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Radiolocation Techniques

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24.1 Introduction

Several location technologies have been developed and commercially deployed for locating wireless radios including Decca, Loran, Omega, the Global Positioning System (GPS), and the Global Navigation Satellite System (GLONASS). GPS, originally developed for military use, is perhaps the most popular commercial location system today, providing location accuracies to within 100 m.

All of the above systems use a location technique known as radiolocation. A radiolocation system operates by measuring radio signals traveling between a mobile station (MS) and a set of fixed stations (FSs). The measurements are then used to determine the length and/or direction of the radio paths, and the MS's position is derived from known geometrical relationships. In general, measurements from $n + 1$ FSs are necessary to locate an MS in n dimensions. To achieve high accuracy in a radiolocation system, it is necessary that a line-of-sight (LoS) exist between the MS and FSs. Otherwise, large errors are likely to be incurred.

With the above mentioned radiolocation technologies, the MS formulates its own position by using signals received from the FSs. This form of location is often referred to as *self-positioning*. In these systems, a special receiver is placed in the MS to calculate the MS's position. Alternatively, the position of the MS could be calculated at a remote location by using signals received at the FSs. This form of radiolocation is known as *remote-positioning* and requires a transmitter for the MS.

Over the last several years, there has been increased interest in developing location services for wireless communications systems. An array of applications for such technology exists including location sensitive billing, fraud detection, cellular system design and resource management, fleet management, and Intelligent Transportation Services (ITS) [8]. The greatest driving force behind location system development in wireless systems has been the FCC's Emergency-911 (E-911) requirements, where a wireless E-911 caller must be located within an *rms* accuracy of 125 m in 67% of the cases [4]. Adding GPS to the handset is not a universal solution because of the large pool of existing handsets. Remote-positioning radiolocation is a natural choice since it requires no modification of existing MS handsets and most, if not all, of the complexity could be incorporated into the network side.

In this chapter, techniques for locating wireless users using measurements from radio signals are described. A few algorithms for location estimation are developed along with a discussion of measures of accuracy. The radiolocation methods that are appropriate for wireless location and the major sources of error in various mobile cellular networks are discussed.

24.2 Description of Radiolocation Methods

Radiolocation systems can be implemented that are based on angle-of-arrival (AoA), signal strength, time-of-arrival (ToA), time-difference-of-arrival (TDoA), or their combinations. These are briefly discussed below.

24.2.1 Angle of Arrival

AoA techniques estimate the MS location by first measuring the arrival angles of a signal from a MS at several FSs (Fig. 24.1). The AoA can be determined through the use of directive antennas or antenna arrays. Simple geometric relationships are then used to determine the location by finding the intersections of the lines-of-position (see Fig. 24.1). To generate a position fix, the AoA method requires that the signal transmitted from the MS be received by a minimum of two FSs.

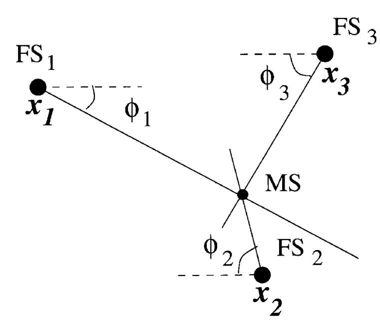

FIGURE 24.1: The measured angles, ϕ_i, determine the position of the MS for a given FS geometry.

24.2.2 Signal Strength

Radiolocation based on signal strength measurements uses a known mathematical model describing the **path loss** attenuation with distance. Since measurement of signal strength provides a distance estimate between a MS and FS, the MS must lie on a circle centered at the FS. Hence, for signal strength based radiolocation, the lines-of-position are defined by circles. By using measurements from multiple FSs, the location of the MS can be determined from the intersection of circles (Fig. 24.2).

