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Locating an IS-95 Mobile Using Its Signal

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1 Introduction

Recently, there has been a great deal of interest in developing mobile location systems for cellular telephones. The motivation is a series of regulations passed by the Federal Communications Commission (FCC) in 1996 [1]. The purpose of these regulations is to improve the 911 service provided to mobile phone users. The new FCC regulations will require all cellular service providers to implement a new level of emergency call service called Enhanced 911 (E911).

The final phase of E911 service must be implemented by 2001. By this date, all cellular networks must be able to determine the physical location of a mobile making a 911 call. The location system must be able to provide location estimates with an accuracy of 125 m RMS. Implementing this type of location system for an IS-95 cellular network is the focus of this paper.

Developing a reliable location system for IS-95 cellular networks is a priority. CDMA cellular systems are becoming a very popular choice for providing digital cellular and PCS service. A recent survey revealed that CDMA cellular networks are already located in 25 countries, serving over 6 million subscribers [2].

This paper investigates implementing mobile location on IS-95 CDMA systems. First, a detailed characterization of the mobile location problem is performed. Then, the accuracy of some conventional location techniques when applied to this problem are investigated and some new approaches for locating an IS-95 mobile are presented.

2 IS-95 System Simulation

Most conventional location techniques use the signal being transmitted by a mobile to determine its location. Generally, the mobile's signal is received at several receivers with known positions. After reception, some characteristics of that signal are combined with the known positions of the receivers and used to solve for the mobile's position. This could be the angle-of-arrival of the signal, the time-of-arrival of the signal, or even the received strength of the signal. For practical reasons, the reception points are usually existing base stations. This minimizes the extra equipment that has to be added to the network to implement location.

There are two characteristics of an IS-95 cellular system that make receiving a mobile at more than one base station difficult. The first is interference from other users. IS-95 uses code division multiple access which means that many mobiles in the system transmit on the same carrier. This produces a high level of interference that can obscure the signal of the mobile being located, depending on the relative received signal power of the mobile. The second characteristic is power control. As a mobile gets closer to the base station it is communicating with, it turns its power down. If the mobile's signal is also being received at a base station in a neighbouring cell for location purposes, the received power of the mobile's signal at that point is considerably reduced.

The received level of the mobile's signal will dictate what location techniques are practical for this problem. Therefore, it is useful to have a detailed picture of the signal levels that can be expected from an IS-95 mobile at a base station in a neighbouring cell.

The cellular system simulated in this paper has a seven cell topology as shown in Figure 1. The base stations in the center of each cell are indicated by the numbered circles. Each cell is scattered with uniformly distributed interfering users that remain stationary for the entire simulation. It is assumed that the mobile being located is in the center cell. This mobile is referred to as the quarry. The quarry is moved in a grid pattern in the center cell. For each grid position, the signal to interference ratio (SIR) of the quarry at base station 1 is determined. Due to the symmetric nature of the cell arrangement, the SIR values at base station 1 will be representative of the values at the other neighbouring base stations.

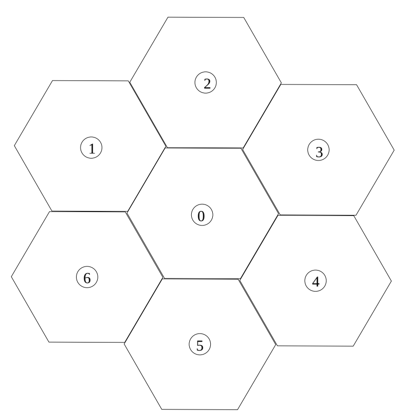

Figure 1: Cell Topology

The signals from each mobile in the system are generated separately and then combined. The QPSK signal from each mobile is simulated using the long and short code spreading schemes and the pulse shape filtering specified in the IS-95 standard [3]. The signals have a chip rate of 1.2288 Mcps and are simulated at 2 samples per chip. An omni-directional antenna is assumed for each of the mobiles and 120 degree sectorizing antennas are assumed for the base stations. An approximation equation for a non-ideal antenna gain pattern for the sectorized antennas is used from a paper by Wang *et. al.* [4].

