CHAPTER 14

WIRELESS GEOLOCATION SYSTEMS

14.1 INTRODUCTION

Geolocation, position location, and radiolocation are terms that are widely used today to indicate the ability to determine the location of an MS. Location usually implies the coordinates of the MS that may be in two or three dimensions, and usually includes information such as the latitude and longitude where the MS is located. In indoor areas and within buildings, alternative coordinates and visualization techniques may be employed. Geolocation technologies are gaining prominence in the wireless market for several reasons, primarily the FCC mandate requiring all wireless cellular carriers to be able to provide the location of emergency 911 callers to a *public safety answering point.* However, geolocation technology has proved to be significant for both military and commercial applications in general beyond emergency location. Commercial applications include the need for hospitals to locate patients and equipment in a timely fashion, in homes to locate children and pets, and in the evolution toward 4G networks, the need to provide *location aware* services. In the military and public sector, enabling soldiers, policemen, and firefighters with knowledge of their location and the location of other personnel, victims, exits, dangers, and so on proves to be invaluable. The GPS has been the most successful positioning technique in outdoor areas, and we now see the GPS receiver as an inexpensive commonplace gadget. Although GPS has been hugely successful, it also has several drawbacks for use in the applications that we have discussed so far, especially in indoor areas. In this chapter, we discuss position location issues in today's wireless networks, alternative technologies that are being investigated and standardized for position location in outdoor and indoor areas, and trends in this area.

14.2 WHAT IS WIRELESS GEOLOCATION?

The term "location-based service" is used to denote services provided to mobile users based on their geographic location, position, or known presence. These are primarily based on a geolocation infrastructure and system put in place to obtain location information of users. Positioning systems have found a variety of applications both in the civilian and military environments. There are numerous such applications that are already available today such as mapping services (that provide driving directions), information services (that provide local news, weather, traffic, etc.), and concierge services (for making dinner reservations, movie tickets, directory services, etc.). Commercially, content, advertising, and personalization services that are location dependent are being deployed today. We discuss example indoor and outdoor applications that are becoming increasingly important.

Indoor geolocation applications traditionally have been directed toward locating people and assets within buildings. Finding mentally impaired patients in hospitals and portable equipment such as projectors, wheelchairs, and so on that are often moved and never returned to a tractable location are two common examples. The so-called *personal locator services* (PLS) [KOS00], which could also operate outdoors, employ a *locator device* that resides with a person whose location is to be determined. There are two possible scenarios—in the first case, someone requests a service to provide them with the location of the individual and appropriate steps are taken to determine the person's location. In the second case, the person is lost or in some other dire predicament and can employ a panic button to request help. Here the locator service will determine the location and provide the requested assistance. For locating equipment, only the former scenario applies.

Existing communications and computing environments, both in residential areas and offices, have been statically configured, making the task of reconfiguration extremely complex and cumbersome and requiring manual intervention. To overcome this inconvenience, smart spaces and smart office environments are being considered for deployment that can automatically change their functionality depending on the context [WAR97]. Such *context-aware* networks are based on awareness of who or what is present around them. With location awareness, computing devices ranging from small PDAs to desktops and Internet appliances could personalize and adapt themselves to their current set of users, each requiring their own services from the smart environment. For this purpose, not only should the smart space be aware of who is present, but it should also be aware of where the user is located and whether there are other mobile devices in the vicinity. For instance, a handheld computer should be able to automatically determine the closest printer to print a document in an office environment. Such nontraditional applications also demand geolocation services.

There are several outdoor geolocation applications, the most common of which is simply the application of locating one's own self using GPS while traveling on the road. Information technology has increased the number of applications far beyond this simple self-location application.

The term *telematics* is used to imply the convergence of telecommunications and information processing, and it has since then evolved to refer to automobile systems that combine the GPS location mechanism with wireless communications for services such as automatic roadside assistance, remote diagnostics, and content delivery (information and entertainment) to the automobile. A good example of such a system is General Motors's OnStar system [OnSweb].

Intelligent transportation systems (ITS) refer to the ability to autonomously navigate vehicles while making use of the latest traffic information, road conditions, travel duration, and so on. This includes fleet management as well as the automatic steering of vehicles. In order to obtain relevant information from service providers or servers across a network or the Internet, the vehicles should be able to provide their location and destination information. Alternatively, the service provider should be able to determine the vehicle's location.

Wireless enhanced-911 or E-911 services, by far, have provided to be the biggest catalyst for investment and development of geolocation technology suitable for cellular communications. A caller on a wired telephone to an E-911 service is immediately located because the location of the fixed telephone is known with an accuracy of within a couple of rooms in a building. If the same caller is on a mobile telephone, there does not currently exist any technology that can obtain the location except that the caller was connected to a particular BS. In order to improve emergency response, the FCC had mandated that all cellular telephones, PCS handheld communicators, and specialized mobile radios should provide geolocation services by October 1, 2001. (This date has since been postponed.) The mandate requires that a public safety answering point (PSAP) be able to locate the mobile device to within 50 m, for 67 percent of E-911 calls and 150 m for 95 percent of the calls if a *handset-based* geolocation technology is used and to within 100 m (300 m) for 67 percent (95 percent) of calls if *network-based* geolocation technology is employed. We discuss handset-based and network-based technologies in subsequent sections.

