Geolocation and Assisted-GPS

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The Federal Communications Commission (FCC) requires that starting October 1, 2001, all wireless carriers be able to provide the position (or *geolocation*) of an emergency 911 caller to the appropriate Public Safety Answering Point (PSAP) [1]. Location technologies not requiring new, modified, or upgraded mobile stations (MS) must determine the caller's longitude and latitude within 100 meters for 67% of the emergency calls, and 300 meters for 95% of the calls. If new, modified, or upgraded handsets are required, the requirements are more stringent: 50 meters for 67% of the calls, and 150 meters for 95% of the calls.

An obvious idea is to use the Global Positioning System (GPS) and incorporate GPS receivers into mobile phones, especially considering substantial increase in GPS accuracy after the May 2000 removal of deliberately introduced errors through Selective Availability (SA). But to operate properly, conventional GPS receivers require a clear view of the skies and signals from at least four satellites, which excludes operation in buildings or other RF-shadowed environments. Furthermore, it takes a GPS receiver from the "cold" start (that is, without any knowledge about the state of the GPS constellation), up to several minutes to achieve the MS location fix. This is a considerable delay for many applications, especially for emergency services. Finally, there remain questions of cost, size, and power consumption when incorporating GPS receivers into trendy, miniature handsets.

Assisted-GPS (A-GPS) technology overcomes the downsides of the conventional GPS solution, and achieves high location accuracy at reasonable cost [2, 3]. The assistance to the mobile phone trying to determine its own location comes from the network over the air-interface, and this distributed approach leads to performance levels that exceed those of conventional GPS. What makes this technology work so well is that the wireless network, using its own GPS receivers, as well as an estimate of the mobile's location down to cell/sector, can predict with great accuracy the GPS signal the handset will receive and convey that information to the mobile. With this assistance the size of the search space is greatly reduced, and the time-to-first-fix (TTFF) shortened from minutes to a second or less. In addition, an A-GPS receiver in the handset can detect and demodulate signals that are order of magnitude weaker than those required by conventional GPS receivers. Only a partial GPS receiver is required in the handset to

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achieve this functionality, but legacy terminals cannot be used and new handsets are required for the technology to operate.

Although A-GPS and differential GPS (DGPS) are superficially similar, since in both technologies satellite-signal measurements are enhanced using information from terrestrial infrastructure, they differ in the essentials. DGPS increases the location accuracy of conventional GPS, but does not increase the sensitivity of GPS receivers. A-GPS improves the performance of conventional GPS receivers in low-SNR conditions, and can be combined with DGPS to increase the geolocation accuracy as well.

Besides emergency services, numerous geolocation-based applications are envisioned for the future. Among them are network optimization, where spatio-temporal wireless traffic distribution is to be used in planning, design, and operation of wireless networks; information services, which are to provide mobile users with directions to gas stations, restaurants, hotels and the like; tracking of personnel, vehicles, and assets in managing company operations; and location-sensitive billing of mobile users, to enable more precise rate structure for wireless service providers.

Geolocation Technologies

To place the assisted-GPS technology in proper perspective, we summarize the proposed geolocation technologies. The classification in Table 1 is made according to where signals are measured, since subsequent calculations for location determination can be done anywhere in the system. (In the Table, BTS denotes a wireless base station, MS a mobile handset, PDE is position-determination equipment, RTD is the real time difference, and LMU stands for Location Measurement Unit.)

Many factors greatly affect the accuracy of location technologies, especially multipath due to terrain (hilly vs. flat) and environment (urban vs. suburban vs. rural). Other factors, like cell size and interference, have smaller but noticeable effects. Most location methods work better in flat terrain and rural environments, but they all have their weak points and hybrid approaches appear to be the most robust. A particularly successful class of hybrid solutions is the combination of A-GPS with other location technologies. A-GPS is a natural fit for hybrid solutions since it uses the wireless network to supply assistance data to GPS receivers in handsets. Therefore, it is easy to augment the assistance-data message with handset-to-BTSs distances measured by the network equipment. Such hybrid solutions benefit from the fact that in dense urban environments, which are hostile to GPS signals, there is a high density of BTSs. And, conversely, in rural environments where BTSs are too scarce for network-based solutions to achieve high accuracy, operating conditions are ideal for A-GPS.

