Standardization of Mobile Phone Positioning for 3G Systems

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ABSTRACT

Finding the location of the mobile phone is one of the important features of the 3G mobile communication system. Many valuable location-based services can be enabled by this new feature. Telecommunication managers and engineers are often puzzled by location terminologies and techniques as well as how to implement them, since location systems are not natural evolution from past generations of telecommunication systems. In this paper, we discuss briefly why locating mobile phone becomes a hot topic and what technologies are being studied. We then describe and clarify the latest standards issues surrounding the positioning methods specified for 3G systems. These include cell-ID-based, assisted GPS, and TDOA-based methods, such as OTDOA, E-OTD, and A-FLT.

INTRODUCTION

The U.S. Federal Communications Commission (FCC) has made Emergency 911 (E911) a mandatory requirement for wireless communications services such as cellular telephone, wideband (broadband) personal communications services (PCS), and geographic area specialized mobile radio (SMR). This ruling and upcoming service is called wireless E911. For Phase II implementation, the FCC required that public safety answering point (PSAP) attendants of wireless communications networks must be able to know a 911 caller's phone number for return calls and the location of the caller so that calls can be routed to an appropriate PSAP and related emergency assistance attendants. In 1999 the FCC decided to tighten the Phase II location accuracy requirement from 125 m in 67 percent of all cases to new numbers: for handset-based solutions, 50 m in 67 percent of calls and 150 m in 95 percent of calls; for network-based solutions, 100 m in 67 percent of calls and 300 m in 95 percent of calls. Handset-based solutions are for nonlegacy phones. Network-based solutions are for legacy phones. In 2000 the FCC required wireless communications operators to offer operational location-capable phones by October 1, 2001. On September 8, 2000, the FCC granted a limited waiver to VoiceStream with relaxed accuracy for an extended period. Right after the October deadline of 2001, waivers were granted to Alltel, AT&T Wireless, Cingular, NEXTEL, Sprint PCS, and Verizon, permitting them to postpone selling and activating location-capable phones that satisfy the new numbers until 2002 or later.

The executive body of the European Union (EU), the European Commission (EC), has similar initiatives for their wireless emergency calls, E112. Coordination groups within EC have been organizing meetings to specify similar requirements as their counterpart in the United States. On March 26, 2002, EU transport ministers approved $482.4 million in funding for the development of the European satellite system, called Galileo. This new system will rival the U.S.-developed global positioning system (GPS), which has already been adopted as one of the technologies for positioning, as discussed later.

In the United States, a recent survey by Harris Interactive indicated that consumers were more interested in E911 than other new mobile phone features. Out of 1006 adults, 59 percent selected E911 service. At a distant second, 7 percent selected e-mail service.

Besides emergency assistance, wireless E911 and its positioning capability will certainly trigger and enhance many location-based services. For instance, the telematics system [1] currently offered by automotive manufacturers, such as GM's OnStar and Mercedes-Benz's TeleAid, can be improved significantly. Future systems may no longer need to have separated location and communication devices attached permanently to the vehicle. Therefore, it is not difficult to understand why telecommunications manufacturers and operators have been actively pursuing the technologies to locate the mobile phone.

In this article we discuss location technologies specified by the 3rd Generation Partnership Project (3GPP) and 3GPP2, respectively. 3GPP has been concentrating on wideband code-division multiple access (W-CDMA) and Global System for Mobile Communications (GSM) systems while 3GPP2 has been focusing on cdma2000 and cdmaOne systems.