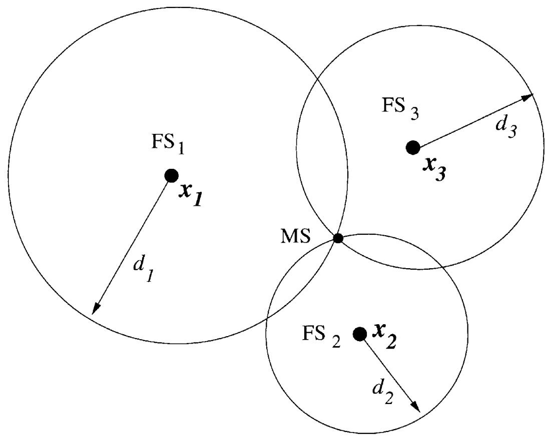

FIGURE 24.2: For signal strength and ToA based radiolocation systems the location of the MS is at the intersection of circles of radius d_i.

A second method makes use of premeasured signal strength contours around each FS. Received signal strength measured at multiple FSs can be mapped to a location by overlaying the contours for each FS. This technique can be used to combat **shadowing**, as discussed in Section 24.6.1.

24.2.3 Time-Based Location

The final class of radiolocation techniques are those based on estimating the ToAs of a signal transmitted by the MS and received at multiple FSs or the TDoAs of a signal received at multiple pairs of FSs. In the ToA approach, the distance between a MS and FS is measured by finding the one-way propagation time between the MS and FS. Geometrically, this provides a circle, centered at the FS, on which the MS must lie. Given a ToA at FS i, the equation for the circle is given by

$$\tau_i = D_i\left(\boldsymbol{x}_s\right)/c \tag{24.1}$$

where $D_i(\boldsymbol{x}_s) = \|\boldsymbol{x}_i - \boldsymbol{x}_s\|$, $\boldsymbol{x}_i$ is the position of ith FS, $\boldsymbol{x}_s$ is the position of the MS and c is the speed of light. By using at least three base stations to resolve ambiguities, the MS's position is given by the intersection of circles (Fig. 24.2). Since the ToA and path loss based signal strength methods are based on distance measurements between the MS and FSs, they are often referred to as *ranging* systems.

In the TDoA approach, time differences of arrival are used. Hence, the time of signal transmission need not be known. Since the hyperbola is a curve of constant time *difference* of arrival for two FSs, a TDoA measurement defines a line-of-position as a hyperbola, with the foci located at one of the two FSs. For FSs i and j, the equation of the hyperbola, $\rho_{i,j}$, for a given TDoA is

$$\rho_{i,j} = \frac{D_i\left(\boldsymbol{x}_s\right) - D_j\left(\boldsymbol{x}_s\right)}{c}\,. \tag{24.2}$$

The location of the MS is at the intersection of the hyperbolas (Fig. 24.3). In general, for N FSs receiving the signal from the MS, $N-1$ non-redundant TDoA measurements can be made. Thus, a MS can be located in $N-1$ dimensions.

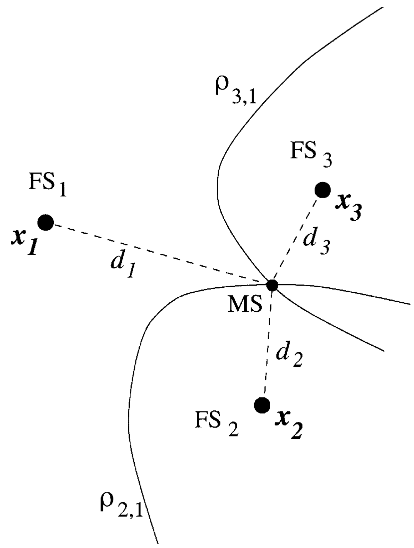

FIGURE 24.3: For TDoA based radiolocation the position of the MS is at the intersection of hyperbolas. The curves represent constant differences in distance to the MS with respect to the first FS, $\rho_{i,1} = d_i - d_1$.

24.3 Location Algorithms

When there are no measurement errors, the lines-of-position intersect at a point and a geometric solution can be obtained for the MS's location by finding the intersection of the lines of position. However, in practice, measurement errors occur and the lines of position do not intersect at a point. Consequently, other solution methods must be utilized. In the following, a solution approach is developed for two-dimensional location systems where the MS is located at $\boldsymbol{x}_s = [x_s, y_s]^T$ and the FSs are located at $\boldsymbol{x}_i = [x_i, y_i]^T$ for $i = 1, \ldots, N$.