14.3 WIRELESS GEOLOCATION SYSTEM ARCHITECTURE

A functional architecture of a geolocation system is shown in Figure 14.1 [CHA99]. The two essential functional ingredients for position location are the location estimation of the MS U and this information with appropriate attributes shared with the network N. Geolocation systems measure parameters of radio signals that travel from a mobile and a fixed set of receivers or from a fixed set of transmitters to a mobile receiver. There are thus two ways in which the actual estimate of the location of the MS can be obtained. In a *self-positioning system,* the MS locates its own position using measurements of its distance or direction from known locations of transmitters (for example GPS receivers). In some cases, *dead reckoning*, a predictive method of estimating the position of the mobile by applying the course and distance traveled since to a previously determined position, could be employed. Self-positioning systems are often referred to as mobile-based or terminal-centric [MEY96] positioning systems. In *remote positioning systems,* receivers at known locations on a network together compute the location of a mobile transmitter using the measurements of the distance or direction of this mobile from each of the re-

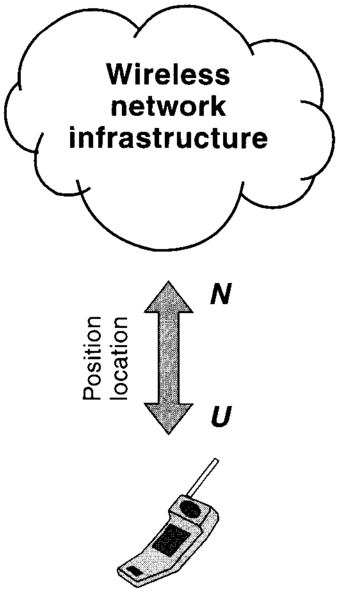

Figure 14.1 Functional architecture of a geolocation system.

ceivers [DRA98]. Remote positioning systems are also called network-based or network-centric [MEY96] positioning systems. Network-based positioning systems have the advantage that the MS can be implemented as a simple transceiver with small size and low-power consumption for easy carrying or attachment to valuable equipment as a tag. In addition, it is possible to have *indirect* remote or self-positioning systems where the mobile may transmit information about its location to a location control center, or the location control center transmits the location of each mobile to itself through an appropriate communications channel.

An example of a geolocation system architecture [KOS00] is shown in Figure 14.2. A geolocation service provider provides location information and location aware services to subscribers. Upon a request from a subscriber for location

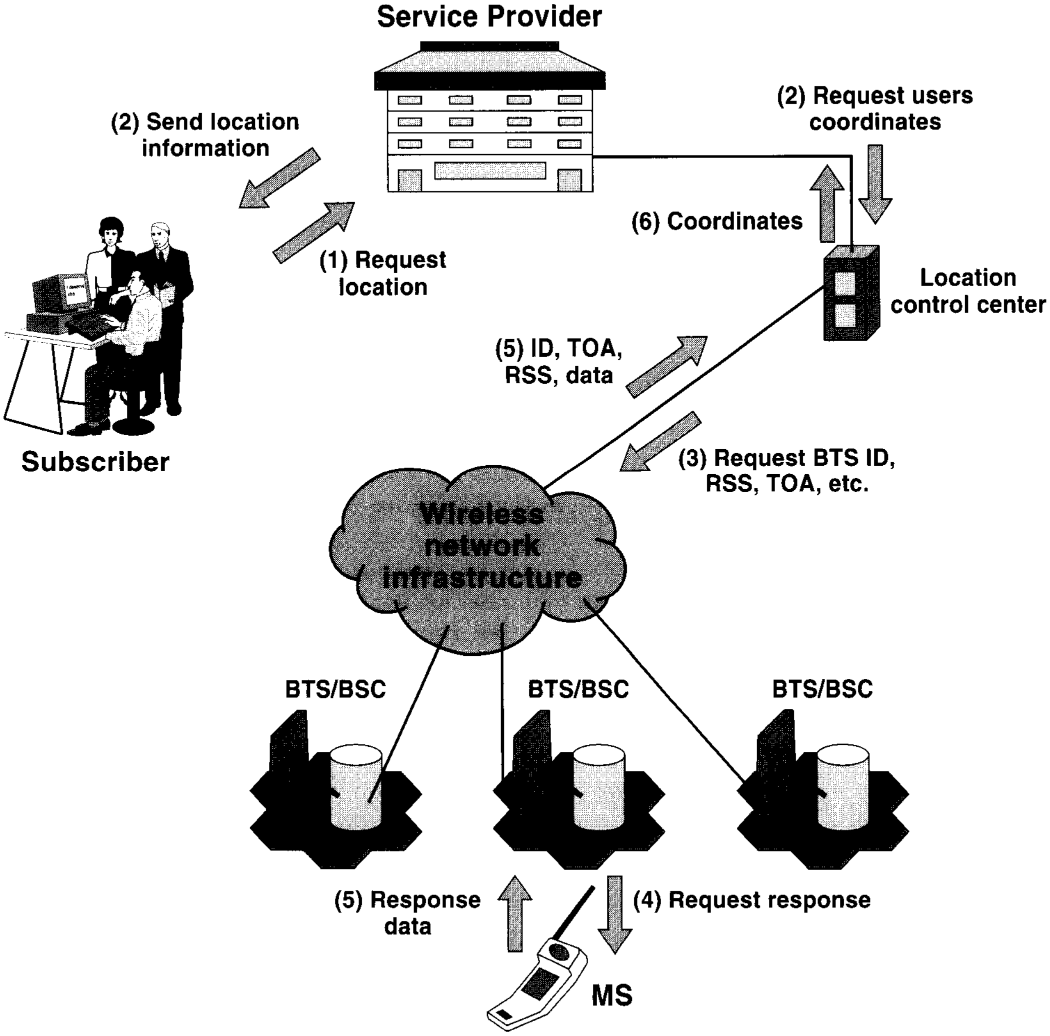

Figure 14.2 General architecture of a geolocation system.

information about an MS, the service provider will contact a location control center querying it for the coordinates of the MS. This subscriber could be a commercial subscriber desiring to track a mobile device or a PSAP trying to answer an E-911 call. The location control center will gather information required to compute the MS's location. This information could be parameters such as received signal strength, BTS ID, TOA of signals, and so on that we discuss later. Depending on past information about the MS, a set of BSs could be used to page the MS, and directly or indirectly obtain the location parameters. These are sometimes called *geolocation base* stations (GBSs). Once this information is collected, the location control center can determine the location of the mobile with certain accuracy and convey this information to the service provider. The service provider will then use this information to visually display the MS's location to the subscriber. Sometimes the subscriber could be the MS itself, in which case the messaging and architecture will be simplified, especially if the application involves self-positioning.