Table 1. Geolocation technologies

MS-Based Geolocation	**Global Positioning System (GPS)**	Built into the handset is a full-fledged GPS receiver that operates as a standalone device (see description in the Section on GPS).
	Assisted GPS (A-GPS)	A partial GPS receiver in the handset is aided in its operation by the wireless network (see description in the Section on A-GPS).
	Observed Time Difference (OTD)	MS monitors signals from at least three BTSs and observes time differences of arrivals. BTS locations are known and fixed and position is calculated by triangulation after subtracting OTD from RTD. LMUs required if BTSs not synchronized (e.g. GPS at each site). Added network traffic is minimal (data are gathered at MS,) but handsets need firmware upgrade. In GSM, method is known as Enhanced OTD (E-OTD).
Network-Based Geolocation	**Time of Arrival (TOA)**	MS signal is received by at least three BTSs, which measure TOA independently and send data to PDE where geolocation is calculated. No handset modifications are needed, but network requires upgrade and signaling is increased.
	Time Difference of Arrival (TDOA)	At least three BTSs monitor MS signals using dedicated location receivers. Location estimate based on apparent arrival time differences between pairs of sites. Strict time synchronism among all BTSs is a must. Time difference measurements less accurate in analog and digital narrowband systems (AMPS, TDMA,) leading to inferior performance.
	Angle of Arrival (AOA)	Special antenna arrays and location receivers in BTS determine AOA of the MS signal. Location is found at the intersection of apparent arrival directions. At least two BTSs needed, but three or more used to increase accuracy and reduce uncertainty due to multipath. No modifications to MS are needed.
	Multipath Fingerprinting	MS location found by matching the multipath-produced "fingerprint" of the signal received by one or more BTSs with location/fingerprint database. Technique requires continuous database management and updating.
	Timing Advance (TA)	During link establishment MS aligns its frame/slot times with the serving BTS, and uses this as a measure of its distance to BTS (TDMA or GSM). Using network-enforced handoff, at least three measurements with different BTSs are made and location is determined via triangulation. Sequential measurements make the method unreliable when MS is moving. No modifications to handsets and minor changes in BTS software.
Network/MS-Based Geolocation	**Enhanced Forward Link Triangulation (E-FLT)**	Solution unique to CDMA. Primarily based on TDOA using forward-link signals received by MS. Performance enhanced by complementary methods, including pattern matching of RF characteristics, statistical modeling, round trip delay measurements, and AOA.
Hybrid-Type Geolocation	**TDOA & Received Signal Strength (RSS)**	Combine highly accurate with highly robust methods, and use multiple inputs to improve both the robustness and coverage. E.g., in A-FLT/A-GPS, A-FLT can extend coverage deep indoors where not enough GPS satellites are visible; in TDOA/AOA, AOA enables operation even when only two BTSs can receive the MS signal.
	TDOA & AOA	
	A-FLT & A-GPS	
	E-OTD & A-GPS	

In Table 2 we show the current status of geolocation technologies in the standardization process that will specify messages and parameters needed for interoperability among proposals. Note that A-GPS is being standardized for all air-interfaces: first-generation analog (AMPS), second-generation digital (GSM, CDMA, TDMA), as well as for 3GPP (3rd Generation Partnership Project for mobile systems based on evolved GSM core networks) and 3GPP2 (for systems evolving from TIA/EIA-41 networks).

A-FLT (Advanced Forward Link Trilateration) and E-FLT (from Table 1) are similar in algorithms. The difference being that the former uses the IS-801 standardized message to carry the measurements at the software-upgraded MS, and the latter uses the Pilot Strength Measurement Message from TIA/EIA-95 (which was not designed for geolocation but for hand-off purpose) and therefore covers the legacy handsets. OTDOA (Observed Time Difference of Arrival) follows the same idea as OTD from Table 1. An improvement on the idea is IPDL (Idle Period DownLink), where base stations are periodically shut off so that MS can more accurately measure time-of-arrival of pilot signals from neighboring stations.

