Position Location Technologies for Wireless Systems

Prashant Krishnamurthy, David Tipper, and James Joshi
Department of Information Science and Telecommunications
University of Pittsburgh, Pittsburgh, PA 15260

Introduction

Wireless communications and wireless systems have experienced phenomenal growth over the past decade (Pahlavan & Krishnamurthy, 2002) and have become part of the critical infrastructure of the US. The use of wireless devices such as cell phones, PDAs, and laptops (in general mobile stations – MSs) has become the enabler of viable location based services and applications that need position location information (Barnes, 2003; Dru & Saada, 2001; Warrior *et al*, 2003). The position location information is usually specified with certain accuracy and precision. Accuracy refers to the error in distance from the determined position and the actual position. Precision refers to the fraction of time that the error is smaller than the above number. Other performance measures are possible (Tekinay *et al*, 1998), but are of limited interest at this point in time. The Federal Communications Commission (FCC) is also mandating the provision of enhanced-911 (E-911) emergency services that need similar information (Meyer *et al*, 1996; Reed *et al*, 1998). Any system that locates a MS needs to *sense* some characteristics related to the MS to determine its location. The position is determined using some algorithms. In addition, there are protocols that are required to transport the sensed information to entities that determine the location or provide other services. In this article, we will describe two aspects of locating the position of a mobile station *viz.* the sensing process and the location algorithms. These influence (a) where the position location is determined (at the MS or in the wireless network), (b) the number and nature of reference locations necessary, and (c) the accuracy and precision of the estimated location. We will also consider the standard specifications for cellular telephone systems. There are several articles that have considered positioning of MSs and the reader is referred to (FCC; Zhao 2000; Zhao, 2002; Hightower & Borriello, 2001;) for more details.

Regulatory Issues and Cellular Standards

In this section, we will provide an introduction to the requirements of location based services and E-911 in wireless environments. The requirements are primarily in terms of performance metrics of interest such as accuracy and precision. We will also describe some of the regulatory aspects related to the provisioning of location information and performance metrics. We provide a brief summary of different cellular standards that we refer to later in the article.

There are several applications that need location information such as automated vehicle location, concierge services, mobile commerce and public safety. Each of these applications requires accuracy and precision of position that is specific to its needs. In indoor areas, for applications such as inventory and asset management (such as locating wheelchairs in hospitals), the accuracy has to be within a few meters on a given floor of the building. Cellular service providers may use the position information for network related issues such as handoff or location management (3GPP, Drane *et al*, 1998).

However, much of the accuracy and precision levels for mobile phones are being driven by the values mandated by the FCC for E-911 public safety applications in the USA. The FCC is responsible for regulatory issues related to telecommunications services in the United States. The E-911 service provides emergency assistance to callers through a *public safety access point* (PSAP). FCC has specified accuracy and precision values for E-911 calls. The service provider must be able to locate the caller within an accuracy of 100m at least 67% of the time and within 300m at least 95% of the time and provide this information to the PSAPs. The reader is referred to (FCC, Meyer *et al*, 1996; Reed *et al*, 1998) for more details. In Europe, emergency services are referred to as E-112 services and regulatory authorities are in the process of specifying accuracy and precision levels for E-112.

Cellular systems use many different physical layer and networking standards making position location different in different systems. The first generation cellular systems (also called 1G systems) use analog modulation schemes and do not support any position location services. Second generation or 2G systems use digital modulation and two primary multiple access technologies – time division multiple access (TDMA) in the Global System for Mobile Communications (GSM) based systems and code division multiple access (CDMA) in IS-95 or cdmaOne systems. Third generation or 3G systems are based entirely on CDMA, but again have two primary standards: cdma2000 and UMTS. UMTS is the successor of GSM and cdma2000 is the successor of IS-95. All of the 2G and 3G standards are expected to satisfy the FCC mandate. While the positioning schemes in all of them have some common features, the standards and terms are somewhat different as discussed in Section 4.

There are no mandated positioning requirements for wireless local area networks (WLANs). Most deployed WLAN equipment follows the IEEE 802.11 standard or its enhancements like 802.11a,b, or g. There are proprietary solutions for positioning with 802.11 WLANs, which primarily use RF signatures described below. Accuracy with such systems ranges from a few meters to tens of meters with varying levels of precision depending on the environment (building material, architecture, campus area and so on). As there are no specific standards for WLANs, we restrict ourselves to cellular telephone systems in this article.

Positioning Methodologies

In this section of the article, we will describe *basic* positioning methodologies. Positioning processes use the point of association (POA) of a MS with the network, the time of arrival (TOA) or time difference of arrival (TDOA) of signals, the angle or direction of arrival (A/DOA) of signals, the received signal strength, a fingerprint or signature of signal characteristics at a location, or a combination of these to estimate the location of a MS (3GPP). Figure 1 shows how the first four positioning methodologies operate. In the following discussion, we describe *self-positioning* where a MS estimates its own position based on transmissions from fixed transmitters. However, *indirect positioning*, where the fixed transmitters cooperate to estimate the position of a MS is possible in similar ways.