Example 14.1: Indirect Remote Positioning

In indirect remote positioning, an E-911 PSAP requires the location information of a caller. If a mobile-based positioning system is used, the MS determines its own position either using GPS or signals from multiple BSs. This information has to be transmitted to the location control center by the mobile terminal through one of the BSs.

14.4 TECHNOLOGIES FOR WIRELESS GEOLOCATION

The location of an MS can be determined as follows. Let us consider, for example, a remote-positioning system where the GBSs are together determining the MS's position. A similar approach is applicable for self-positioning systems. It is possible to exploit characteristics of radio signals transmitted by an MS to fixed receivers of known location to determine the location of the MS. The GBSs measure certain signal characteristics and make an estimate of the location of the MS based on the knowledge of their own location. The general problem can be stated as follows:

> The locations of N receivers (GBSs) are known via their coordinates (x_i,y_i) for i = 1, 2, 3, . . ., N. We need to determine the location of the MS (x_m,y_m) using characteristics of the signals received by these transmitters.

Clearly, in order to determine (x_m,y_m), the distance or direction (or both) of the MS must be estimated by several of the GBSs from their received signals. Distances can be determined using properties of the received signal such as the signal strength, the signal phase, or the time of arrival. The directions of the MS can be determined from the angle of arrival of the received signal.

14.4.1 Direction-Based Techniques

The angle of arrival (AOA) geolocation technique uses the direction of arrival of the received signal to determine the location of the MS as shown in Figure 14.3. The receiver measures the direction of received signals (i.e., the AOA with respect to a fixed direction [east in Figure 14.3]) from the target transmitter using directional antennas or antenna arrays. If the accuracy of the direction measurement (roughly the beam width of the antenna array) is $\pm\theta_s$, the AOA measurement at the receiver will restrict the transmitter position around the LOS signal path with an angular spread of $2\theta_s$. Two such AOA measurements will provide a position fix as illustrated in Figure 14.3.

The accuracy of the position estimation depends on where the transmitter is located with respect to the receivers. If the transmitter lies in between the two receivers along a straight line, AOA measurements will not be able to provide a position fix. As a result, more than two receivers are usually needed to improve the location accuracy. For macrocellular environments, where the primary scatterers

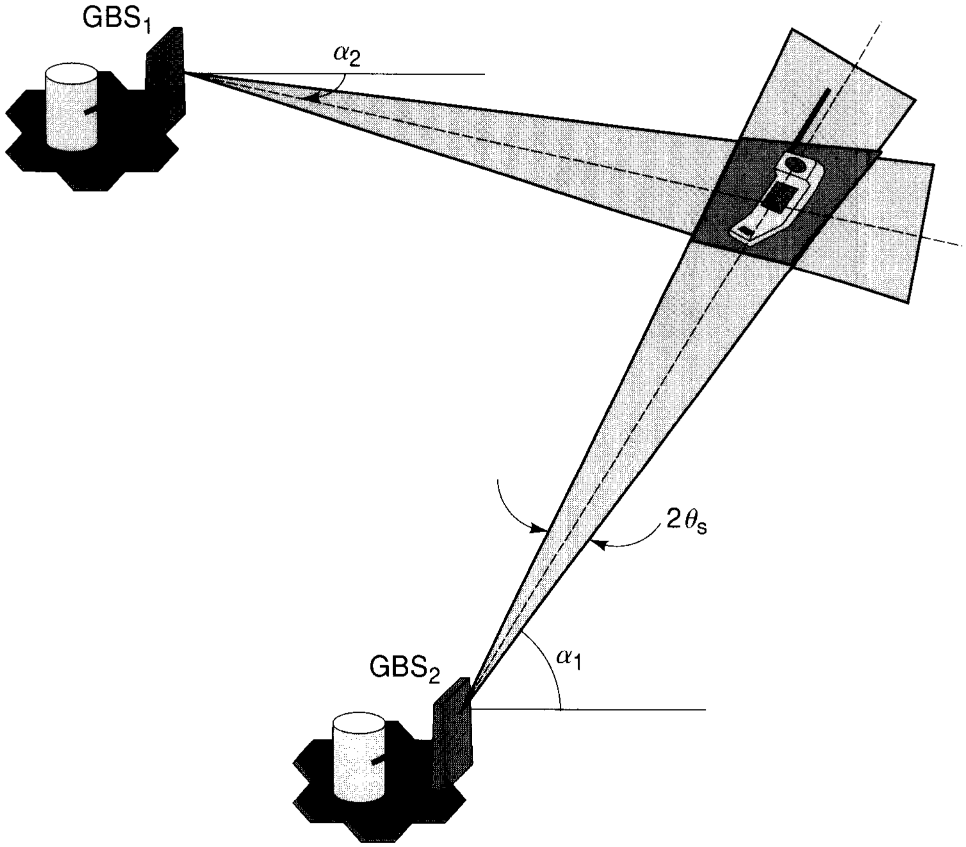

Figure 14.3 AOA technique for geolocation.

are located around the transmitter and far away from the receivers (the GBSs), the AOA method can provide acceptable location accuracy [CAF98]. But dramatically large location errors occur if the LOS signal path is blocked and the AOA of a reflected or a scattered signal component is used for estimating the direction. In indoor environments, surrounding objects or walls mostly block the LOS signal path. Thus the AOA technique is not suitable for indoor geolocation systems. In addition, this requires placing expensive array antennas at the receivers to track the direction of arrival of the signal. Although this is a feasible option in the next generation cellular systems where smart antennas are expected to be deployed to increase capacity, it is in general not a good solution for low-cost indoor applications.