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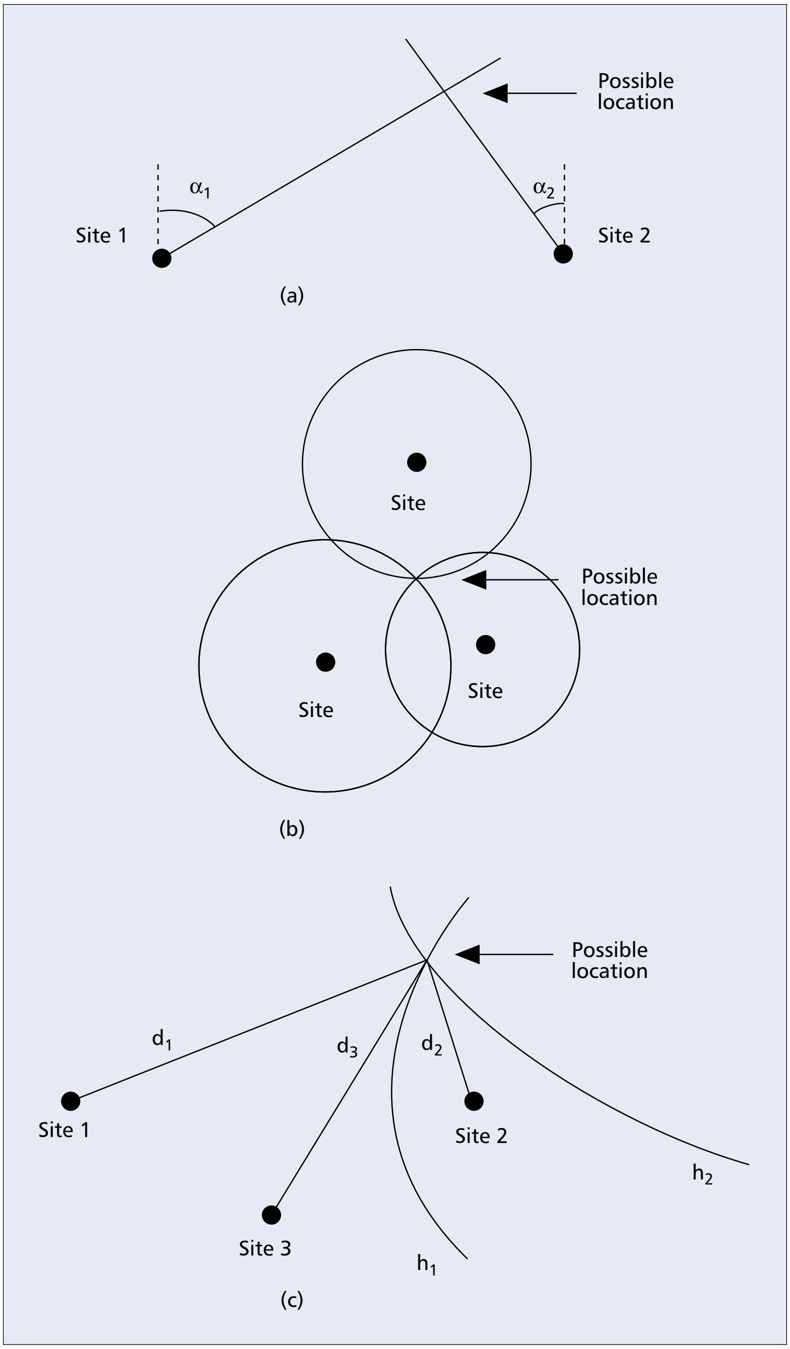
BASIC LOCATION TECHNOLOGIES

There are three most commonly used location technologies: standalone, satellite-based, and terrestrial-radio-based [2]. As examples, a typical standalone technology is dead reckoning; a typical satellite-based technology is GPS; and a typical terrestrial radio-based technology is the "C" configuration of the Long Range Navigation (LORAN-C) system. For wireless E911, E112, and many other applications, radio-based (satellite and terrestrial) technologies are most popular. Cellular networks are terrestrial-based communications systems. It is natural to utilize the signals of the network to determine the mobile phone location or assist in location determination. Research in this area has been very active recently as evidenced by the latest round of publications and conferences. The principles behind them are discussed below.

Radio-based technology typically uses base stations, satellites, or other devices emitting radio signals to the mobile receiver to determine the position of its user. Signals can also be emitted from the mobile device to the base. Commonly studied techniques are *angle of arrival* (AOA) positioning, *time of arrival* (TOA) positioning, and *time difference of arrival* (TDOA) positioning. All these methods require radio transmitters, receivers, or transceivers. In other words, they depend on emitting and receiving radio signals to determine the location of an object on which a radio receiver or transceiver is attached. To make the position determination, these methods generally work under the assumption that one end of the positioning system is fixed or known and the other movable (e.g., a mobile phone). However, the location determination capability can be at either the fixed or the mobile end. Generally, it is up to the system designer to decide where the final location determination capability should reside. For performance improvement, hybrid methods (various combinations of the techniques discussed or with additional techniques) are possible. To simplify our discussion, in the following we use two-dimensional (2D) cases as application examples. Readers should be able to expand the principles presented to 3D cases.

The AOA system determines the mobile phone position based on triangulation, as shown in Fig. 1a. It is also called direction of arrival in some literature. The intersection of two directional lines of bearing defines a unique position, each formed by a radial from a base station to the mobile phone in a 2D space. This technique requires a minimum of two stations (or one pair) to determine a position. If available, more than one pair can be used in practice. Because directional antennas or antenna arrays are required, it is difficult to realize AOA at the mobile phone.

The TOA system determines the mobile phone position based on the intersection of the distance (or range) circles (Fig. 1b shows a 2D example). Since the propagation time of the radio wave is directly proportional to its traversed range, multiplying the speed of light to the time obtains the range from the mobile phone to the communicating base station. Two range measurements provide an ambiguous fix, and three measurements determine a unique position. The same principle is used by GPS, where the circle becomes the sphere in space and the fourth measurement is required to solve the receiver-clock bias for a 3D solution. The bias is caused by the unsynchronized clocks between the receiver and the satellite.



■ **Figure 1.** *Position determination methods: a) angle of arrival; b) time of arrival; c) time difference of arrival.*

The TDOA system determines the mobile phone position based on trilateration, as shown in Fig. 1c. This system uses time difference measurements rather than absolute time measurements as TOA does. It is often referred to as the *hyperbolic system* because the time difference is converted to a constant distance difference to two base stations (as foci) to define a hyperbolic