The simulations are performed using perfect mobile power control. Initial mobile transmit levels are calculated using the 73 dB rule [3]. Those power levels are then adjusted so every mobile in the system is received at exactly the same power at the base station in their respective cells. This is an approximation to simplify the simulation. Due to the finite response time of closed loop power control in a real system, mobile received power levels will usually vary 1-2 dB from ideal levels.

The channel model used for the simulations is a simple log-distance path loss model, where the received power, P_{ld}, is calculated using Equation 1 [5].

$$P_{ld} = k(d)^{-n} \tag{1}$$

The constant k is calculated using the transmit power of the base station, the antenna gain patterns of the base station and mobile and some properties of the channel. The d term is the distance of the mobile from the base station and n is the path loss exponent of the channel. This channel model gives the average received power of a mobile's signal.

Three different types of coverage areas are simulated. The area types are urban, suburban and rural. The number of users per cell, channel path loss exponent and cell radius for each of these coverage areas are listed in Table 1.

Coverage Area	Path Loss Exponent	Number of Users	Cell Radius (m)
Urban	4	25	750
Suburban	2.7	20	1500
Rural	2.7	15	5000

Table 1: Coverage Area Parameters

The simulation results are plotted using contour plots. The contour plots show what the SIR levels for the quarry's signal are at base station 1 in different regions of the center cell. The plot for the urban simulation is shown in Figure 2, the suburban plot is shown in Figure 3 and the rural plot is shown in Figure 4.

All three plots show that the region of lowest SIR is in the center of the cell. This is due to power control reducing the transmit power of the quarry as it gets closer to the base station in the center cell. The roughly symmetric rings of contour lines around the center of the cell show that power control has an even greater effect on the attenuation of the signal with distance, while the mobile is close to the center base station.

The plots also indicate that a larger portion of the coverage areas of the less populated area types are covered by regions of higher SIR. This means that a mobile location technique that needs a strong signal from the mobile would be more effective in a rural area than a dense urban one.