14.4.2 Distance-Based Techniques

With the received signal strength, the TOA or the time difference of arrival techniques, the distances between the MS and receiver are estimated. In such a case, three measurements are required to estimate the position of the mobile in two dimensions, and four measurements are required for estimating the position in three dimensions. In Figure 14.4, the need for three measurements for estimating the po-

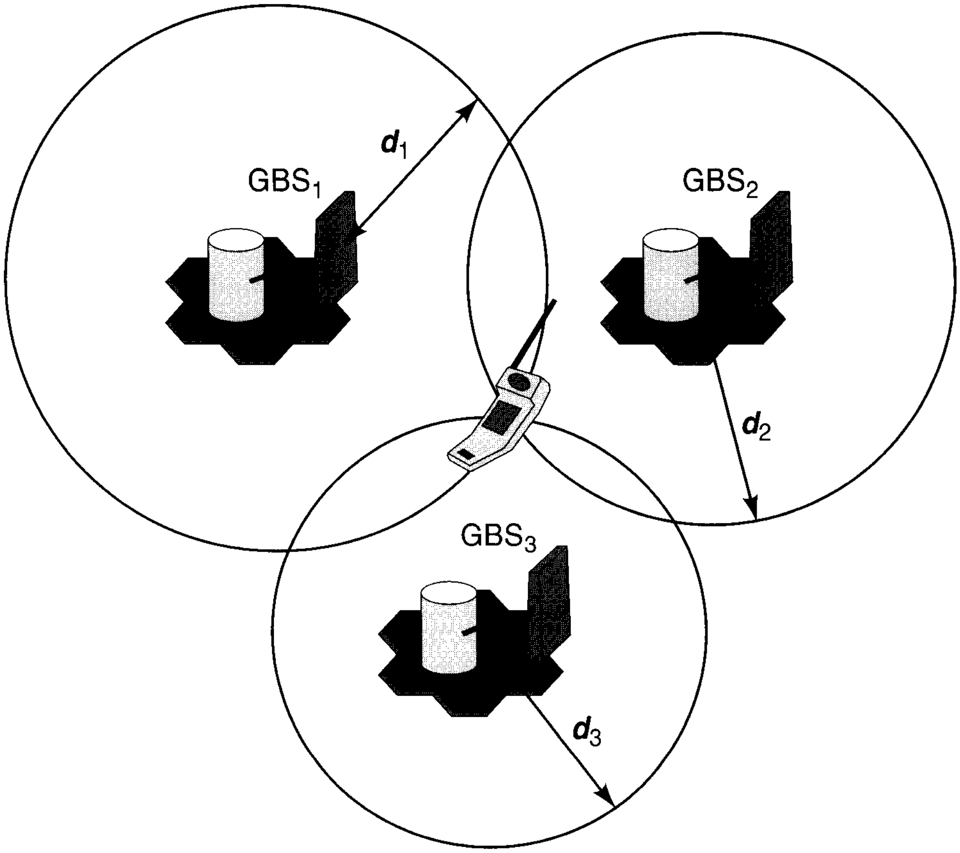

Figure 14.4 Direction-based geolocation technique.

sition in two dimensions is illustrated. If the distance between the receiver and the mobile is estimated to be *d*, it is obvious that the mobile could be located on a circle of radius *d* centered on the receiver. A second measurement reduces the position ambiguity to the endpoints of the chord that is common to the two circles. The third measurement provides a fix on the location of the mobile.

14.4.2.1 Arrival Time Methods

A transmitted signal travels 3×10^8 m in one second in air or free space, and this property can be exploited to determine the distance between the transmitter and receiver. This is the TOA technique that is employed with some modifications in current GPS receivers [KAP96], as well as certain E-911 location systems. When a GBS detects a signal, its absolute TOA is determined. If the time at which the MS transmitted the signal is known, the difference in the two times will give an estimate of the time taken by the signal to arrive at the GBS from the MS. Three distinct measurements (in two dimensions) and four distinct measurements (in three dimensions) can be employed to determine the location of the mobile. The TOA technique provides circles centered on the mobile or fixed transceiver as described previously (see Figure 14.4).

Example 14.2: Commercial Indoor Location Systems Based on TOA

Recently, a few commercial products for indoor geolocation appeared in the market [WER98]. The overall system architecture of a system is shown in Figure 14.5. These systems use simple-structured *tags* that can be attached to valuable assets or personnel badges. Indoor areas are divided into cells with each cell being served by a *cell controller*. The cell controller is connected to a number of antennas (16 in [WER98]) located at known positions. To locate the tag position, a cell controller transmits a 2.4 GHz spread spectrum signal in the unlicensed ISM bands through different antennas in time division multiplexed mode. Upon receiving signals from the cell controller antenna network, tags simply change the frequency of the received signal to another portion of the available unlicensed bands, either in 2.4 GHz or 5.8 GHz, and transmit the signal back to the cell controller with tag ID information phase-modulated onto the signal. The distance between tag and antenna is determined by measuring round trip time of flight. With the measured distances from tag to antennas, the tag position can be obtained using the TOA method. A host computer is connected to each cell controller, through a TCP/IP network or other means, to manage the location information of the tags. Because the cell controller generates the signal and measures round trip time of flight, there is no need to synchronize the clocks of tags and antennas.

The multipath effect is one of the limiting factors for indoor geolocation (see Chapter 2 for a discussion). Without multipath signal components, the TOA can be easily determined from the autocorrelation function of the spread spectrum signal. The autocorrelation is two chips wide, and the time to rise from the noise floor to the peak is one chip. If the chipping rate were 1 MHz, it would take 1,000 ns to rise from the noise floor to the peak, providing a "ruler" with a thousand 30-cm increments. In this manner, a 40 MHz chipping rate, chosen for the PinPoint system, provides a ruler of 25 ns that provides real-world increments of about 3.8 m. Because of regulatory restrictions in the 2.4 and 5.8 GHz unlicensed bands, faster chipping rates are not easy to achieve, and signal-processing tech-