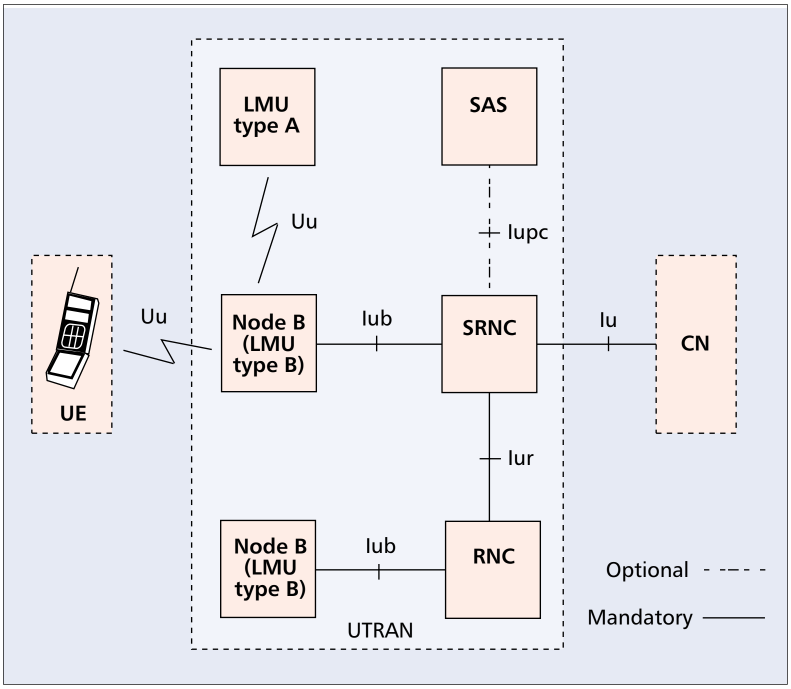


Figure 2. *System architecture of UE positioning.*

curve. The intersection of two hyperbolas determines the position. Therefore, it utilizes two pairs of base stations (at least three for the 2D case shown in Fig. 1c) for positioning. The accuracy of the system is a function of the relative base station geometric locations. For terrestrial-based systems, it also requires either precisely synchronized clocks for all transmitters and receivers or a means to measure these time differences. Otherwise, a 1 µs timing error could lead to a 300 m position error.

Other location methods can also be used. One simple method for mobile phone positioning is to use the cell area (or *cell ID*) of the caller, assisted by other coarse estimates, as the approximate location of the mobile phone. We will discuss this method further in the next section. Another method is to use *short-range beacons* (or signposts in some literature) installed in the coverage area to provide location-specific information to the mobile receiver [2]. Due to its limited communication zones, discontinuous communication, and high system installation and maintenance costs, it has not been considered for mobile phone positioning. Another alternative is to use *other radio signals*, such as TV or AM/FM radio broadcast signals, in place of cellular or satellite signals. In most areas there are plenty of these radio signals. The coverage is generally better than that provided by cellular signals. Other methods are based on measuring the *signal strength* or *signal characteristic patterns* and multipath characteristics of radio signals arriving at a cell site from a caller. For measuring the signal strength, it employs multiple cell sites to find the location. For measuring the signal characteristic patterns, it identifies the unique radio frequency pattern or *signature* of the call and matches it to a similar pattern stored in its central database.

Location Technologies Specified by 3GPP

Location Technologies Specified for UTRAN

In the Universal Terrestrial Radio Access Network (UTRAN), a handset is called user equipment (UE) and a base station is called node B. There are two operational modes for UTRAN: frequency-division duplex (FDD) and time-division duplex (TDD). The original standards specifications were developed based on FDD mode.

Three location techniques have been specified for UTRAN [3–8]: the cell-ID-based, observed TDOA (OTDOA), and assisted GPS (A-GPS) methods. When the mobile phone position is calculated at the network, we call it a UE-assisted solution. When the position is calculated at the handset, we call it a UE-based solution. Note that except for the UE-assisted OTDOA method, the rest of the methods are optional in the UE.

Figure 2 illustrates the system architecture of UE positioning (UP). The UTRAN interfaces (Uu, Iub, Iur, and Iupc) are used to communicate among all relevant entities. In this figure SRNC stands for serving radio network controller, LMU for location measurement unit, SAS for standalone serving mobile location center (SMLC), and CN for core network. LMU type A is a standalone LMU; type B is integrated with a base station.

For Release 99 (standards release frozen in December 1999) and Release 4 (frozen in March 2001), the SAS supports A-GPS only. In Release 5 (frozen in March 2002), the SAS will support two other location methods as well (Cell ID and OTDOA). Deployment of the SAS is optional. If an SAS is not included in the system, the SMLC (location server) will be an integral part of the RNC or SRNC. Note that later releases have more features (functionalities) than early ones. "Frozen" means that the contents (or features) of a specific release have been decided, but the detailed protocols and functionalities may not be stable or finalized. These releases are updated quarterly.

The Cell-ID-Based Positioning Method — The cell-ID-based method determines the UE position at the network. In other words, the position of a UE is estimated based on the coverage information of its serving node B. This knowledge can be obtained by paging, locating area update, cell update, UTRAN registration area (URA) update, or routing area update. This method is optional for the network. Despite not being mandatory, it is the author's suggestion that we should implement it as a default location method. Whenever OTDOA or A-GPS fails to locate the UE, we can always use this method to provide approximate information on mobile phone position to the network.