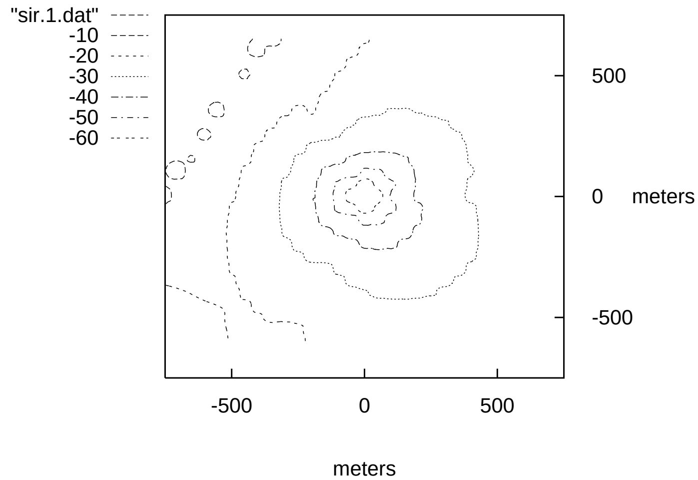

Figure 2: Urban SIR Contour Plot

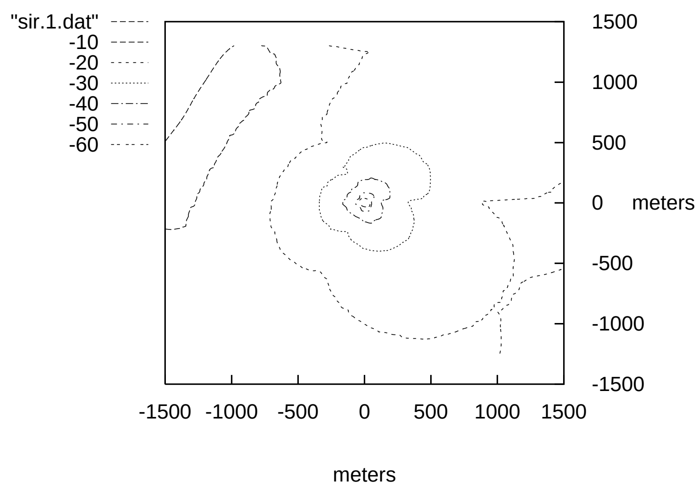

Figure 3: Suburban SIR Contour Plot

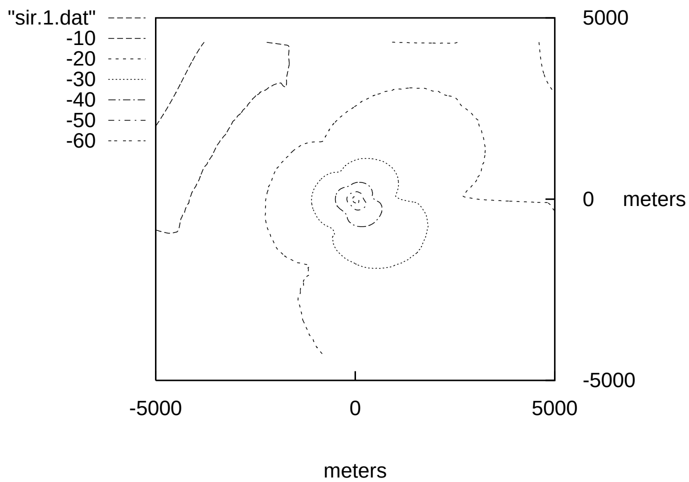

Figure 4: Rural SIR Contour Plot

It is also important to examine the worst case SIR values for each of the three cases. The FCC regulations require that even if the location system isn't able to satisfy the 125 m accuracy requirement every time, it should always be able to provide some kind of location estimate. That means the system should be able to receive the mobile's signal no matter where it is in the cell. It therefore must be designed to handle the worst case received SIR. The worst case SIR values for the three simulations are shown in Table 2. These values assume that the mobile cannot get closer than 75 m to the base station. Therefore, all SIR values inside a 75 m square in the center of the cell are ignored when determining the worst case SIR.

Coverage Area	Worst Case SIR (dB)
Urban	-53.9
Suburban	-51.1
Rural	-58.3

Table 2: Worst Case SIR Values

These values indicate that approximately the same worst case SIR can be found in all three coverage area types. This means that a location system would have to be designed to handle the same worst case signal levels, no matter where it was being deployed.

Simulations are, at best, an approximation of the actual signal levels that can be expected in a real system. While the absolute signal values given above are only estimates, they do show that extremely weak signals are possible when trying to receive a IS-95 mobile's signal at a neighbouring base station. As a result, any location system designed to use the signal from the mobile must be prepared to handle these signal levels.

3 Mobile Signal Location

Most traditional location techniques use some characteristic of the mobile's signal to determine its location. The characteristic used for the location systems in this section is the time-of-arrival (TOA) of the signal. TOA based location was investigated due to its advantages over angle-of-arrival (AOA) and signal strength based location methods.

Signal strength location takes advantage of the fact that the average received power of a radio signal decays in a known fashion with distance. The received signal power of the mobile at several locations can be used to calculate the distance of the mobile from those locations. These distances can then be used to calculate the coordinate position of the mobile. The disadvantage of using this method is the large, random deviations from the mean received signal strength caused by small scale channel effects and shadowing. This can result in received power variation of 10 dB or more from the mean that translates into significant position error.

AOA systems are considerably more accurate than signal strength based ones. However, this technique also has disadvantages. First, determining the AOA of a signal usually requires an antenna array. This increases the amount of modification required on the base stations. AOA based systems also perform slightly worse than TOA based ones in a multipath environment and the accuracy of AOA systems tends to degrade as the distance to the mobile increases [6].