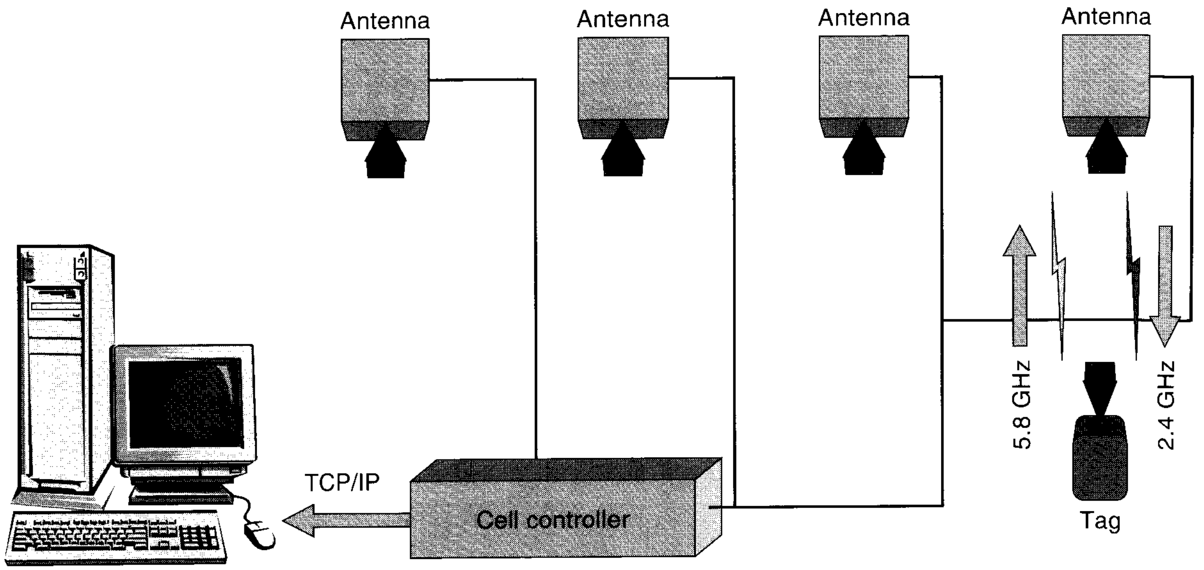

Figure 14.5 The PinPoint local positioning system.

niques must be used to further improve the accuracy. If different frequency bands are used for uplink and downlink communications, the interference between the channels can be further isolated.

In GPS, the *time difference of arrival* (TDOA) technique is used where the differences in the TOAs are used to locate the mobile. The TDOA technique defines hyperbolas (rather than circles) on which the transmitter must be located with foci at the receivers. Three or more TDOA measurements provide a position fix at the intersection of hyperbolas. Even though geometric interpretation can be used to calculate the intersection of circles or hyperbolas, when there are errors, estimates have to be used. Exact solutions and Taylor series approximations are available [COM98] for solving these equations. Compared with the TOA method, the main advantage of the TDOA method is that it does not require the knowledge of the transmit time from the transmitter. As a result, strict time synchronization between the MS and the GBSs is not required. However, the TDOA method requires time synchronization among all the receivers used for geolocation.

A recursive least squares estimate is used when there are errors in the distance measurements. Let the distance d_i from the ith GBS be determined from the absolute TOA of the signal it receives as $d_i = c \times \tau$ where c is the velocity of light and τ is the time taken by the signal to reach the GBS. If the location of the ith GBS is (x_i, y_i) and the location of the mobile is (x,y), we have N equations of the form:

$$f_i(x, y) = (x - x_i)^2 + (y - y_i)^2 - d_i^2 = 0 \tag{14.1}$$

for $i = 1, 2, \ldots, N$. As a geolocation problem, extensive research has been done to improve upon the accuracy of algorithms that are used to estimate the position of a mobile. Especially when N is more than three or four (thus providing redundancy in the measurements), information in the redundant measurements can be used to reduce errors that are introduced by noise, environment, multipath, and so on, [KAP96]. Figure 14.6 shows the example of using a recursive least squares technique to arrive at the location of the MS. Signals from seven receivers are combined to arrive at this location.

Wireless systems that employ the TOA (or TDOA) technique employ pulse transmission, phase information, or spread spectrum techniques to form time estimates. For instance, the time difference between two signals received for either self-positioning or remote positioning, can be estimated from their cross-correlation. As already mentioned, TOA techniques are generally superior compared with AOA techniques. In [CAF98], it has been reported that TOA techniques outperform the AOA technique by approximately 100 m in absolute position error in cellular systems with three BSs, and the incremental returns are worse if more BSs are used.

14.4.2.2 Signal Strength Method

If the transmitted power at the MS is known, measuring the RSS at the GBS can provide an estimate of the distance between the transmitter and the receiver using known mathematical models for radio signal path loss that depend on distances (see Chapter 2). As with the TOA method, the measured distance will determine a circle, centered on the receiver, on which the mobile transmitter must lie.