Depending on the operational status of the UE, additional operations may be needed in order for the SRNC to determine the cell ID. When the location service (LCS) request is received from the CN, the SRNC checks the state of the target UE. If the UE is in a state where the cell ID is not available, the UE is paged so that the SRNC can establish the cell with which the target UE is associated. In states where the cell ID is available, the target cell ID is chosen as the basis for the UE positioning. In soft handover, the UE may have several signal branches connected to different cells while reporting different cell IDs. The SRNC needs to combine the information about all cells associated with the UE to determine a proper cell ID. The SRNC should also map the cell ID to geographical coordinates or a corresponding service area identity (SAI) before sending it from the UTRAN to the CN. This can easily match the service coverage information available in the CN.

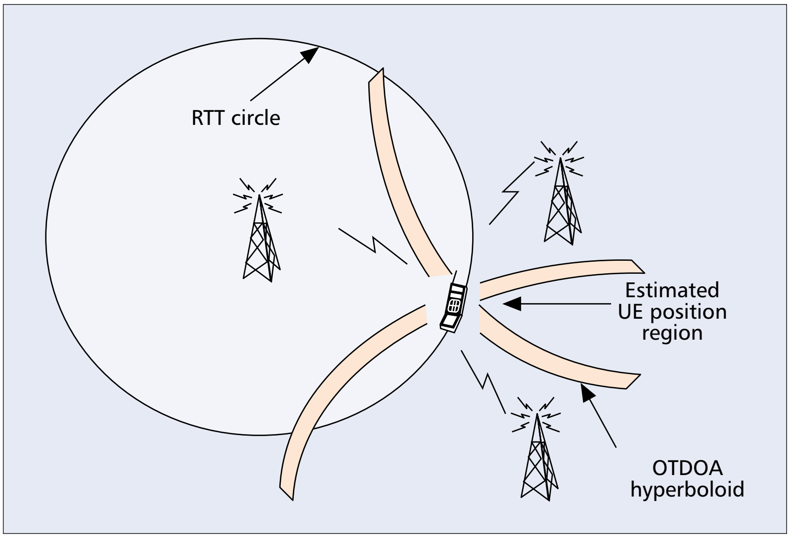
In order to improve the accuracy of the LCS response, the SRNC may also request additional measurements from node B or the LMU. These measurements are originally specified for soft handover. For FDD mode, round-trip time (RTT) can be used as a radius of a cell to further confine the cell coverage. RTT is the time difference between the transmission of the beginning of a downlink dedicated physical channel (DPCH) frame to a UE and the reception of the beginning of the corresponding uplink from the UE. For TDD mode, received (RX) timing deviation can be used. RX timing deviation is the time difference between the reception in node B of the first detected uplink path and the beginning of the respective slot according to the internal timing of node B. The measurements are reported to higher layers, where timing advance values are calculated and signaled to the UE. For better accuracy, for instance in FDD mode, a mandatory UE Rx-Tx time difference type 1 or an optional type 2, if available, can be combined with RTT to determine the distance from a node B to a UE. UE Rx-Tx time difference is the difference between the UE uplink DPCCH/DPDCH frame transmission and the first detected path (in time) of the downlink DPCH frame from the measured radio link, where DPCCH stands for dedicated physical control channel and DPDCH stands for dedicated physical data channel. The main differences in type 1 and type 2 are the measurement resolution and reference Rx path (or first detected path). For type 2, the resolution is better and the reference path must be the path among all paths detected by the UE. In contrast, for type 1, the reference path is the one used in the demodulation process.

The cell-ID-based method should determine the position of the UE regardless of the UE operational mode (i.e., connected or idle). This method results in a position error as large as the cell area if no additional measurements are used. For instance, a picocell could be 150 m in radius, while a large cell could be more than 30,000 m in radius. Therefore, this method has not demonstrated that it can achieve 100 m accuracy reliably even under the best of conditions.

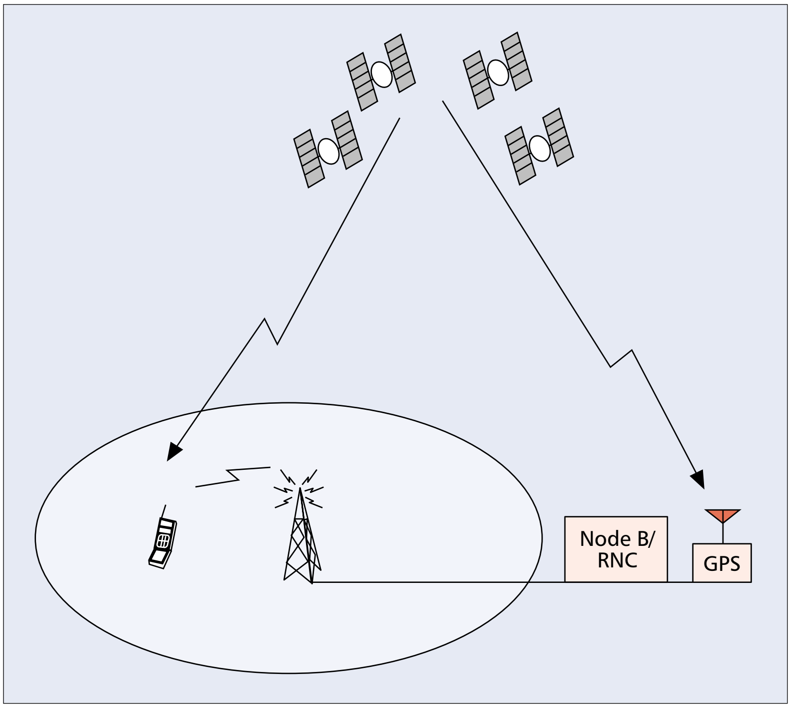
The OTDOA Positioning Method — OTDOA is a TDOA-based positioning method. It determines the position of the mobile phone based on trilateration as shown in Fig. 3. Two methods are specified for OTDOA: UE-assisted OTDOA and UE-based OTDOA.