TOA based schemes have some advantages that make them a good choice for mobile location. First, TOA location systems can be implemented using existing base station antennas. This reduces implementation complexity. The second advantage is that TOA systems are fairly robust in multipath channels. Multipath reflections arrive after the first line-of-sight (LOS) component of the signal. This means that as long as the rising edge of the signal is used, the multipath channel won't cause as much error for a TOA system as it does for the previous two techniques.

One possible disadvantage of the system is that it requires several different reception points to have very good time synchronization. One solution to this problem is to synchronize the different base stations using the time reference from GPS receivers. Since GPS receivers are already being used in IS-95 base stations, this can be implemented with very little extra cost.

In order to locate a mobile using TOA, several base stations in the vicinity of the mobile determine the TOA of the mobile's signal at their respective locations. These TOA estimates are then forwarded to a central location and combined with the known base station locations to determine the location of the mobile.

While absolute TOA can be used to solve for mobile position, a common technique is to use time difference of arrival (TDOA). In this technique, the difference of the time-of-arrival of the mobile's signal at two different base stations is used to determine its location. This is known as hyperbolic trilateration. The TDOA of a mobile's signal is given by

$$t_i - t_j = \frac{d_i - d_j}{c} \tag{2}$$

where t_i and t_j are the TOA's of the mobile's signal at base station i and j, respectively. The distance of the mobile from base station i and j is given by d_i and d_j and the speed of light is denoted by c. These distances can be expressed in terms of the coordinate position of the mobile (x, y) and the known positions of base station i and j, given by (x_i, y_i) and (x_j, y_j). After this substitution, the equation becomes a function only of the unknown position of the mobile.

This equation defines a hyperbola. Several TDOA measurements define several hyperbolas and the mobile's position is determined by calculating the intersection of those hyperbolas. While there are others, a popular technique for performing this calculation is using a least squares solution to a linearized version of the hyperbolic equations [7]. This technique was used for the simulations in this section.

Locating a cellular mobile using the TOA of its signal is a popular technique. Several TOA mobile location systems have been proposed for CDMA as well as other cellular systems. Several systems have been proposed that use round-trip time delay to locate the mobile [8] [9] [10]. Other systems use the actual TOA of the mobile's signal to determine its position [11] [12] [13] [14].

The major problem that must be overcome when attempting to locate an IS-95 mobile using TOA is the extremely low signal levels shown in Section 2. The first solution to this problem is to simply ask the mobile being located to turn up its transmit power. This can be done using the Power Up Function (PUF). This causes the mobile to turn up its power to its maximum level and transmit a known spreading sequence. The TOA of the mobile's signal can then be determined using a sliding correlator at each base station that correlates a copy of the signal transmitted by the mobile with what is being received over the channel. A spike in the correlator output indicates the TOA of the signal. The big disadvantage of this approach is the disruption it causes to the other users. While a mobile transmits at maximum power, the interference experienced by the other users in the vicinity is increased sharply, which corrupts the signals of the other mobiles. This results in a decrease in call quality and system capacity.

Another solution is to increase the length of the correlation used to determine the TOA of the mobile's signal. This allows the processing gain of the correlation to compensate for the weakness of the mobile's signal. Ideally, the length of the correlation would be increased to the point where the mobile does not have to turn up its power at all. However, in order to overcome the SIR levels shown in Section 2, correlations on the order of 10^6 chips would be required. At IS-95 spreading rates, the duration of the correlation would be 1 second or more.

Correlations this long will experience problems with the non-stationarity of the wireless channel. The coherence time of a wireless channel is given by

$$T_c \approx \frac{9}{16\pi f_m} \tag{3}$$

where f_m is the maximum Doppler shift of the channel. The Doppler shift is equal to v/λ where v is equal to the velocity of the user and λ is the wavelength of the carrier. For a velocity of 100 km/h and a carrier frequency of 900 MHz, the Doppler shift is 83.3 Hz. This gives a coherence time of approximately 2.1 ms. A correlation much longer than this would experience severe degradation of its processing gain. In order to overcome this problem, the long correlation would have to be divided up into smaller correlations and non-coherently combined.