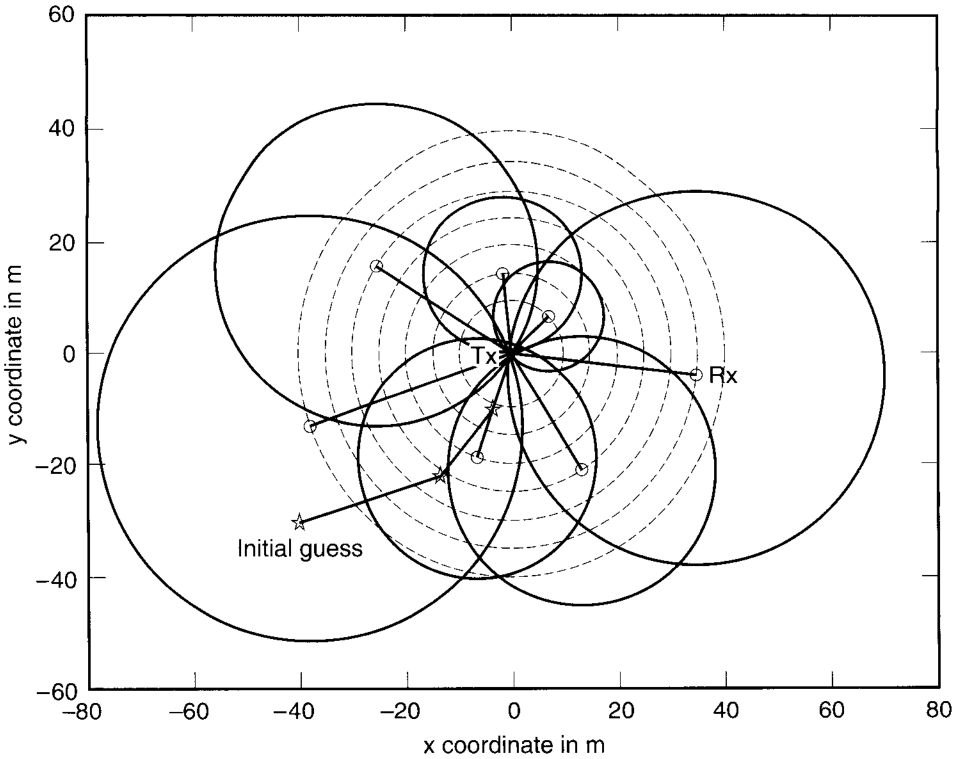

Figure 14.6 Recursive least squares to determine the MS location using measurements at seven GBSs.

This technique results in a low complexity receiver for a self-positioning system. This method is, however, very unreliable because of the wide variety in path loss models and the large standard deviations in the errors associated with these models due to shadow fading effects. Receivers do not distinguish between signal strength in the LOS path and in reflected paths [MEY96]. Especially indoors, the power distance gradients can vary anywhere between 15–20 dB/decade to as high as 70 dB/decade. Also, these gradients and other parameters employed in path loss models are site specific. As a result, this technique cannot be employed in situations where the required accuracy is a few meters. The accuracy of this method can be improved by utilizing premeasured RSS contours centered at the receiver [FIG69] and multiple measurements at several BSs [KOS00]. A fuzzy logic algorithm was shown in [SON94] to be able to significantly improve the location accuracy.

Example 14.3: A Commercial Geolocation System Based on RSS

The infrastructure of Paltrack indoor geolocation system [PALweb], developed by Sovereign Technologies Corp., consists of tags, antennas, cell controllers, and an administrative software server system. The PalTrack system utilizes a network structure that resides on an RS-485 node platform. A network of transceivers is located at known positions within the serving area while the transmitter tags are attached to assets. The tag transmitters transmit a unique identification code at 418 MHz frequency band to a network of transceivers when on motion or at predefined time intervals. Transceivers estimate the tag location by measuring RSS and utilize a robust RSS-based algorithm patented by Sovereign Technologies Corp. The master transceiver collects measured information from the transceivers and relays it to a PC-based server system. The accuracy for PalTrack is 0.6 to 2.4 m. The key component of the PalTrack system is the RSS-based geolocation algorithm.

14.3.2.3 Received Signal Phase Method

The received signal phase is another possible geolocation metric. It is well known that with the aid of reference receivers to measure the carrier phase, differential GPS (DGPS) can improve the location accuracy from about 20 m to within 1 m compared with standard GPS, which only uses range measurements [KAP96]. One problem associated with the phase measurements lies in the ambiguity resulting from the periodic property (with period 2π) of the signal phase while the standard range measurements are unambiguous. Consequently, in DGPS, the ambiguous carrier phase measurement is used for fine-tuning the range measurement. A complementary Kalman filter is used to combine the low-noise ambiguous carrier phase measurements and the unambiguous but noisier range measurements [KAP96]. For an indoor geolocation system, it is possible to use the signal phase method together with the TOA/TDOA or RSS method to fine-tune the location estimate. However unlike DGPS, where the LOS signal path is always observed, the serious multipath condition of the indoor geolocation environment causes more errors in the phase measurements.

14.4.3 Fingerprinting-Based Techniques

Recently, signal fingerprinting has been adopted as yet another technique for position location [KOS00]. The received signal is extremely site-specific because of its dependence on the terrain and intervening obstacles. So the multipath structure of the channel is unique to every location and can be considered as a fingerprint or signature of the location if the same RF signal is transmitted from that location. This property has been exploited in proprietary systems to develop a "signature database" of a location grid in specific service areas. The received signal is measured as a vehicle moves along this grid and recorded in the signature database. When another vehicle moves in the same area, the signal received from it is compared with the entry in the database, and thus its location is determined. Such a scheme may also be useful for indoor applications where the multipath structure in an area can be exploited.

Example 14.4: A Commercial Geolocation System Based on Fingerprinting

A company called U.S. Wireless Corporation has designed and implemented a system based on this scheme called RadioCamera in downtown Oakland in California [RADweb]. The mobile transmits RF signals, which scatter because of multipath conditions. RadioCamera^{TM} takes measurements of the RF signals and collects all the multipath rays. A *location pattern signature* is developed using the multipath rays. The location signature is compared with a learned database, and a location is determined. Continuous measurements of the location pattern signature provide tracking.

14.5 GEOLOCATION STANDARDS FOR E-911 SERVICES

Commercial geolocation products have already appeared in the market outside of traditional GPS systems that are extremely popular. The enhanced 911 services are still the primary driving force for geolocation services. The options for E-911 services when they were first mandated included traditional GPS or a network centric approach based on TDOA techniques. GPS, especially after the elimination of selective availability of the signal by the U.S. government, provides sufficient accuracy for E-911 systems. The one disadvantage of GPS is that the time to first fix (TTFF) can be very long depending on what satellite constellation a MS may be able to see. There is also the problem of using GPS in urban canyons. However, compared with stand-alone GPS, network-centric approaches can provide a faster TTFF but are unreliable and inaccurate.

To solve this problem, a new technique called *assisted GPS* (AGPS) has been proposed whereby an entity in the cellular network is enabled with a GPS receiver that can see the same satellites as the MS. By predicting what signal an MS may see and sending that information to the MS, the network entity can enable a faster TTFF, shortening it from minutes to a second or less [DJU01]. Assisted GPS also enables the network entity to detect signals with a weaker signal strength than an MS and send a *sensitivity assistance message* to the MS. It can also reduce the satellite search space for an MS by informing the MS of what satellites may be visible and what will be their expected code phase for synchronization.