Point of Association: Most wireless networks use a fixed point of access to the network. These points of access are called base stations (BSs) in cellular networks and access points (APs) in WLANs. BSs or APs have radio transceivers that provide service over a specific geographical area called a “cell”. In the POA approach, the position of the MS is known to be somewhere within the cell. For example, in Figure 1(a), the receiver (Rx) is known to be in the coverage area (cell) of transmitter (Tx) A. Unfortunately, the size of a cell may be as small as 100m in microcellular areas and as large as 15 km in macrocellular areas. Thus the accuracy and precision can vary significantly depending on the density of deployment of BSs or APs and their coverage areas.

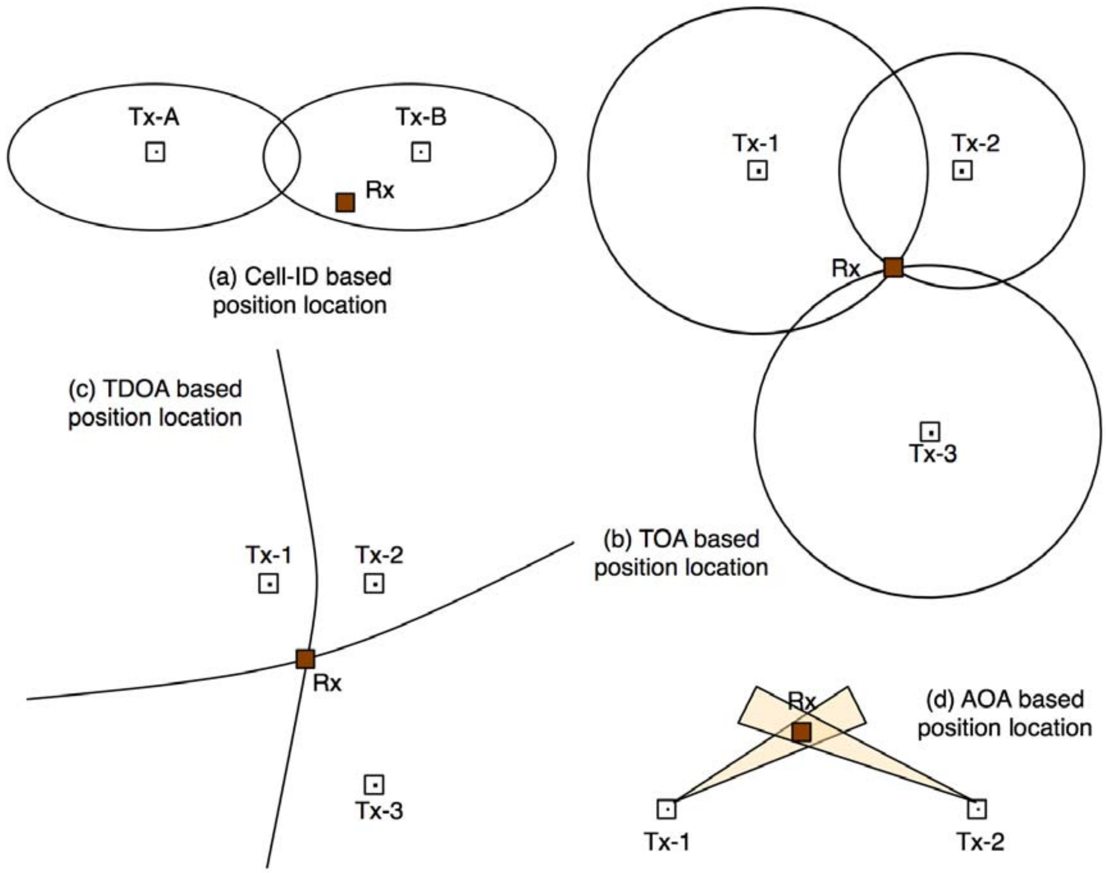

Figure 1: Location Sensing Methodologies

Time/Time Difference of Arrival: If the time taken for a signal to reach a receiver is known from at least three distinct known transmitters, it is possible for the receiver to construct three overlapping circles as shown in Figure 1(b). The point where the three circles intersect is the position of the receiver. Errors in determining the time of arrival often make the intersection of the circles a region rather than a point. However, the position location estimation algorithm will pick some point within this region as the estimated position. If the absolute times of arrival are unknown, the TDOA technique, which uses time differences between pairs of transmitters, is preferred. In this case, the measured times from two transmitters are subtracted and the result is the intersection of two parabolas as shown in Figure 1(c). Multipath propagation of signals (Pahlavan and Krishnamurthy, 2002) impact errors in the time (difference) of arrival of signals as signals may take more time to reach the receiver because of multiple reflections.

