fading. It was observed that although the performance is worse in frequency selective fading and flat fading channels as compared to AWGN channels, the degradation is not very severe. Performance was found to be slightly better in frequency selective fading than in the flat fading channel model and the IS-95 rake receiver was identified as the reason for the enhancement, as it exploits the additional information in multipath components.

It was concluded that imperfect power control is not a very serious problem for position location accuracy as long as the power variance is within the limits usually experienced in practice, in real systems. Although, there was a slight degradation in performance as compared to the perfect power control case, this negative effect did not increase with the small increases in the variance of power control.

We also looked into the effect of increasing user traffic and interference on TDOA PL performance and discovered that for typical user numbers for CDMA cells nowadays, there is only a slight affect on PL success percentage, which is not considerable.

7.4 Solutions Proposed for Improved Performance

To improve the performance of the TDOA PL in CDMA systems, we suggested and experimented with a few methods and presented the results. Following is a discussion on the methods proposed in this work.

Using Higher Power for 911 User Signal: It was proposed that the handset of user dialing 911 can be instructed to transmit at relatively higher power to improve the signal quality at the neighboring base stations. It was shown that instead of just switching to the maximum power, it would be more practical and realistic to increase the mobile transmit power in increments, until the desired signal quality at the neighboring cell sites is obtained.

It was shown that when we cancel the strong 911 user signal, its negative effect on the received signal quality of other users is eliminated and the system BER is restored to its normal values. Hence, this method presents a very feasible option to increase the accuracy and coverage of the E-911 service within the service area.

Parallel Interference Cancellation at Other Base Stations: Another technique that was suggested, was the use of parallel interference cancellation at other base stations to improve the reception of the 911 user's signal at the neighboring cell sites. It was proposed that if other base stations detect and cancel their own users before detecting the 911 user, it will decrease the MAI for the desired 911 user signal.

Simulations showed that this method also improves the TDOA PL performance. However, it was observed that the improvements gained through this method are smaller as compared to the method discussed previously. And another drawback with this approach is that it is computationally much more intensive than the other technique. In the previous method, we just have to cancel one user which has the strongest received signal, whereas, in this method each neighboring cell has to cancel all of its users' signals. Hence, this technique is not as feasible as the method of using higher power transmission for the 911 mobile.

The Improved TDOA Estimation Method: The cross-correlation process poses some problems in CDMA systems as the signals of all the users are overlapping in time and frequency domains and also exhibit the same periodic properties. Hence, it is a problem to find the TDOA belonging to the 911 user when we cross-correlate the received signals at the base stations. The method proposed and used in this work solved this problem by replacing the composite signal snap shot by the desired user's spread spectrum signal, bit by bit. In this way, we only get one TDOA estimate at the cross-correlator output, which belongs to the desired user.

It was observed that when this method is used, errors in the TDOA estimates always occur in discrete amounts which is always in multiples of the bit duration. This occurs in almost all cases. This property can be exploited and we can identify the TDOA errors, because even one bit duration is much more than the maximum possible TDOA. Hence, we can correct the TDOA estimate, once it is found to be in error, by subtracting an appropriate multiple of bit duration. This method was applied and the results were obtained.

It was observed that this method keeps the errors below the required threshold in almost all cases and gives highly consistent and better results than the unmodified simple TDOA estimation. This method can always be applied if the bit rate, spreading gain of the CDMA system and the maximum possible TDOA (determined by the separation between the given pair of base stations) are adjusted in such a way that the duration of a single bit is always more than the maximum possible TDOA.

7.5 Contributions of this Research

Among the contributions of this work are:

- Comparative analysis of different methods and algorithms for TDOA position location and selection of the ones that are optimum.
- Method for cross-correlating received CDMA signals.
- Evaluation of performance according to a measure suitable for wireless E-911.
- Optimum observation window length for CDMA IS-95 systems.
- Proof of feasibility of the high transmit power method for the 911 mobile.
- Application of parallel interference cancellation at neighboring base stations for higher TDOA accuracy.
- Improved TDOA estimation method for reducing predictable errors.

7.6 Future Research

The work done in this research can be extended in many ways. One of the interesting observations made in this research was the negative effect of non-ideal base station arrangement on the PL accuracy. It was seen that if we deviate from the ideal hexagonal cellular layout, then the effect of errors in TDOA estimation on the overall PL errors increases. Since cellular layouts in real situations seldom follow the ideal hexagonal layout, hence we can expect that performance in real systems will also degrade as compared to the case with ideal cellular layout. Hence, it would be a useful contribution if practical cellular patterns can be graded in terms of their GDOP values. In this way, it may be possible to compare different layout designs from the standpoint of TDOA PL and to chose the ones that are better suited for this application. Hence, GDOP measurements may also become a factor for choosing cell sites beside the coverage requirements and real estate issues.

Another avenue of progress may be the study of different ways of combining information when more than one position location method is used to locate the mobile units such as the combination of AOA and TDOA methods. It is of importance in such hybrid systems that the overall PL solution should be able to combine the results from both methods in such a way that the inaccuracies in the results from both the methods should not add to each other, thus adversely affecting the overall PL solution. The resultant PL fix from the combination should be more accurate than the one obtained from either of the two solutions.

Another area of research may be to study the inaccuracies resulting from the total absence of a LOS component in the 911 user's signal. In this study we had assumed that even when there are multiple signal components, there always is a LOS component which may though sometimes be weaker than the later arriving components. However, if we don't have even a very weak LOS component, then the earliest arriving component other than the LOS will be used to compose the respread signal for cross-correlation. This would result in errors in TDOA estimation. The study of this type of situation is important because there can be such cases in real environments where there is no LOS component at all.

Apart from the study of the TDOA method itself, research can also be directed towards some related technical issues. There may be some situations when only one base station is able to receive the signal from the 911 mobile. Such a situation may occur in rural or suburban areas where extensive coverage is not needed. One of the solutions proposed for such situations is to use a combination of AOA and TOA methods. However, if putting antenna arrays is not desirable in such cases, then one way to use TDOA method may be the use of "sniffer" receivers in the cell just for the purpose of taking signal snap shots. For the TDOA methods, at least two additional receivers will be needed in addition to the base station receiver itself. A similar technical issue that can be explored is the effect of additional position location data on the data lines between the base stations and switching center. If the position location process is to be executed only for 911 calls, then the additional traffic may not be significant. However, if the position location is performed more often, then the load on the data lines may become significant.

It may also be interesting to study the problems faced when the TDOA method proposed in this research are practically implemented in the CDMA systems now being deployed. In this work we suggested that the signal snap shot should be recomposed with the respread data of the desired user before performing the cross-correlation. From an application standpoint, it is important to know exactly at which stage of processing should this process be executed and how much additional processing load would it cause for the switching center.

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