Assisted GPS is now the technology of choice and is being standardized for AMPS and IS-95 based cellular telephones. It is being incorporated in the TIA 45.1 and 45.5 standards and will likely be approved for the TDMA (TIA TR45.3) standard as well. For GSM telephones, ETSI and T1P1.5 are looking at AGPS, network-based TOA, and enhanced-observed time difference (E-OTD) technologies [ZHA00].

Example 14.5: TDOA in GSM

In GSM, the MS already observes bursts from different BSs and determines the time interval between the receptions of bursts from two different BTSs. This difference is called the observed time difference (OTD). The real time difference (RTD) between BSs is also known. These two values can be used in a TDOA technique similar to the one discussed earlier to determine the location of the MS.

Example 14.6: TDOA in CDMA

In CDMA, the BSs are already synchronized and time difference measurement is easier than in GSM. By measuring the phase delay between CDMA pilot signals, the MS can obtain range information, and this method is called *advanced forward link trilateration*. The calculations can either be done in the MS or the phase differences could be reported to the network, which will then calculate the location.

Architectural changes will be required to the backbone of the cellular telephone networks to provide geolocation services. Figure 14.7 shows one such architecture [MEY96]. The MSC communicates the location parameters to the E-911 selective router that routes the information to the appropriate PSAP. An automatic location information (ALI) database is queried by the PSAP with the location parameters and receives the location back along with information related to the mobile station. A geographic information service (GIS) can be added to the PSAP to provide a visual display pinpointing the roads, streets, addresses, jurisdiction, and so on. Eventually a wireless intelligent network or data backbone could be incorporated to interface the geolocation technology system with the wireless network backbone. Several possibilities are being considered to convey data from the geolocation BSs to the PSAP. One approach is to use SS-7 as proposed in [MEY96]. Another approach is to use a data backbone such as GPRS [CHA99].

14.6 PERFORMANCE MEASURES FOR GEOLOCATION SYSTEMS

In this section, we consider performance benchmarking of geolocation systems [TEK98] and compare their relative advantages and disadvantages. Wireless systems have traditionally focused on telecommunications performance issues such as QoS, grade of service, BERs, capacity, reliability, and coverage. For geolocation systems, some of these performance issues are still valid although new performance benchmarks need to be introduced.

Table 14.1 compares performance measures for telecommunications and geolocation systems based on [TEK98].

One of the most important performance measures of a geolocation system is the accuracy with which the location is determined. This is similar to the BER or packet error rate requirements in telecommunications systems. As in the case of BER, the actual benchmark values may be different depending on the application in question. For example, voice packets can tolerate a BER of 1 percent, but data packets need a BER of at least 10^{-6}. In the same way, outdoor position location applications demand a lower accuracy compared with indoor applications.

Location system accuracy is often defined as the area of uncertainty around the exact location where a percentage of repeated location measurements are reported. For example, 67 percent of the measurements of the location of an MS lie within 50 m of the actual location or 95 percent of the measurements lie within 1 m