Table 2 . Geolocation technologies in wireless standards

Wireless Standard	Standards Body	Geolocation Technologies Used	Relevant Documents	Publication Date
GSM	ETSI SMG30	TOA AOA E-OTD A-GPS	GSM 03.71 GSM 04.71 GSM 09.31	January 2000
GSM (North America)	T1P1.5 ETSI SMG31	TOA AOA E-OTD A-GPS	GSM 04.35	January 2000
CDMA: TIA/EIA-95 cdma2000	TR45.5	A-GPS A-FLT	IS-801	November 1999 December 2000 (Addendum)
TDMA: TIA/EIA-136	TR45.3	A-GPS	TIA/EIA-136 Rev. C Part 740	June 2000 (draft) December 2000
AMPS	TR45.1	A-GPS	IS-817	June 2000 December 2000 (Addendum)
3GPP	3GPP	A-GPS OTDOA IPDL	TS25.305/331/215/133/171	April 2001
3GPP2	3GPP2	A-GPS A-FLT	IS-801 IS-801A	November1999 December 2000 (Addendum) February 2002 (Revision A)

Global Positioning System (GPS)

Navstar GPS (as it is known in the US) was designed for and is operated by the US military but currently used by civilians worldwide [4, 5]. GPS satellites broadcast specially coded signals that can be processed in GPS receivers, and four signals are needed to compute the receiver's position in 3-D (latitude, longitude, and altitude) with accuracy of ~10 meters or better, velocity vector within 0.1-0.2 m/sec, and time with precision of ~0.1 μsec. Since there is no return channel from GPS receivers to satellites, any number of users can get their positions simultaneously. GPS signals are resistant to interference and jamming, but are transmitted at very low power.

GPS constellation has 24 satellites in 12-hour orbits, 20,200 kilometers above Earth, positioned in six orbital planes with (nominally) four satellites in each, equally spaced at 60° apart and inclined at 55° with respect to the equatorial plane (see Figure 1). Users can see from 6 to 11 satellites from any point on Earth (8 is the most likely number). Measurements from satellite tracking and monitoring stations located around the world are incorporated into orbital models for each satellite, in order to compute precise orbital data (the so-called ephemeris) and satellite clock corrections. Master control facility uploads ephemeris and clock data to the satellites, which then broadcast subsets of the orbital ephemeris to GPS receivers.

Satellites transmit two carrier signals: L1 frequency (1575.42 MHz) that carries the navigation message and the Standard Positioning Service (SPS) code signals intended for civilian use; and the L2 frequency (1227.60 MHz) used to measure the ionospheric delay by Precise Positioning Service (PPS) equipped receivers for military and government users. Three binary sequences modulate the L1 and/or L2 carriers. The Coarse Acquisition (C/A) code is a repeating, 1023-bit (1 msec) pseudorandom noise (PRN) sequence that modulates the L1 carrier, "spreading" it at 1.023 Mchip/sec rate. A different PRN sequence is used for each GPS satellite, giving it a unique identifier used in ranging measurements. The (Precise) P-Code that modulates both the L1 and L2 carrier phases is a seven day-period PRN sequence at 10-MHz rate. Finally, the Navigation Message sequence that also modulates the L1-C/A code signal, is a 50-bit/s signal carrying data that describe GPS satellite orbits, clock corrections, and other system parameters.

The distance from a user to the satellite is determined from the signal propagation time. Namely, the replica C/A code generated in the receiver is shifted in time until it achieves correlation with the C/A code in the satellite signal. If satellite and receiver clocks were perfectly synchronized, the result would be a true propagation time. Since it is generally not the case, the measured range is referred to as pseudorange, ρ. From four satellite signals ($j = 1$ to 4), one can determine user coordinates (x_u, y_u, z_u) and t_u, the user-clock offset from GPS time, from the set of non-linear equations,

$$\rho_j = \sqrt{(x_j - x_u)^2 + (y_j - y_u)^2 + (z_j - z_u)^2} + c\,t_u$$

where (x_j, y_j, z_j) are satellite positions (received in the ephemeris message), and c is the speed of light [6]. The solution can be found in a closed form, through iterative techniques, or by Kalman filtering.