As discussed above for a TDOA-based method, the accuracy of the system is a function of the relative node B geometric locations. Additional environmental constraints dictate that the more measurements we can obtain, the better position fixes we will receive. Since these measurements are based on the signals from node Bs, the locations of these base stations are necessary for the network or UE to calculate the handset positions. If the transmitters of node B in UTRAN are unsynchronized, the relative time difference (RTD) must be provided for system frame numbers (SFN). It is named SFN-SFN observed time difference. One way to obtain these measurements is to deploy LMUs, which perform timing measurements of all the local transmitters in fixed locations of the network. These measurements can be converted to RTDs and transmitted to the UE or RNC for positional calculations. In addition, the UE also measures the SFN-SFN observed time difference, which identifies the time difference between two cells as TDOA. Two types are defined. As explained later, type 1 is used for soft handover and type 2 is used for positioning. The main difference of these two types is that type 2 is applicable for both idle and connected modes, while type 1 supports intrafrequency measurements and cannot do interfrequency measurements for the connected mode. Since node Bs in TDD mode are generally synchronized, the RTDs are typically constant. Similarly, in FDD if the relevant cells are synchronized, measurements of RTDs would not be necessary. For FDD mode, RTT and Rx-Tx time difference can be obtained to improve the performance of the OTDOA. For TDD mode, RX timing deviation can be obtained to improve performance. Since adaptive or smart antennas have been specified as a feature for 1.28 Mchips/s TDD networks, AOA can be used to further improve the OTDOA and cell ID performances.

The OTDOA location method in UTRAN has its problems, such as hearability, unsynchronized base stations for FDD mode, geometric location of the base stations, and capacity loss. For the hearability problem, this can occur when the UE is very close to its serving node B, which



■ **Figure 3.** *OTDOA positioning method.*



■ **Figure 4.** *Assisted GPS positioning method.*

could block the reception of other base station signals in the same frequency. From Fig. 3 we know the UE must be able to hear at least three base stations in order to perform its location duty. For the unsynchronized base station problem, it causes significant uncertainty to the TDOA measurements. For the geometric location of the base station problem, the locations of the contributing base stations could affect the availability and quality of the position fixes. For instance, on a long straight highway in a rural area, OTDOA may fail to produce required solutions because node Bs may simply lie along the same highway. For the capacity loss problem, the system could provide less capacity to customers since the signal and traffic channels as well as some of the computing power of the UE or network entity could be occupied by the location services.

In order to improve the hearability of neighboring node Bs, one option specified is the idle period downlink (IPDL). In this method, each node B ceases its transmission for short periods of time (idle periods). During an idle period of a node B, UEs within the cell can measure other node Bs, so the hearability problem is reduced. By using signaling over the Uu interface, UEs are made aware of the occurrences of IPDLs, so they can arrange the time difference measurements accordingly. Since the IPDL method is based on downlink, the location service can be provided efficiently to a large number of UEs simultaneously.

For UE-assisted OTDOA, essential information elements (IEs) or assistance data from UTRAN to UE are reference and neighbor cell information. For UE-based OTDOA, they are reference and neighbor cell information as well as node B positions of these cells. UE-assisted OTDOA is mandatory for the UE and optional for the UTRAN. The UE-based OTDOA is optional for both the UE and UTRAN. Notice that for UE-based OTDOA, the length of the downlink IE is longer than the UE-assisted OTDOA. In contrast, the length of the uplink IE is shorter since one reports 2D/3D UE position and another reports measured TDOA results. In addition, UTRAN-to-UE information transfer is specified for both point-to-point and broadcast transmissions. For broadcast, UE-assisted OTDOA IEs are defined as system information block type 15.4 and UE-based OTDOA IEs are defined in as system information block type 15.5 [8].

The Assisted GPS Positioning Method — GPS provides an affordable means to determine position, velocity, and time around the globe. The satellite constellation is developed and maintained by the U.S. Department of Defense. Civilian access is guaranteed through an agreement with the Department of Transportation. GPS satellites transmit two carrier frequencies. Typically, only one is used by civilian receivers. From the perspective of these civilian receivers, GPS satellites transmit at 1575.42 MHz using CDMA, which uses a direct-sequence spread-spectrum (DS-SS) signal at 1.023 MHz (Mchips/s) with a code period of 1 ms. Each satellite's DS-SS signal is modulated by a 50 b/s navigation message that includes accurate time and coefficients (ephemeris) to an equation that describes the satellite's position as a function of time. The receiver (more precisely, its antenna) position determination is based on TOA.