24.3.1 Problem Formulation

In general, the $N \times 1$ vector of noisy measurements, $\boldsymbol{r}$, from a set of N FSs can be modeled by

$$\boldsymbol{r} = \boldsymbol{C}(\boldsymbol{x}_s) + \boldsymbol{n} \tag{24.3}$$

where $\boldsymbol{n}$ is an $N \times 1$ measurement noise vector, generally assumed to have zero mean and an $N \times N$ covariance matrix Σ. The system measurement model $\boldsymbol{C}(\boldsymbol{x}_s)$ depends on the location method used:

$$\boldsymbol{C}(\boldsymbol{x}_s) = \begin{cases} \boldsymbol{D}(\boldsymbol{x}_s) & \text{for ToA} \\ \boldsymbol{\mathcal{R}}(\boldsymbol{x}_s) & \text{for TDoA} \\ \Phi(\boldsymbol{x}_s) & \text{for AoA} \end{cases} \tag{24.4}$$

where

$$\boldsymbol{D}(\boldsymbol{x}_s) = [\tau_1, \tau_2, \ldots, \tau_N]^T \tag{24.5}$$

$$\boldsymbol{\mathcal{R}}(\boldsymbol{x}_s) = \left[\rho_{2,1}, \rho_{3,1}, \ldots \rho_{N,1}\right]^T \tag{24.6}$$

$$\Phi(\boldsymbol{x}_s) = [\phi_1, \phi_2, \ldots, \phi_N]^T \ . \tag{24.7}$$

The terms τ_i and $\rho_{i,1}$ are the ToAs and TDoAs defined in Eqs. (24.1) and (24.2), respectively, where without loss of generality, the TDoAs are referenced to the first FS. If the time of transmission τ_s is needed to form the ToA estimates, it can be incorporated into $\boldsymbol{x}_s$ as a parameter to be estimated along with x_s and y_s. The unknown parameter vector can then be modified to $\boldsymbol{x}_s = [x_s, y_s, \tau_s]^T$, while the system measurement model becomes $\boldsymbol{C}(\boldsymbol{x}_s) = \boldsymbol{D}(x_s, y_s) + \tau_s \mathbf{1}$.

The AoAs are defined by

$$\phi_i = \tan^{-1}\left(\frac{y_i - y_s}{x_i - x_s}\right) \ . \tag{24.8}$$

Although not explicitly shown in the above equations, τ_i, $\rho_{i,1}$ and ϕ_i are nonlinear functions of $\boldsymbol{x}_s$.

A well-known approach for determining an estimate from a noisy set of measurements is the method of **least squares** (LS) estimation. The weighted least squares (WLS) solution is formed as the vector $\hat{\boldsymbol{x}}_s$ that minimizes the cost function

$$\mathcal{E}(\hat{\boldsymbol{x}}_s) = \left[\boldsymbol{r} - \boldsymbol{C}(\hat{\boldsymbol{x}}_s)\right]^T \boldsymbol{W} \left[\boldsymbol{r} - \boldsymbol{C}(\hat{\boldsymbol{x}}_s)\right] \ . \tag{24.9}$$

LS methods can achieve the **maximum likelihood** (ML) estimate when the measurement noise vector is Gaussian with $\mathrm{E}[\boldsymbol{n}] = 0$ and equal variances, i.e., $\Sigma = \sigma_n^2 \boldsymbol{I}$. For unequal variances, WLS with $\boldsymbol{W} = \Sigma^{-1}$ gives the ML estimate. In the following, $\boldsymbol{W} = \boldsymbol{I}$ will be assumed.

24.3.2 Location Solutions

As Eq. (24.4) indicates, $\boldsymbol{C}(\boldsymbol{x}_s)$ is a nonlinear function of the unknown parameter vector $\boldsymbol{x}_s$ so that the LS problem is a nonlinear one. One straightforward approach is to iteratively search for the minimum of the function using a **gradient descent method**. With this approach, an initial guess is made of the MS location and successive estimates are updated according to

$$\hat{\boldsymbol{x}}_s^{(k+1)} = \hat{\boldsymbol{x}}_s^{(k)} - \boldsymbol{\nu}\, \nabla \mathcal{E}\left(\hat{\boldsymbol{x}}_s^{(k)}\right) \tag{24.10}$$

where the matrix $\boldsymbol{\nu} = \mathrm{diag}(\nu_x, \nu_y)$ is the step size, $\hat{\boldsymbol{x}}_s^{(k)}$ is the estimate at time k, and $\nabla = \partial/\partial \boldsymbol{x}$ denotes the gradient vector with respect to the vector $\boldsymbol{x}$.