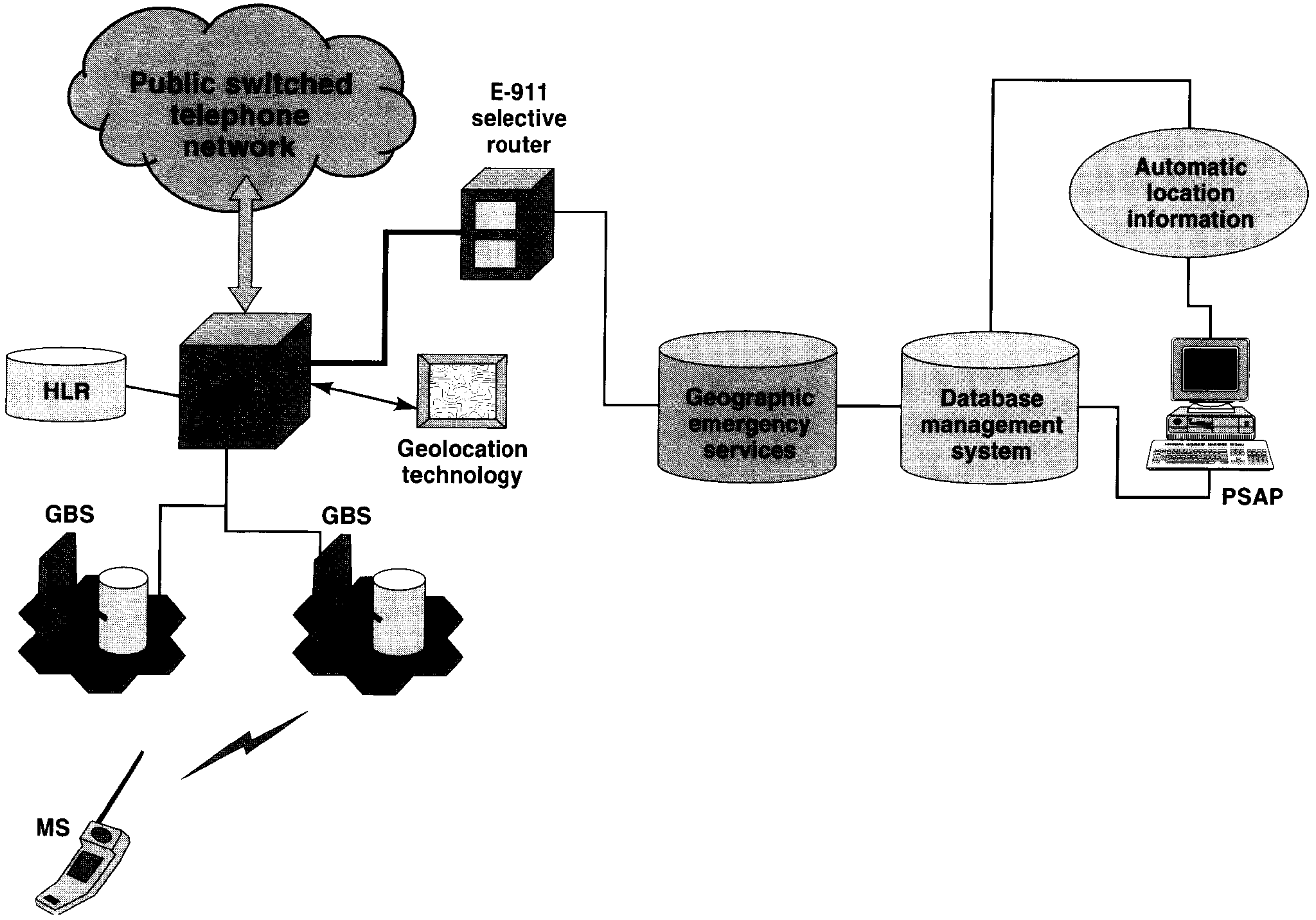

Figure 14.7 E-911 phase 2 architecture.

Table 14.1 Comparison of Performance Measures for Telecommunications and Geolocation Systems

Telecommunications Systems	**Geolocation Systems**
Quality of service	*Accuracy of service*
• Signal to interference ratio	• Percentage of calls located to within an accuracy of δ meters
• Packet error rate	• Distribution of distance error at a geolocation receiver
• Bit error rate	
Grade of service	*Location availability*
• Call blocking probability	• Percent of location requests not fulfilled
• Availability of resources	• Unacceptable uncertainty in location
• Unacceptable quality	
Coverage	*Coverage*
Capacity	*Capacity*
• Subscriber density that can be handled	• Location requests/frequency that can be handled
Miscellaneous	*Miscellaneous*
• Delay in call setup	• Delay in location computation
• Reliability	• Reliability
• Database look-up time	• Database look-up time
• Management and complexity	• Management and complexity

of the actual location. This accuracy heavily depends on the radio propagation environment, receiver design, noise and interference characteristics, number of redundant measurements available for the same location, and the complexity of signal processing performed. In [PAH98], [KRI98], the distribution of the distance error that ultimately affects the area of uncertainty is discussed in detail based on measurements and simulations.

The grade of service for telecommunication systems is usually the call-blocking rate during the peak hour. In a similar manner, the probability that a location request will not be fulfilled is a measure of the grade of service for a geolocation system. The location request will not be fulfilled if TOA, AOA, or other measurements are not available in sufficient number or the measurements lead to unacceptable location accuracy.

Coverage in telecommunications systems is related to the service area where, at a bare minimum, access to the wireless network is possible. For geolocation systems, coverage corresponds to the availability of a sufficient number of TOA, AOA, RSS, or fingerprint measurements to perform a location computation.

Finally several other issues [TEK98] are also important in geolocation systems in a manner similar to telecommunications systems—delay in triggering a location measurement, location algorithm calculation time, network transmission delay, database look-up time, end-to-end delay between the time a location request is made and the location information is received, and so on. Reliability—the mean time between failures and the mean time to repair—management, and complexity are also important.

Table 14.2 Comparison of Geolocation Techniques

Geolocation Technique	Coverage	Accuracy	Delay	Complexity/Cost/Others
Mobile Centric based on GPS	No indoor coverage Fails in radio shadows	Good in rural and open areas Poor in urban and indoor areas	Low backhaul requirements—forward only location estimate Long time to first fix	No changes to network, but changes to all handsets System upgrades limited by deployed handset base Privacy is user controlled Robust under failure of some network components
Network Centric AOA	Good in outdoor areas	Poor	Low: only angular information needs to be transmitted	High-BS cost due to complex antenna array systems BSs need to be changed No changes to handsets Privacy is network controlled
Network Centric TOA/TDOA	Good	Medium, sometimes unreliable	Low to high depending on how many samples need to be transmitted	Additional investment in infrastructure No changes to handsets Privacy is network controlled
Assisted GPS	Good; indoor coverage is suspect	Superior	Short time to first fix Lots of signaling between network and mobile	System evolves with network upgrades, but both the network and handsets need changes Privacy is partly user controlled Interoperability issues between network and mobile terminals Computation is offloaded to the network so that there is minimum impact on handset battery life

Table 14.2 compares different geolocation approaches based on some of the performance measures discussed earlier [DJU01], [ZAG98]. The table is self-explanatory.

QUESTIONS

14.1 Explain the differences between GPS, wireless cellular assisted GPS, and indoor geolocation systems.

14.2 Differentiate between remote and self-positioning systems.

14.3 Why is RSS not a very good measure of the distance between a transmitter and a receiver?

14.4 Compare mobile-centric and network-centric geolocation techniques in terms of complexity and accuracy.

14.5 Why are cellular service providers interested in location-dependent services? Give some examples of location-dependent services.

14.6 What are E-911 services and who has mandated these services?

14.7 What are the basic elements of a wireless geolocation system?

14.8 Name the three major metrics used for location finding and explain how they are implemented in a system.

14.9 Why are AOA techniques not popular in indoor geolocation applications?

PROBLEMS

14.1 Two base stations located at (500, 150) and (200, 200) are measuring the angle of arrival of the signal from a mobile terminal with respect to the *x*-axis. The first base station measures this angle as 45 degrees and the second as 75 degrees. What are the coordinates of the mobile terminal?

14.2 In Problem 14.1, what happens if the first base station incorrectly measures the AOA from the mobile terminal as 50 degrees? 30 degrees?

14.3 Base stations A, B, and C located at (50, 50), (300, 0), and (0, 134) are found to be at distances 90, 200, and 100 m from a mobile terminal. Draw circles corresponding to these values and try to determine the location of the mobile terminal.

14.4 In Problem 14.2, what happens if the mobile incorrectly measures the distance from base station B as 100 m? 300 m?