Regardless of how the problem of low SIR is overcome, it is worthwhile investigating the accuracy of a TOA location system that operates on a mobile's signal. The simulations used to evaluate the accuracy of TOA location use the same cell topology as shown in Figure 1. Several random quarry positions are generated in the center cell. For each position, the received signal from the quarry is simulated at each of the base stations in the system. Each base station correlates the signal they receive over the radio channel with a clean copy of the mobile's signal. The peak of that correlation is used to determine the TOA of the signal. Once the TOA estimates are determined, the coordinate position of the mobile is solved using a least-squares approach [7]. Error statistics are collected for the quarry position estimates. The quarry's QPSK signal is simulated at 2 samples/chip using the spreading schemes and pulse shaping specified in the IS-95 standard [3].

A four ray channel model is used for the simulation. The model consists of a single line-of-sight (LOS) ray, followed by 3 multipath interferers, shown in Figure 5. Since the first ray is line-of-sight, $T0 = d_i/c$, where d_i is the distance from the quarry to base station i and c is the speed of light. The arrival times, $T1$, $T2$ and $T3$ are exponentially distributed after $T0$. When generating these arrival times, a value y_i is first generated from a uniform distribution between 0 and 1. The value y_i is then mapped to a value x_i using the function $y = f(x) = 1 - e^{-x}$. The number x_i is a unitless value that is multiplied by a value t_{dmax}. This value is called the maximum delay spread of the channel and has units of seconds. For this simulation, the maximum delay spread was 10 μs. When 400,000 impulse responses are simulated with this value, the average RMS delay spread of the generated impulse responses is $1.26 \cdot 10^{-6}$ seconds. This is a typical average RMS delay spread value found in an outdoor channel [5].

Initially, the TOA detection algorithm used on the correlation peaks was a simple rising edge threshold method. This method selects a sample on the rising edge of the correlation peak and uses that sample time as the TOA of the signal. The method assumes that the system would know what cell the mobile is located in. This defines a certain time window in which the mobile's signal can arrive. Within that window, the rising edge method determines the maximum sample amplitude in the window, A_{max}, and the standard deviation of the amplitude of the samples, σ. A threshold amplitude, A_t is defined as

$$A_t = A_{max} - \gamma(A_{max} - \sigma) \tag{4}$$

where γ is a constant between 0 and 1. The first sample in the TOA window that exceeds A_t is considered the rising edge of the spike at the correlation output and used as the TOA of the signal. For these simulations, γ is set to 0.6.