In order to mold the problem into a linear LS problem, the nonlinear function $\boldsymbol{C}(\boldsymbol{x}_s)$ can be linearized by using a Taylor series expansion about some reference point $\boldsymbol{x}_0$ so that

$$\boldsymbol{C}(\boldsymbol{x}_s) \approx \boldsymbol{C}(\boldsymbol{x}_0) + \boldsymbol{H}(\boldsymbol{x}_s - \boldsymbol{x}_0) \tag{24.11}$$

where $\boldsymbol{H}$ is the Jacobian matrix of $\boldsymbol{C}(\boldsymbol{x}_s)$. Then the LS solution can be formed as

$$\hat{\boldsymbol{x}}_s = \boldsymbol{x}_0 + \left(\boldsymbol{H}^T \boldsymbol{H}\right)^{-1} \boldsymbol{H}^T \left[\boldsymbol{r} - \boldsymbol{C}\left(\boldsymbol{x}_0\right)\right] . \tag{24.12}$$

This approach can be performed iteratively, with each successive estimate being closer to the final estimate. A key drawback to this approach is that an initial guess, $\boldsymbol{x}_0$, must be made of the MS's position.

The Taylor series approach introduces error when the linearized function $\boldsymbol{C}(\boldsymbol{x}_s)$ does not accurately approximate the nonlinear function. Other approaches have been developed for TDoA that avoid linearization by transforming the TDoA measurements into "pseudo-measurements." The pseudo-measurements are given by [5],

$$\boldsymbol{\varphi} = \Delta \boldsymbol{x}_s + D_1\left(\boldsymbol{x}_s\right) \boldsymbol{r} \tag{24.13}$$

where

$$\Delta = \begin{bmatrix} (\boldsymbol{x}_2 - \boldsymbol{x}_1)^T \\ \vdots \\ (\boldsymbol{x}_N - \boldsymbol{x}_1)^T \end{bmatrix} \qquad \boldsymbol{\varphi} = \frac{1}{2} \begin{bmatrix} \|\boldsymbol{x}_2\|^2 - \|\boldsymbol{x}_1\|^2 - \rho_{2,1}^2 \\ \vdots \\ \|\boldsymbol{x}_N\|^2 - \|\boldsymbol{x}_1\|^2 - \rho_{N,1}^2 \end{bmatrix} . \tag{24.14}$$

The term $D_1(\boldsymbol{x}_s)$ is nonlinear in the unknown vector $\boldsymbol{x}_s$ and can be removed by using a projection matrix that has $\boldsymbol{r}$ in its null space. A suggested projection is $\boldsymbol{P} = (\boldsymbol{I} - \boldsymbol{Z})[\mathrm{diag}(\boldsymbol{r})]^{-1}$ where $\boldsymbol{Z}$ is a circular shift matrix [5]. Projecting (24.13) with $\boldsymbol{P}$, the following linear equation results:

$$\boldsymbol{P}\boldsymbol{\varphi} = \boldsymbol{P} \Delta \boldsymbol{x}_s \tag{24.15}$$

which leads to the following linear LS solution for the location of the MS

$$\hat{\boldsymbol{x}}_s = \left(\Delta^T \boldsymbol{P}^T \boldsymbol{P} \Delta\right)^{-1} \Delta^T \boldsymbol{P}^T \boldsymbol{P} \boldsymbol{\varphi} . \tag{24.16}$$

24.4 Measures of Location Accuracy

To evaluate the performance of a location method, several benchmarks have been proposed. A common measure of accuracy is the comparison of the mean-squared-error (MSE) of the location estimate with the Cramér-Rao lower bound (CRLB) [10]. The concepts of circular error probability (CEP) [9] and geometric dilution of precision (GDOP) [6] have also been used as accuracy measures.