The four main conventional GPS receiver functions are:
- Measuring distance from the satellites to the receiver by determining the pseudo-ranges (code phases)
- Extracting the TOA of the signal from the contents of the satellite transmitted message
- Computing the position of the satellites by evaluating the ephemeris data at the indicated TOA
- Calculating the position of the receiving antenna and the clock bias of the receiver by using the above data items

Position errors at the receiver are contributed by the satellite clock, satellite orbit, ephemeris prediction, ionospheric delay, tropospheric delay, and selective availability (SA). SA is an accuracy degradation scheme to reduce the accuracy available to civilian users to a level within the national security requirements of the United States. It decreases the accuracy capability of autonomous GPS to the 100 m (2D-RMS) level, where RMS stands for root mean square. To reduce these errors, range and range-rate corrections can be applied to the raw pseudo-range measurements in order to create a position solution that is accurate to a few meters in open environments. The most important correction technique is differential GPS (DGPS). It uses a reference receiver at a surveyed position to send correcting information to a mobile receiver over a communications link. Note that since May 2000 SA has been turned off, which often results in an accuracy of under 20 m in unobstructed environments.

To deal with the following problems facing the standalone conventional GPS receiver, the A-GPS method was specified to improve the performance of GPS (Fig. 4):

- Its startup time (from turning on to the initial position fix) is relatively long due to the long acquisition time of the navigation message (at least 30 s to a few minutes).
- It is unable to detect weak signals that result from indoor and urban canyon operations as well as small cellular-sized antennas.
- Its power dissipation is relatively high per fix, primarily due to the long signal acquisition time in an unaided application.

The basic idea of assisted GPS is to establish a GPS reference network (or a wide-area DGPS network) whose receivers have clear views of the sky and that can operate continuously. This reference network is also connected with the cellular infrastructure, continuously monitors the real-time constellation status, and provides data such as approximate handset position (or base station location), satellite visibility, ephemeris and clock correction, Doppler, and even the pseudorandom noise code phase for each satellite at a particular epoch time. At the request of the mobile phone or location-based application, the assist data derived from the GPS reference network are transmitted to the mobile phone GPS receiver (or sensor) to aid fast startup and increase sensor sensitivity. Acquisition time is reduced because the Doppler vs. code phase uncertainty space is much smaller than in conventional GPS due to the fact that the search space has been predicted by the reference receiver and network. This allows for rapid search speed and a much narrower signal search bandwidth, which enhances sensitivity and reduces mobile receiver power consumption. Once the embedded GPS receiver acquires the available satellite signals, the pseudo-range measurements can be delivered to RNC or SAS in UTRAN for position calculation or used internally in the UE to compute position.

Additional assisted data, such as real-time integrity, DGPS corrections, satellite almanac, ionospheric delay, and universal time coordinated (UTC) offset can be transmitted to improve the location accuracy, decrease acquisition time, and allow for different position computation solutions. Besides adding a GPS reference network and additional location determination units in the network, the mobile phone must embed, at a minimum, a GPS antenna and RF downconverter circuits, as well as make provision for some form of digital signal processing software or dedicated hardware. Despite the fact that A-GPS can improve the performance of a conventional GPS receiver, it cannot be used for legacy phones already on the market. As in the case of OTDOA, there are two solutions for A-GPS. A UE can support either one or both of them.

The UE-assisted solution shifts the majority of the traditional GPS receiver functions to the network processor. This method requires an antenna, RF section, and digital processor in the UE for making measurements by generating replica codes and correlating them with the received GPS signals. The network transmits an assistance message to the mobile station, consisting of time, visible satellite list, satellite signal Doppler and code phase, as well as their search windows or, alternatively, approximate handset position and ephemeris. These IEs help the embedded GPS sensor reduce the GPS acquisition time. The assistance data of Doppler and code phase are valid for a few minutes, while ephemeris data last two to four hours. It returns from the UE the pseudo-range data processed by the GPS sensor. After receiving the pseudo-range data, the location server in the SRNC or SAS estimates the position of the UE. The differential correction (DGPS) can be applied to the pseudo-range data or final result at the network side to improve the position accuracy.

The UE-based solution maintains a fully functional GPS receiver in the handset. This requires the same functionality described for UE-assisted GPS, plus additional means for computing the positions of the satellites and ultimately the UE's position. This additional handset function generally adds to the handset's total memory (RAM, ROM) requirements in addition to extra computing capability such as million instructions per second (MIPS). In the initial startup scenario, data in the form of the precise satellite orbital elements (ephemeris) must be provided to the UE. This data is valid for two to four hours and can be extended to cover the entire visible period of the GPS satellite (i.e., up to 12 hours), as discussed later. Thus, once the handset has the data, subsequent updates are rare. For better positional accuracy or longer ephemeris life, differential correction (DGPS) data should be transmitted to the UE. The final position of the UE is generated at the UE itself. The calculated UE position can then be sent to an application outside of the UE if required.

For UE-assisted GPS, the essential IEs from UTRAN to UE are reference UE position, GPS reference time, plus either code phase and Doppler (acquisition assistance) or satellite positions (ephemeris and clock correction). For UE-based GPS, they are reference UE position, GPS reference time, plus satellite positions and failed/failing satellites information (real-time integrity). The UE can also request additional GPS IEs. From UE to UTRAN, UE-assisted GPS reports measured pseudo-range results, while UE-based GPS reports 2D/3G UE position. For UE-based GPS, UTRAN-to-UE information transfer is specified for both point-to-point and broadcast transmission. For broadcast, the essential IEs are defined as system information block types 15 and 15.2 [8].