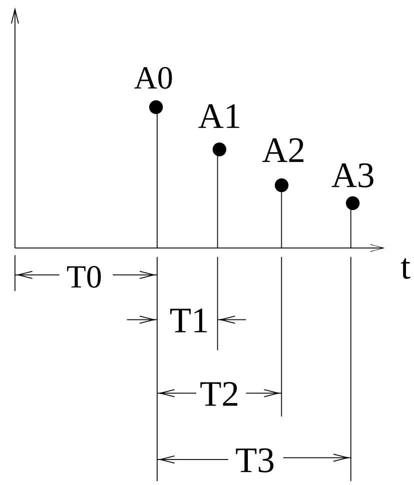

Figure 5: Four Ray Channel Impulse Response

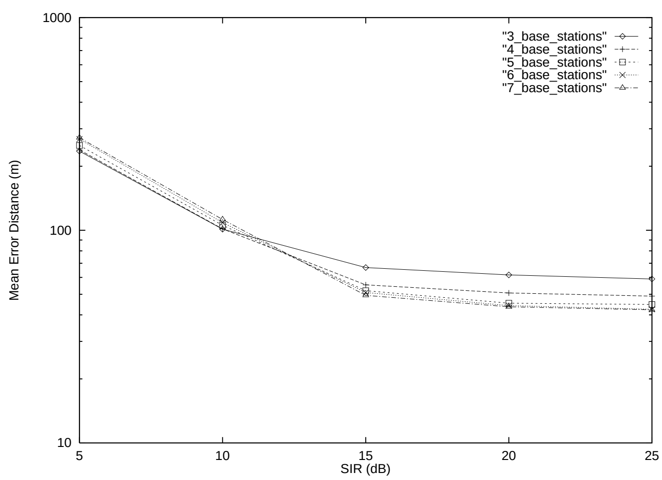

Figure 6: Mean Radial Error Distance (Rising Edge Detection, 4 Ray Channel)

The mean and standard deviation plots of the radial error distance of the position estimates are given in Figures 6 and 7, respectively. Radial error distance is defined as the distance between the position estimate returned by the algorithm and the actual position of the mobile. The mean and standard deviation are plotted versus the SIR of the correlation spike used to determine the TOA. Each plot shows 5 curves. Each curve is generated assuming TOA estimates are available from a different number of base stations. In all cases, the base stations closest to the mobile are used to generate the TOA estimates.

The plots show two things. First, increasing the number of base stations providing TOA estimates increases the accuracy of the simulations. The exception to this is at low SIR levels, where adding more estimates just introduces more error into the system. The plots also show that with sufficient SIR, even with this crude TOA detection method, TOA location can satisfy the accuracy requirements of the FCC.

However, even though this technique satisfies the FCC requirements in these sim-

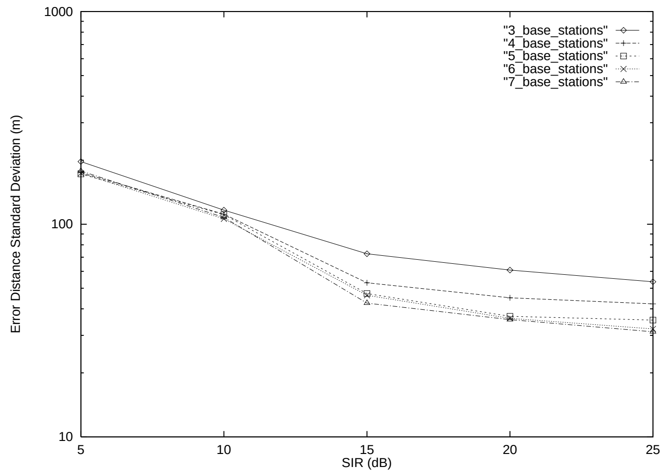

Figure 7: Radial Error Distance Standard Deviation (Rising Edge Detection, 4 Ray Channel)

ulations, situations could arise in a real cellular network where the location estimates produced by this approach would not be accurate enough. This relates to the geometry of the location system. In this simulation, the mobile is uniformly surrounded by several nearby base stations. This is an example of good geometry that is likely to produce good position estimates. A situation could arise where the mobile is located a significant distance outside a cluster of base stations being used to determine the TOA of the mobile's signal. This is an example of poor geometry that would yield poor position estimates.

A quantitative measure of geometry is the Dilution of Precision (DOP) factor. This relates the standard deviation of position estimates, σ_p, to the standard deviation of TOA estimates, σ_{TOA}.

$$\sigma_p = (DOP)(\sigma_{TOA}) \tag{5}$$

Situations commonly arise where the DOP factor is greater than one. This means that errors in the TOA estimate of the mobile's signal have to be less than 125 m to satisfy the FCC requirements in these situations.

One way of improving the TOA estimates is to use super-resolution techniques [15]. In this paper, the Root-MUSIC algorithm is used to improve TOA estimate accuracy, since it had been successfully applied to other cellular mobile location systems [12] [13].