24.4.1 Cramér-Rao Lower Bound

For location in M dimensions, the MSE of the position estimate is given by

$$\mathrm{MSE} = \sqrt{\mathrm{E}\left[\left(\boldsymbol{x}_s - \hat{\boldsymbol{x}}_s\right)^T \left(\boldsymbol{x}_s - \hat{\boldsymbol{x}}_s\right)\right]} \tag{24.17}$$

where E[·] denotes expectation. The calculated MSE is often compared to the theoretical minimum MSE given by the CRLB which sets a lower bound on the variance of any unbiased estimator. The CRLB is the inverse of the information matrix $\boldsymbol{J}$ defined as [10]

$$\boldsymbol{J} = \mathrm{E}\left[\left(\frac{\partial p(\boldsymbol{r}|\boldsymbol{x})}{\partial \boldsymbol{x}}\right)\left(\frac{\partial p(\boldsymbol{r}|\boldsymbol{x})}{\partial \boldsymbol{x}}\right)^T\right]\Bigg|_{\boldsymbol{x}=\boldsymbol{x}_s} \tag{24.18}$$

where $\boldsymbol{r}$ is the vector of TDoA, ToA, or AoA estimates and $p(\boldsymbol{r}|\boldsymbol{x})$ is the probability density function of $\boldsymbol{r}$ conditioned on the parameter vector $\boldsymbol{x}$. Assuming Gaussian measurement noise, $p(\boldsymbol{r}|\boldsymbol{x})$ is Gaussian with mean $\boldsymbol{r}_0$ and covariance matrix $\boldsymbol{Q}$, and the CRLB reduces to

$$\text{CRLB} = \boldsymbol{J}^{-1} = c^2 \left(\frac{\partial \boldsymbol{r}_o^T}{\partial \boldsymbol{x}} \boldsymbol{Q}^{-1} \frac{\partial \boldsymbol{r}_0}{\partial \boldsymbol{x}^T} \right)^{-1} \Bigg|_{\boldsymbol{x}=\boldsymbol{x}_s} . \tag{24.19}$$

24.4.2 Circular Error Probability

A simple measure of accuracy is the CEP which is defined as the radius of the circle that has its center at the mean and contains half the realizations of a random vector. The CEP is a measure of the uncertainty in the location estimator $\hat{\boldsymbol{x}}_s$ relative to its mean $\mathrm{E}\left[\, \hat{\boldsymbol{x}}_s \,\right]$. If the location estimator is unbiased, the CEP is a measure of the estimator uncertainty relative to the true MS position. If the magnitude of the bias vector is bounded by B, then with a probability of one-half, a particular estimate is within a distance of B+CEP from the true position.

Because it is difficult to derive an exact expression for the CEP, an approximation that is accurate to within 10% is often used. The approximation for CEP is given as [9]

$$\text{CEP} \approx 0.75\sqrt{\mathrm{E}\left[\left(\hat{\boldsymbol{x}}_s - \hat{\boldsymbol{\mu}}\right)^T \left(\hat{\boldsymbol{x}}_s - \hat{\boldsymbol{\mu}}\right) \right]} \tag{24.20}$$

$$= 0.75 \sqrt{\sum_{i=1}^{M} \sigma^2_{\hat{x}_{s,i}}} \tag{24.21}$$

where $\hat{\boldsymbol{\mu}} = \mathrm{E}\left[\hat{\boldsymbol{x}}_s\right]$ is the mean location estimate and $\sigma^2_{\hat{x}_{s,i}}$ is the variance of the ith estimated coordinate, $i = 1, \ldots, M$.

24.4.3 Geometric Dilution of Precision

The GDOP provides a measure of the effect of the geometric configuration of the FSs on the location estimate. It is defined as the ratio of the *rms* position error to the *rms* ranging error [9, 6]. Hence, for an unbiased estimator, the GDOP is given by

$$\text{GDOP} = \frac{\sqrt{\mathrm{E}\left[\left(\hat{\boldsymbol{x}}_s - \hat{\boldsymbol{\mu}}\right)^T \left(\hat{\boldsymbol{x}}_s - \hat{\boldsymbol{\mu}}\right) \right]}}{\sigma_r} \tag{24.22}$$

where σ_r denotes the fundamental ranging error for ToA and TDoA systems. For AoA, σ_r^2 is the average variance of the distance between each FS and a reference point near the true position of the MS.