There are some interesting features defined in the specifications to improve the performance of the A-GPS. In the DGPS corrections IE [8], three pairs of pseudo-range correction (PRC) and range-rate correction (RRC) related fields are specified. Proper usage of these pairs will extend the life of the ephemeris and clock correction IE [8], which in turn will reduce transmission bandwidth, handset power consumption, memory, and CPU load. Typically, the ephemeris IE is valid at the UE for 2–4 h. The PRC2/RRC2 pair is used to extend the life for 6 h and the

The basic idea of assisted GPS is to establish a GPS reference network (or a wide-area DGPS network) whose receivers have clear views of the sky and which can operate continuously. This reference network is also connected with the cellular infrastructure.

The basic idea is to remove the errors contained in the ephemeris IE when needed. Since the maximum visible period of GPS satellites for one path is 12 hours, this feature avoids transmitting the long ephemeris IE more than once during the period.

Pros/Cons	UE-Based GPS	UE-Assisted GPS
Advantage	Relatively short uplink IE	Relatively short downlink assistance IE if code phase and Doppler are used
	Assistance IE valid for 2–4 hours or up to 12 hours at the UE if ephemeris life extension feature is used (less signaling)	Network in control of position determination
	Good for tracking/navigation applications	Need less computing power and memory at the UE
	Can be used as a standalone GPS receiver	
	Do not need LMU	
Disadvantage	Relatively long downlink assistance IE	Relatively long uplink IE
	Need more computing power and memory at the UE	Assistance IE valid for a few minutes at the UE if code phase and Doppler are used (more signaling for tracking/navigation applications)
		Need accurate timestamps at the UE
		Certain event trigger mechanisms will not work
		Need LMU for certain assistance data

Table 1. *Comparison of UE-assisted and UE-based GPS.*

PRC3/RRC3 pair is used for 8 h. To extend the life of the ephemeris IE beyond 8 h in broadcast or beyond 2–4 h in point-to-point operations, tailored DGPS can be used: a UE informs the RNC or SAS of its issue of data ephemeris (IODEs) and expected use time of its stored ephemeris [8]; then the RNC provides a PRC/RRC pair specific to that UE. The basic idea is to remove the errors contained in the ephemeris IE when needed. Since the maximum visible period of GPS satellites for one path is 12 h, this feature avoids transmitting the long ephemeris IE more than once during the period. By using this method, a UE wakes up for a particular correction pair only when a location fix is required.

The real-time integrity IE [8] is essential for proper operation of A-GPS. What this message covers is abnormal situations out of the control of the GPS control segment (master stations on the ground). For example, the atomic clock of a GPS satellite can fail suddenly, which in turn produces wrong satellite signals. In other words, the location accuracy can degrade substantially when undetected GPS satellite failures are present. Such failures can render the positioning information derived by a UE completely unusable. Although the control segment monitors the health of the GPS satellites, this activity is not performed continuously. It may require more than 30 min for the control segment to communicate this to GPS users. To provide the real-time integrity IE, one has to deploy an integrity monitor (IM) in the RNC or SAS. Besides informing of failed/failing satellites, it also tells the UE of measurement quality when satellites are healthy. This is done through the supplied user differential range error (UDRE), which is one field in the DGPS correction IE. The UE uses the UDRE as a factor in weighing data obtained from associated satellites in its position calculation.

The above features are also specified in GSM standards. To reduce infrastructure investment, a shared location server can be implemented to support dual-mode phones operating in both GSM and UMTS/W-CDMA networks. An additional benefit of implementing these features is that the RNC or SAS has to provide differential capability to the system. This capability can greatly improve positioning performance, such as with unexpected multipath in the server and poor geometry of visible satellites for the UE.

Finally, in order to better understand the A-GPS method, we list the pros and cons of UE-based and UE-assisted GPS in Table 1. Readers can compare them to decide which is suitable for their specific application.

To clarify positioning measurements, Table 2 lists all UE and UTRAN related measurement elements. For UE, three elements are specified for other purposes. SFN-SFN observed time difference type 1 is used to identify the time difference between two cells. SFN-CFN observed time difference is used for handover timing purpose to identify active cell and neighbor cell time difference, where CFN stands for connection frame number. Note that SFN-CFN observed time difference is defined as cell synchronization information in radio resource control protocol [8]. Both are used for soft handover. The difference is that SFN-SFN is for establishment of a call directly into soft handover, and SFN-CFN is for addition of new radio links into the soft handover for an already existing call. Rx-Tx timing difference type 1 is used for call setup purposes to compensate for the propagation delay between uplink and downlink transmissions, and to tell the network that the received timing of a cell is moving out of the UE's soft combining window. In addition to soft handover, it can also be used to improve position determination performance. For UTRAN, all the elements listed are optional