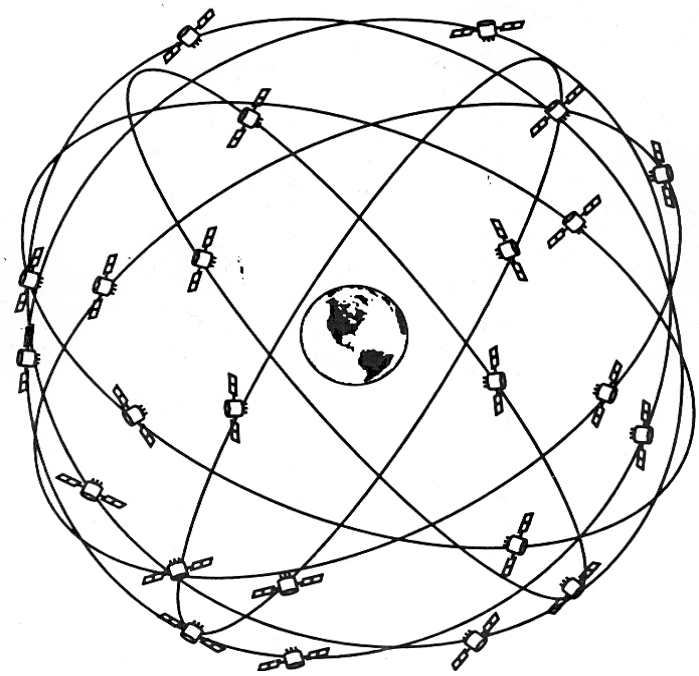

Figure 1. GPS satellite constellation

Assisted-GPS

The A-GPS technology concept is shown in Figure 2. The main system components are a wireless handset with partial GPS receiver; A-GPS server with reference GPS receiver that can "see" the same satellites as the handset (DGPS service can be used as well); and wireless network infrastructure, that is, base stations and a mobile switching center (MSC).

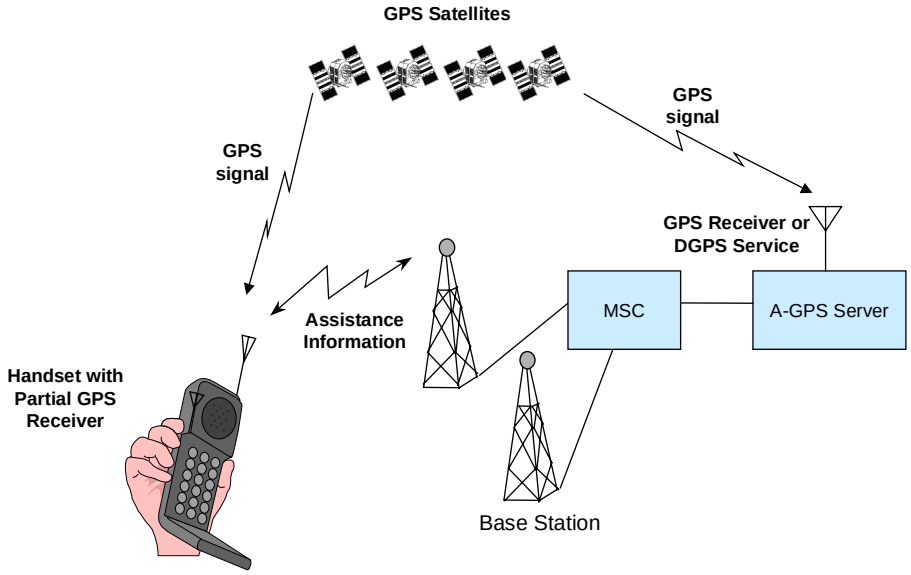

Figure 2. Assisted-GPS concept

Since an A-GPS server can obtain from the MSC the handset's position (up to the level of cell and sector), and at the same time monitors signals from GPS satellites seen by MS, it can predict the signals received by the handset for any given time. Specifically, it can predict the Doppler shift (due to satellite motion) of GPS signals experienced by the handset receiver, as well as other signal parameters that are a function of the mobile's location. In a typical sector, the uncertainty in the predicted time of arrival of a satellite signal at the mobile is about ±5 μs, which corresponds to ±5 chips of the C/A spreading code sequence. Therefore, A-GPS server can predict to within ±5 chips the phase of the PRN sequence that the receiver should use to de-spread the C/A signal from a particular satellite, and communicate that prediction to the mobile. The search space for the actual Doppler shift and PRN phase is therefore greatly reduced, and the A-GPS handset receiver can accomplish the task in a small fraction of the time required by conventional GPS receivers. In addition, the A-GPS server maintains a connection with the handset receiver over the wireless link, asking it to make specific measurements, collect the results, and communicate them back.