Angle/Direction of Arrival: If the positions of two fixed transmitters are known, a receiver can compute its own position by determining the angles at which these transmitters are located with respect to itself as shown in Figure 1(d). This is called the direction or angle of arrival technique for position location. One of the problems with this technique is the wide angular ranges for transmissions of most signals in wireless systems. Antennas are either omnidirectional or transmit over angles as wide as 120^o. Moreover, radio signals propagate through reflections and diffraction making the direction from which a signal arrives random. D/AOA techniques are thus not specified in any of the positioning standards for cellular systems.

Fingerprint/Signature: Problems in TOA or AOA schemes arising due to multipath propagation can be overcome by exploiting multipath propagation for position location. The idea behind this technique is that specific positions in a given environment have specific or unique *radio signatures* or *fingerprints*. For example, the received signal strength from three different APs at a given position will be different from the values observed at a different position. By creating a database of signatures and the associated positions, it will be possible to estimate the position of a MS if it can measure the radio signature at its own position and compare it with entries in the database. Unfortunately, for two reasons, this method is not exact. Radio signatures change with time due to changes in the environment. Moreover, the size of the database needs to be reasonable and may not capture all possible signatures.

Positioning Standards for Cellular Telephone Systems

In this section of the article, we will describe standard techniques specified by cellular telephone standards for location sensing.

Techniques based on Point of Access: The standard specified for locating MSs using POA is called the Cell-ID technique (Trevisani & Vitaletti, 2004; 3GPP). In most cellular standards, the BS serving a cell broadcasts information about itself. In GSM, the broadcast control channel (BCCH) carries this information. In IS-95 and cdma2000, the pilot channel and sync channels together provide information about the BS. In UMTS, the Cell-ID technique can use paging, location or routing area updates, or cell update messages to get information about the serving BS (3GPP). When a MS associates itself with the BS, it is aware of the cell (or cell sector) in which it is located. One may assume that this will be the BS closest to the MS. This is true only of the received signal strength of the BCCH or pilot channels from the nearest cell are the strongest. In most cases, MSs latch on to the BS with the strongest signal. Due to radio propagation effects, a MS may sometimes associate itself with a BS that is farther away. As reported in (Trevisani & Vitaletti, 2004), this could be as high as 43% of the cases. The coverage of a cell is irregular and needs to be known a priori to know in what region a MS is located. The accuracy reported in (Trevisani & Vitaletti, 2004) was 800m in the New York area and 500m in Italy using the Cell-ID technique. The accuracy of the Cell-ID technique can be improved by using the round-trip time in CDMA systems or timing advancement information used in the framing structure in TDMA systems.

Techniques based on TOA/TDOA: Most standard cellular positioning schemes use TOA or TDOA for estimating the position of the MS. The standards include Enhanced Observed Time Difference (E-OTD), Observed Time Difference of Arrival – Idle Period on DownLink (OTDOA-IPDL), Uplink Time Difference of Arrival (UTDOA), Assisted GPS (AGPS), and Advanced Forward Link Trilateration (A-FLT). We discuss these standards briefly below.

The E-OTD standard was the earliest standard for positioning of MSs and it is suggested for GSM and EDGE (Enhanced Data for Global Evolution) systems. The idea here is that the MS will determine the TDOA from multiple BSs and determine its position using standard TDOA techniques or using improved algorithms. It is called "enhanced" because additional *location measurement units* are required to compute the timing difference between the clocks in different GSM base stations (that are not synchronized). The accuracy and precision with this method does not usually meet the FCC mandate because of clock accuracy and timing accuracy issues with E-OTD. The accuracy of E-OTD has been reported to be between 50m and 400m with availability varying between 70% and 95% depending on whether the area covered is urban or rural (Martin-Escalona *et al*, 2002). Moreover, the time to obtain the position estimate can be as large as 5s and software changes are necessary in the handset to enable it to work with E-OTD.

The A-FLT standard is similar to E-OTD except that it uses the pilot signals in IS-95 based cellular systems. Pilot signals from the serving base station and a neighboring base station are used to compute the TDOA hyperbolas. The advantage here is that base stations in IS-95 are already time synchronized using GPS. The chip duration in the spread spectrum signals used in IS-95 is 0.813μs, which results in better accuracy. In A-FLT, the resolution used for reporting is actually 1/8 of the chip duration. Measurement reports in (Nissani & Shperling, 2000) indicate that the accuracy is 48m 67% of the time and 130m 90% of the time. The Enhanced Forward Link Trilateration (E-FLT) is similar to A-FLT, but it uses a different signaling protocol with the network and it also could use additional information from location measurement units or radio signatures to improve accuracy. Because of cdma2000's similarity to IS-95, A-FLT and E-FLT are also used with that standard.