The GDOP is an indicator of the extent to which the fundamental ranging error is magnified by the geometric relation between the MS and FSs. Furthermore, comparing (24.21) and (24.22), we find that the CEP and GDOP are related by

$$\text{CEP} \approx (0.75\sigma_r)\,\text{GDOP} . \tag{24.23}$$

The GDOP serves as a useful criterion for selecting the set of FSs from a large set to produce the minimum location error. In addition, it may aid cell site planning for cellular networks which plan to provide location services to their users.

24.5 Location in Cellular Systems

The location requirements set forth by the FCC [4] must be met not only by the new digital cellular systems, but the older analog system as well. In cellular networks, the BSs serve the role of the FSs in the algorithms of Section 24.3.1. With several different wireless systems on the market (**AMPS**, IS-54/136 **TDMA**, **GSM**, IS-95 **CDMA**), different methods may be necessary to implement location services in each of those systems. The signal strength method is often not implemented for cellular systems because of the large variability of received signal strength resulting from shadowing and **multipath fading** (see Section 24.6.1). AoA requires the placement of antenna arrays at the BSs which may be extremely costly. The AoA measurements can be obtained from array signal processing and is not dependent on the type of cellular system deployed. Unlike AoA, the ToA and TDoA methods require that timing information be obtained from the signals transmitted by a MS which may be implemented in different ways for each cellular system. The time-based methods may also require strict synchronization of the BSs, especially the TDoA approach. The remainder of this section discusses implementation strategies for the ToA and TDoA location methods in current and future generation cellular systems.

The most straightforward approach for obtaining timing information for ToA or TDoA location is the use of signal correlation methods. Specifically, maximizing cross-correlations between the signals received at pairs of BSs will provide an estimate of the TDoAs for each pair of BSs. Of course, this approach requires that the BSs be synchronized. These techniques are necessary for implementing a location system in AMPS since no system message parameters provide useful radiolocation information.

For CDMA, different methods can be used for the uplink (MS to BS) and downlink (BS to MS). On the uplink, the timing information for ToA or TDoA can be obtained using correlation techniques. Since the BSs in IS-95 are synchronized to a GPS time reference, the time of detection of the signal from the MS can serve as a ToA time stamp. Similarly, segments of the detected signal can be sent to a central processing office for cross-correlation in order to determine the set TDoAs for the BSs. The signals for the ToA/TDoA measurements can come from the reverse traffic channel or the access channel. The reverse traffic channel could be used for E-911 calls, for example, since a voice call must be initially made. For other location applications, the location may be desired when the MS is not actively transmitting. In these cases, the MS could be prompted to transmit messages on the access channel in response to commands from its serving BS on the paging channels. Unfortunately, it may be impossible to detect the MS transmissions at other BSs due to the **near–far effect** (see Section 24.6.3), although this problem can be alleviated by having the MS power-up to its maximum power for a short time. However, the use of the power up function must be limited to emergencies (such as E-911) in order to avoid excessive interference to other users.

An alternative for location in CDMA is to utilize pilot monitoring in the MS on the downlink. To assist in the handoff process, the MS monitors the strongest pilots from the surrounding BSs. The serving BS can send a pilot measurement request order (PMRO) causing the BS to respond with a message which includes the magnitudes of the pilots in the candidate set as well as the code phase of each pilot relative to its serving BS [2]. Hence, it is possible to construct TDoA estimates from these system messages. The accuracy of the TDoA estimates is dependent on the resolution of the code phase and the synchronization of the BSs. Fortunately, for IS-95, the BSs are synchronized to a GPS time reference. However, the code phase resolution is limited to a chip time, T_c, which implies a TDoA resolution of approximately 244 m. Finally, the **soft handoff**, during which the MS communicates with nearby BSs during a handoff, can be used for location in CDMA systems as long as at least three BSs are in a soft handoff with the MS.