The Root-MUSIC algorithm is applied on the FFT of the correlation peak. It transforms the correlation peak frequency data back into the time domain, giving a finely resolved picture of the arrival times of the multipath components of the signal. The algorithm produces several poles. Each of the multipath arrivals of the correlation peak corresponds to a pole on the unit circle. The position of the LOS pole is used to calculate a resolved value for the TOA of the signal.

The simulations described above were rerun using Root-MUSIC super-resolution of the TOA estimates. The mean radial error distance for these simulations is shown in Figure 8 and the standard deviation of the radial error distance is shown in Figure 9.

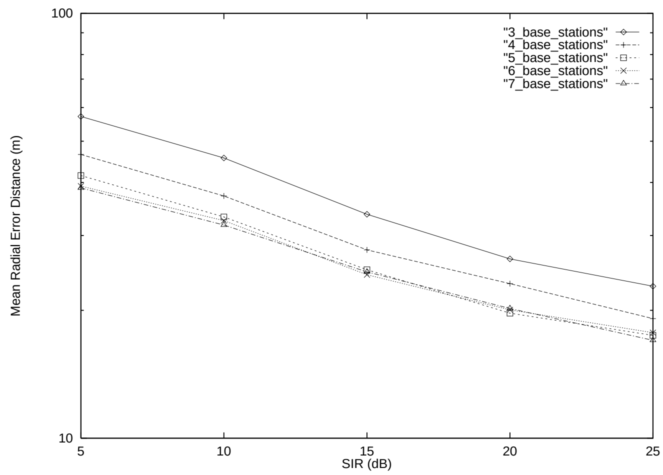

Figure 8: Mean Error Distance (Super-resolution, 4 Ray Channel)

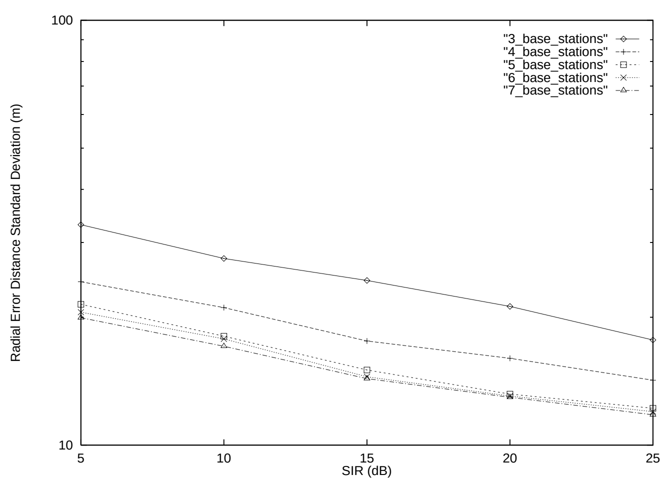

Figure 9: Error Distance Standard Deviation (Super-resolution, 4 Ray Channel)

These results show a significant accuracy improvement over the rising edge threshold technique. While it might not be needed in areas of good geometry, super-resolution would be a good technique for improving accuracy in areas of poor geometry.

4 Conclusion

The simulations presented in Section 2 show that due to interference and power control, it is possible to encounter severely low signal levels when trying to receive a mobile at a base station in a neighbouring cell. Any location system for IS-95 mobiles must deal with these very low signal levels.

Section 3 gave an analysis of a TOA based location scheme that operates using the mobile's signal. The simulation results show that this approach looks very promising for providing accurate position estimates. For areas of good geometry, even a very crude threshold based TOA scheme is able to satisfy the accuracy requirements of the FCC. In addition to this, it is possible to enhance the accuracy of the TOA location technique for areas of poor geometry. The enhancement method investigated in this paper was the Root-MUSIC algorithm. Simulation results show that significant accuracy improvements are possible using this approach.

Mobile location for IS-95 cellular systems is a very complex problem. It is quite possible that a single solution will not be found that will be able to provide reliable position estimates under all circumstances. If this is the case, the final solution to the problem will likely consist of several different techniques that work together to locate the mobile. TOA location using the mobile's signal would make an effective contribution to such a system.

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