The OTDOA standard also uses TDOA measurements, but in the UMTS standard. The MS measures the time difference between frames transmitted by multiple base stations. Location measurement units are used in a manner similar to E-OTD to account for asynchronous transmissions from base stations. Since UMTS uses CDMA as the access scheme, a MS close to a BS may not be able to hear signals from other BSs because they are swamped by the high power of signals from the closer BS. To allow the MS to make measurements from other BSs, each BS ceases its transmission for short periods of time (called idle periods). This technique is called OTDOA-IPDL for this reason. Either the MS can compute its own position or it can report the measurements to the network where a stand-alone mobile location center computes the MS's position. Simulation results in (Porcino, 2001) indicate that the OTDOA method can provide good accuracy and precision. In rural areas, the accuracy is 17m 67% of the time and 27m 95% of the time. In urban areas, the accuracy is between 68m and 86m 67% of the time and 156m and 193m 95% of the time depending on the type of urban environment. In the UTDOA standard, different location measurements units compute the position of a MS by using the TDOA of a signal transmitted by the MS that they all receive. This method does not need the MS to do anything, but location measurement units have to be deployed by the service provider.

Network assisted GPS is a method that significantly improves the accuracy of position estimates in a cellular system (Djuknic and Richton, 2001). It is possible to install a GPS receiver in each MS so that a MS can determine its own position. GPS by itself in a MS is not a viable solution for many reasons. The time to first fix of a cold receiver can be several minutes. The MS needs a clear view of the skies to observe at least 4 satellites and so this approach does not operate well in urban canyons. If the MS has to scan for satellites, the signals from satellites and determine its own position, this could consume the MS battery power significantly. In the case of assisted GPS, a partial (or low-complexity) GPS receiver is built into the MS. Additionally, AGPS servers are placed in the network as appropriate. The wireless network signals information about the reference time, the visible satellite list, the satellite signal spread spectrum code phase, and search windows appropriate for these signals to the MS reducing the burden on the MS. This improves the time to first fix and also the accuracy of position estimates. AGPS can be used in GSM, IS-95, cdma2000 and UMTS systems and in conjunction with other techniques such as Cell-ID, E-OTD, A-FLT or OTDOA when GPS signals are not available. Accuracy estimates for AGPS range between 5m and 30m.

Techniques based on Location Signatures: While there is no standard specified for using RF location signatures for estimating the position of a MS, some companies (Polaris Wireless) and research work have demonstrated the feasibility of this approach. In (Ahonen & Laitinen, 2003), the multipath intensity profile at a given location is used as the RF signature. A database correlation mechanism is used where the measured multipath profile is correlated with profiles stored in a database. The profile in the database with the highest correlation is chosen as the estimated position of the MS. Simulation results in (Ahonen & Laitinen, 2003) show that 67% of the position estimates are within 25m of the exact position and 95% are within 140m.

Summary

Positioning in wireless networks is gaining importance and a major driving force is the FCC mandate for provisioning E-911 services in cellular telephone networks. Several standards have been developed for this purpose that primarily employ time difference of arrival or point of access methods to estimate the position of mobile stations. Accuracy and precision with these methods show considerable variation depending on the environment, wireless technology and positioning algorithm.

Table of Acronyms

A-FLT	Advanced Forward Link Trilateration
AGPS	Assisted Global Positioning System
AOA	Angle of Arrival
AP	Access Point
BS	Base Sttaion
CDMA	Code Division Multiple Access
DOA	Direction of Arrival
EDGE	Enhanced Data for Global Evolution
E-FLT	Enhanced Forward Link Trilateration
E-OTD	Enhanced Observed Time Difference

FCC	Federal Communications Commission
GSM	Global System for Mobile Communications
IPDL	Idle Period on Downlink
MS	Mobile Station
OTDOA	Observed Time Difference of Arrival
POA	Point of Access
TDMA	Time Division Multiple Access
TDOA	Time Difference of Arrival
TOA	Time of Arrival
UTDOA	Uplink Time Difference of Arrival
WLAN	Wireless Local Area Network

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Terms and Definitions

CDMA: A multiple access technology used in second and third generation cellular systems that allows reuse of frequencies in all cells by spreading the spectrum and allocating unique codes for different users.

TDMA: A multiple access technology used primarily in second generation cellular systems that separates user transmissions in time within a cell.

Cell-ID: A positioning technique used to locate mobile stations based on the base station or access point to which they are associated. It typically has poor accuracy.

TDOA: A positioning technique that does not require absolute information about time in locating a mobile station as it uses time differences.

AOA: A positioning technique that employs the direction or angle at which a signal is arriving from (or at) a known location to estimate the location of a mobile station.