	Element	Accuracy (chips)	Choice	Comment
UE	Rx-Tx time difference type 1	1.5 for FDD	Mandatory	For soft handover
	Rx-Tx time difference type 2	TBD for FDD	Optional	For position determination
	SFN-SFN observed time difference type 1	1 for FDD, 0.5 for TDD	Mandatory	For soft handover of establishing a call
	SFN-SFN observed time difference type 2	0.5 for FDD intra-frequency, 1 for FDD inter-frequency, 0.5 for TDD	Mandatory	For position determination
	Cell synchronization information	1 for FDD, 0.5 for TDD	Optional	For soft handover on an existing call
	GPS timing of cell frames	TBD (to be determined)	Optional	For UE-assisted GPS position determination
UTRAN	SFN-SFN observed time difference	0.5	Optional	For position determination
	RTT	0.5 for FDD	Optional	Can also been used for position determination
	RX Timing Deviation	0.5 for TDD	Optional	Can also been used for position determination
	GPS timing of cell frames	TBD	Optional	For position determination

Table 2. *Measurement elements.*

and can be used for position determination. They are also been used for Uu, Iub, Iur, and Iupc interfaces, as shown in Fig. 2.

For 3.84 Mchips/s systems, 1 chip is about 0.26 µs. This translates to 78.125 m in range uncertainty. For 1.28 Mchip/s systems, 1 chip is about 0.78 µs. This translates to 234.375 m in range uncertainty.

Location Technologies Specified for GERAN

In the GSM EDGE Radio Access Network (GERAN), where EDGE stands for enhanced data rates for GSM evolution, three location methods are specified: cell ID, enhanced observed time difference (E-OTD), and A-GPS. They are all inherited and evolved from the methods specified for GSM. E-OTD is a TDOA positioning method based on the OTD feature already existing in GSM. In principle, it is similar to OTDOA but operates in TDMA-based networks. A-GPS method is similar to that specified for UTRAN, but with different IE lengths and formats. Note that GERAN has not adopted an uplink TOA method specified for GSM. Readers can refer to [9] for more information regarding these methods.

Location Technologies Specified by 3GPP2

Advanced forward link trilateration (A-FLT) and A-GPS have been standardized by Telecommunications Industry Association's TR-45.5 as IS-801 (IS-801-1 is its addendum) [10]. The next release, IS-801-A, is being handled by 3GPP2. Unlike GSM and W-CDMA, cdmaOne and cdma2000 are time-synchronized systems. Therefore, time difference measurement from them is easier than for GSM and W-CDMA.

The basic idea of the A-FLT method is to measure the time difference (phase delay) between CDMA pilot signal pairs. Each pair consists of the serving cell pilot and a neighboring pilot. The time difference is converted to range information. Finally, the range data is used to form certain hyperbolic curves at which an intersection is defined for handset location. Since the principle of this method is not much different than TDOA, we will not discuss it in detail.

Although the essential A-GPS IEs specified in IS-801 are very similar to those defined in 3GPP for UE-assisted and UE-based A-GPS, IS-801 offers more options. In other words, it provides more than one way to accomplish the same task. For instance, two IEs are defined to provide the reference UE position, one based on spherical coordinates and one on Cartesian coordinates. Despite these additional options, it does not support DGPS and broadcast specified by 3GPP. The new release, IS-801-A, is likely to address these issues in addition to adding other features and utilizing new channels defined for cdma2000.

Conclusions

In general, among the three methods specified, the cell-ID-based method has the worst positional accuracy, while A-GPS has the best positional accuracy. For cell-ID-based methods, the accuracy should be very close to the radius of the cell. For TDOA-based methods, it may achieve an accuracy of under 100 m in 67 percent of calls. For A-GPS methods, an accuracy of under 20 m is a very reasonable expectation in 67 percent of calls when SA is off. Many factors affect the performance of these methods, as discussed in the previous sections, such as cell sizes, hearability of other base stations, visibility of GPS satellites, and multipath. An experienced GPS user may notice that the accuracy of A-GPS in open sky environments is similar to an ordinary GPS receiver in the market. Meanwhile, an A-GPS receiver may have better coverage in obstructed

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environments. Compared with other radio-based technologies, A-GPS typically has better accuracy, but worse coverage than TDOA/TOA/AOA in buildings and urban canyon areas. On the other hand, the solution quality of TDOA/TOA/AOA depends heavily on the geometric location of the contributing base stations. To further improve these methods, hybrid approaches can be used [9]. One example is to combine OTDOA and A-GPS. Another is to combine OTDOA and AOA. Current specifications have left the door open for such fusions.

In 3GPP, new UE positioning enhancement solutions have been postponed until existing methods have been finished and stable. These new solutions include a thin UE GPS method, an uplink TDOA method, and a cumulative virtual blanking method to replace IPDL. 3GPP RAN is still working on the impact study of IPDL on the quality of service and measurement performance of the UE, and the open interface to support all three positioning methods discussed. GERAN continues working on location service in Iu mode. The proposed new methods have to wait until Release 6 (standards release expected to be frozen in June 2003) to be considered.

In 3GPP2, work for the next standards release has already begun. It is very likely they will address the issues of supporting broadcast, DGPS, and other new features, as well as how to utilize new channels specified for cdma2000. It would be beneficial if 3GPP and 3GPP2, as well as 3GPP GERAN and 3GPP RAN, can study how to harmonize their respective application interfaces and positioning protocols in future releases, particularly those independent of multiple access techniques.

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Biography

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