The TDMA-based systems also provide timing information in their system messages that can be used for ToA or TDoA location. The time alignment parameter in IS-54/136 and timing advance in GSM (both abbreviated TA) are used by each of those networks to ensure that the transmissions of MSs arrive at their serving BSs in the appropriate time slots. Each BS sends the MSs a TA value which is the amount the MS must advance or retard the timing of its transmissions. Additionally, the TA serves as a measure of the propagation time between the MS and BS. By artificially forcing the MS to handoff to two or more BSs, the location of the MS could be found using the ToA method. A primary consideration is the accuracy of the TA. For IS-54, the timing of MS transmissions are advanced or retarded in units of $T_b/2$, where $T_b = 20.6\,\mu s$ is the bit duration [1]. Hence, the TAs are accurate to $T_b/4$, or 1543 m. For GSM, the TA messages are reported in units of bits, with $T_b = 3.7\,\mu s$, which gives a TA resolution of $T_b/2$, or 554 m, in GSM [3].

An alternative for GSM is to use the observed time difference (OTD) measurements which are made at the MS without forcing additional handoffs. The OTDs are used to facilitate handoffs by estimating the amount the timing of the MS would have to be advanced or retarded if it were to be handed over to another BS. With a synchronized network, the OTDs could be used to implement a TDoA location system. Unfortunately, the GSM standard does not require that the network be synchronized. Additionally, the OTD measurements are made to the same accuracy of the TA measurements, 554 m.

Because of the high chip rate and good correlation properties of the spreading code sequences used in CDMA systems, these systems have greater potential than the other systems for accurate location estimates. It is apparent that the resolution of the timing parameters in the system messages needs to be improved in order to provide more accurate estimates of location.

24.6 Sources of Location Error

In all cellular systems, several factors can introduce error in the location estimates. Sources of error that are common to all cellular systems include multipath propagation, non-line-of-sight (NLoS) propagation and multiple-access interference (MAI). However, MAI poses a more significant problem in CDMA systems because of **power control** and the near–far effect. These effects are described below.

24.6.1 Multipath

Multipath propagation can introduce error in signal strength, AoA, ToA, and TDoA measurements. For signal-strength-based location systems, multipath fading and shadowing cause variations in the signal strength that can be as great as 30–40 dB over distances in the order of a half wavelength. Signal strength averaging can help, but low mobility MSs may not be able to average out the effects of multipath fading and there will still be the variability due to shadowing. The errors due to shadowing can be combated by using premeasured signal strength contours that are centered at the BSs. However, this approach assumes a constant physical topography since shadows will change with the tree foliage, construction/destruction of structures, etc.

For AoA-based systems, scattering near and around the MS and BS will affect the measured AoA. Multipath will interfere with the angle measurement even when a LoS component is present. For macrocells, scattering objects are primarily within a small distance of the MS and the BSs are usually elevated well above the local terrain. Consequently, the signals arrive with a relatively narrow AoA spread at the BSs. For microcells, the BSs may be placed below roof top level. Consequently, the BSs will often be surrounded by local scatterers such that the signals arrive at the BSs with a large AoA spread. Thus, the AoA method may be impractical for microcells.

In time-based location systems, the ToA or TDoA estimates can be in error even when there is a LoS path between the MS and BS. Conventional delay estimators, which are usually based on correlation techniques, are influenced by the presence of multipath fading. The result is a shift in the peak of the correlation away from the true value. Conventional delay estimators will detect a delay in the vicinity of these later arriving rays.

24.6.2 NLoS Propagation

With NLoS propagation, the signal transmitted from the MS (or BS) is reflected or diffracted and takes a path that is longer than the direct path or received at a different angle (Fig. 24.4). Obviously, the effect on an AoA system can be disastrous if the received AoAs are in a much different direction than the true AoAs. For the time-based systems, the measured distances can be considerably greater than true distances. For instance, for ToA location in the GSM system, the typical ranging error introduced by NLoS propagation can average 400–700 meters [7]. NLoS propagation will corrupt the ToA or TDoA measurements even when high resolution timing techniques are employed and even if there is no multipath fading.