After de-spreading, an A-GPS receiver could pass the PRN phase information back to the A-GPS server, which would then calculate the mobile location coordinates. To reduce the amount of information sent over the air-interface, a preferred solution is to perform additional signal processing in the handset and return pseudoranges instead. In the recently issued IS-801 (CDMA) and TIA/EIA-136 Rev. C (TDMA) standards, it is even allowed that the mobile completes the location fix.

An additional way to help the handset receiver in detecting GPS signals is the so-called *sensitivity assistance* (or *modulation wipe-off*). The sensitivity-assistance message contains sets of predicted data bits in the GPS navigation message, which are expected to modulate GPS signal of specific satellites at specified times. Consequently, MS receiver can remove bit modulation in the received GPS signal prior to coherent integration. Receiver sensitivity is therefore improved since coherent integration beyond the 20-ms GPS data-bit period becomes possible, and can be extended to 1 second or more (400 ms in fast moving vehicles). For optimal performance of sensitivity assistance, A-GPS server must communicate to the handset the PRN sequence timing with an accuracy of several microseconds. This is achievable in TIA/EIA-95 CDMA systems since base stations and mobiles are in sync with the GPS time. GSM, TDMA or AMPS systems do not maintain such stringent synchronization, and implementation of sensitivity assistance (and A-GPS technology in general) will require novel approaches to satisfying the timing requirement. The standardized solution for TDMA and GSM is to add time calibration receivers in the field, the so-called Location Measurement Units (LMU), which can monitor both the wireless-system timing and GPS signals used as timing reference.

In summary, the most important types of network assistance to handset GPS receivers are reduction of the frequency uncertainty of satellite signals, and provision of ephemeris information.

Conclusions

In the current Phase I of the wireless E-911 mandate, service providers are required to inform the PSAP operator of the location of the cell/sector serving the MS that made the emergency call, as well as to convey call-back number in case the call is dropped. In November 2000, wireless service providers reported to the FCC their plans for the implementation of Phase II Automatic Location Identification (ALI) systems. Network-based solutions were proposed in about a third of the sixty reports, MS-based solutions in another third, and in the remaining reports no technology was selected despite the FCC deadline. (It is worth noting that these plans are only statements of intent, and providers might still change direction before fully implementing a solution.) Even the providers favoring handset-based solutions view the current lack of handsets with location capabilities as a major obstacle. Proponents of network-based solutions obviously considered the obstacle insurmountable. Considering pros and cons from Table 3, however, we believe that assisted-GPS (augmented with elements from other location technologies) is the solution to which most wireless systems will ultimately converge. Such hybrid solutions offer superior location accuracy, are standardized for all air-interfaces, and are potentially the most cost-effective.

Table 3. Advantages and disadvantages of geolocation technologies

Location Technology	Pro	Con
MS-Based Standalone GPS	■ Little or no additional network equipment • Privacy not an issue (user controlled) • Location capability remains in absence of wireless coverage or network assistance	• New handsets • Little or no indoor coverage • Poor accuracy in radio shadows • Additional computing functions add to handset cost • Additional battery consumption • Long TTFF • System upgrades limited by deployed handset base
Network-Based	• No added MS complexity or cost • Quick deployment • Short TTFF • Maps and databases increase accuracy of location fix • Continuous tracking capability for navigation applications • Business opportunity for network operators as exclusive providers of subscriber-location information	• Inferior accuracy • Additional investments in infrastructure, with high up-front costs • Difficult network installation and maintenance • User privacy questionable
Assisted-GPS	• Superior accuracy, availability, and coverage • Very short TTFF • Maps and databases increase location accuracy (if processing done in network) • Minimal impact on battery life • Implementation cost shared by mobiles and the network • System evolves with network upgrades • Location data shared between users and network operator — users can withhold data for privacy reasons, and operator can restrict assistance to subscribers of service • Air-interface traffic optimized by distributing data and processing between network and mobiles	• Network assistance increases signaling load • Interoperability between network and mobiles requires additional standards, delaying deployment • New or upgraded handsets needed for initial deployment

References

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