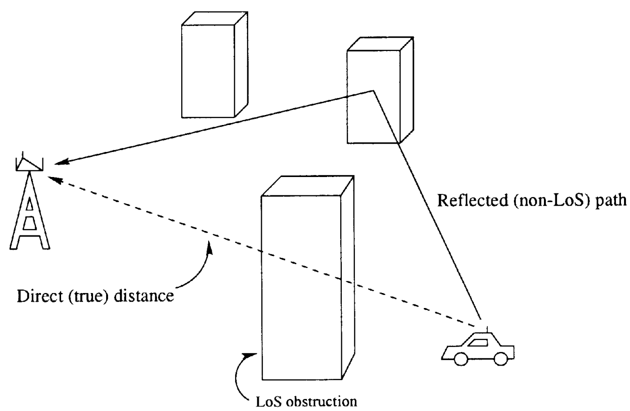

FIGURE 24.4: Propagation in a NLoS environment where signals are received from a reflection rather than a direct (LoS) path.

24.6.3 Multiple-Access Interference

All cellular systems suffer from cochannel interference. The transmissions of other users interfere with the signal of the desired user reducing the accuracy with which location measurements can be made. The problem is most evident in CDMA systems where the users share the same frequency band. As a result, signals from higher-powered users may mask the signals of the lower-powered users, a phenomenon known as the near–far effect. To combat the near–far effect, power control is used. However, for a location system where multiple BSs must receive the transmission from the MS, the near–far problem still exists because the MS is not power-controlled to the other BSs.

Consequently, the signal from the MS may not be detected at enough BSs to form a location estimate. As mentioned in Section 24.5, it may be possible, for instance in E-911 situations, for the MS to power up to maximum level and, therefore, mitigate the near–far effect. A further possibility is to take advantage of soft handoffs. However, the MS must be in position for a three-way soft handoff to be located.

24.7 Summary and Conclusions

This chapter has provided a brief introduction to radiolocation techniques for wireless systems. Several algorithms were developed for locating a MS using AoA, ToA, and TDoA, and measures of locator accuracy were described. For location services in mobile cellular networks, many possibilities exist. However, it is apparent that none has the current capability of providing high accuracy location estimates to meet the FCC requirements.

Defining Terms

AMPS (advanced mobile phone service): Analog cellular system in North America.

CDMA (code-division multiple-access): A technique for spread-spectrum multiple-access digital communications that separates users through the use of unique code sequences.

Gradient descent method: A minimization technique which searches for the minimum of an error surface by taking steps along the direction of greatest slope.

GSM (global system for mobile communications): Pan-European digital cellular standard.

Least squares estimation: A method whose estimate is chosen as the value that minimizes the sum of squares of the measured error.

Maximum likelihood estimation: A method whose estimate is chosen as the parameter value from which the observed data was most likely to come.

Multipath fading: Rapid fluctuation of the complex envelope of the received signal caused by reception of multiple copies of the transmitted signal, each with different amplitude, phase, and delay.

Near–far effect: A phenomenon that arises from unequal received power levels from the MSs. Stronger signals mask the weaker signals.

Path loss: Description of the attenuation of signal power with distance from a transmitter.

Power control: System for controlling the transmission power of the MS. Used to reduce cochannel interference and mitigate the near–far effect on the uplink.

Shadowing: Slow variation in the mean envelope over a distance corresponding to tens of wavelengths.

Soft handoff: Reception and transmission of radio signals between an MS and two or more BSs to achieve a macrodiversity gain.

TDMA (time-division multiple access): A form of multiple access giving each user a different time slot for transmission and reception of signals.

References

[1] EIA/TIA Interim Standard, IS-54., Cellular System Dual Mode Mobile Station–Land Station Compatibility Specifications, May 1990.

[2] EIA/TIA Interim Standard IS-95., Mobile Station–Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System, May 1992.

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Further Information

More information on radiolocation can be found in the April, 1998, issue of *IEEE Communications Magazine*, which provided several articles regarding location service issues for wireless communications networks.

Articles discussing location techniques and algorithms can be found in many IEEE journals including *Transactions on Vehicular Technology, Transactions on Aerospace and Electronic Systems*, and the *Journal of Oceanic Engineering.*

Proceedings of various IEEE conferences such as the *Vehicular Technology Conference* document some of the latest developments for location in cellular networks.