An Overview of the Challenges and Progress in Meeting the E-911 Requirement for Location Service

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ABSTRACT When the FCC created the rules for wireless Enhanced 911 (E-911) service, a flurry of research and development activities dedicated to locating the position of emergency callers followed. The current deadline for this capability is October 1, 2001. In this article, we review the unique challenges and some of the proposed approaches for each of the major wireless standards.

In 1996, after several well publicized stories regarding the inadequacy of emergency service for cellular callers came to light, the Federal Communications Commission (FCC) announced its mandate for enhanced emergency services for cellular phone callers. Emergency organizations such as the National Emergency Number Association (NENA) have fought hard for improved cellular emergency services. Furthermore, since consumer desire for security is one of the main driving factors behind the explosive growth of cellular services, the FCC was obliged to mandate this public safety feature.

Today, the primary motivation for implementing position location is conformance with FCC regulations, which are concerned primarily with the ability to locate mobile telephones originating emergency phone calls. This mandate represents a major deployment and operations challenge to wireless service providers, particularly those that are highly financially leveraged to pay for their spectrum and new infrastructure. However, there are also other position location applications that are of interest to service providers. These applications provide carriers the opportunity to differentiate themselves from competitors through better emergency services and additional services such as mobile yellow pages, equipment tracking, and position dependent billing [1]. Other possible services include location-specific advertising (e.g., restaurant/hotel guides), personnel tracking, and navigation assistance. For equipment service providers and carriers, this new capability represents an $8 billion market [2].

REVIEW OF THE FCC REQUIREMENTS

The FCC report and order issued in October 1996 required a phased implementation of progressively increasing emergency services functionality in wireless 911 systems [3]. The FCC required that all wireless common carrier services — cellular, personal communications services (PCS), and some special mobile radio (SMR) — implement basic 911 service by October 1997. This basic service includes the capability to process emergency calls without user validation, including handsets without Mobile Identification Numbers if requested by the Public Safety Answering Point (PSAP), and to process calls accommodating speech or hearing disabilities.

The FCC mandates that by March 1998 wireless carriers implement Phase I Enhanced 911 service. Phase I E-911 service includes the capability to transmit the originating number of an emergency call as well as the location of the cell site receiving the call to the PSAP. Although good faith efforts to meet this requirement are underway, and several states, such as Texas and California, have launched efforts to coordinate the activities of PSAPs and service providers, it is widely believed that Phase I E-911 service will not be universally operational and tested by the March 1998 deadline.

In the final phase of E-911 implementation, to be completed by October 1, 2001, the wireless carrier must provide latitude and longitude estimates of the caller's position within an accuracy of 125 m RMS (67 percent of the time). While the accuracy required the remaining 33 percent of the time has been the subject of some debate, it is widely accepted that the FCC envisions a graceful degradation of accuracy in the remaining cases. In addition, the FCC has already asked for comments on tightened accuracy requirements, including estimates of vertical position, which might be imposed after the year 2001 deadline.

OVERVIEW OF LOCATION TECHNOLOGIES

A variety of basic technologies are available for accurate position location. These technologies may be loosely grouped into handset-based technologies such as the Global Positioning System (GPS) and network-based technologies that exploit the cellular infrastructure to obtain geolocation information. For a review of the basic principles underlying these technologies, the reader is referred to [1] and the references contained therein. We provide a brief discussion of the relative merits.

A GPS receiver provides a location estimate based on the time of arrival of four or more L-band signals from a network of 24 satellites. Commercial GPS receivers now available for under $150 accurately determine position to within approximately 50 m, and the size and cost of GPS receivers will improve as the volume of commercial units increases [4]. Despite these characteristics, wireless service providers appear unwilling to embrace GPS as the principal location technology within the handset or car phone. This resistance may be attributed to cost, size, complexity, and power consumption associated with integrating a GPS receiver into a handset and to the susceptibility to radio frequency interference. Further-

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more, the reliability of GPS measurements is greatly reduced in urban environments, when one or more satellites are obscured by buildings, or when the mobile antenna is located inside a vehicle.

It is possible to determine the position of a mobile unit with minimal modifications to the handset by making observations of the time of arrival (TOA) or angle of arrival (AOA) of a signal at multiple locations. AOA measurements are most commonly performed using an array of antenna elements. AOA measurements from multiple base stations may be combined through triangulation to provide an estimate of the transmitting mobile unit's location. Field trials on actual cellular signals have demonstrated the potential of AOA techniques [5].

Since radio waves travel at the constant speed of light, the time of arrival (TOA) of a signal at multiple base stations may be used to pinpoint the location of a mobile unit. In practice, time difference of arrival (TDOA) measurements are often employed to eliminate the need for an accurate time reference at the mobile. Although both AOA and TDOA appear to be technically feasible solutions, cost will play an important factor in deployment. AOA requires deployment, precise calibration, and calibration maintenance of an antenna array at each base station, while TDOA requires only time synchronization between each base station, which can be accomplished fairly inexpensively using a GPS time reference. A combination of AOA and TDOA measurements may provide greater accuracy in particularly challenging environments. Furthermore, fewer base stations are required when both types of information are available.

Challenges in Meeting the FCC Requirements

While both phases of the emergency service requirements present significant challenges to the wireless network, the location requirements are perhaps the most daunting and will therefore be the focus of this article. These requirements present many technical challenges, such as the choice of location technology and the influence of radio propagation and coverage on accuracy. However, there are also significant institutional issues to be resolved, such as establishing mechanisms for cooperation between competing carriers and public safety agencies and implementing cost recovery mechanisms. While both types of challenges are significant, this article emphasizes technical issues associated with E-911.

Organization of this Article

The remainder of this article is divided into three sections. The following section considers the progress that has been made toward meeting location requirements for the major wireless air interface standards. Because of the differences in signal structure and protocols, each of the major standards presents a unique set of requirements. The next section then considers issues, such as propagation and coverage, common to all standards. Finally, the last section draws some conclusions about the hurdles that remain in meeting the wireless location challenge.

How Technology Is Developing for the Primary Wireless Standards

AMPS/USDC

The Advanced Mobile Phone System (AMPS) standard, based on analog frequency modulation technology, has been in widespread use for cellular phone service since it was first deployed in 1982. Although recent research attention has focused on digital transmission of signals, a large number of AMPS handsets will be operational in the United States for the foreseeable future. As a result, many initial product development efforts have focused on AMPS systems. Because of the channel and network compatibility between the AMPS and U.S. Digital Cellular (USDC) standards, most of the location solutions for AMPS offer a natural migration path to USDC.

The AMPS standard is challenging for accurate geolocation due to the limited signal bandwidth. Unlike other standards, it has a loosely defined analog signal structure that may vary slightly between vendors. For analog AMPS signals, closely spaced multipath arrival times will not be resolved with conventional time-domain processing because multipath delays commonly found in cellular channels are a small fraction of the width of the autocorrelation function peak. Even in the most severe multipath signal environment, the delay spread of significant multipath components will rarely exceed 10 μs. As a result, the peaks become indistinguishably grouped, and the location measurement is biased as a function of the relative amplitudes, delays, and phases of the cumulative multipath rays. The fundamentals of signal bandwidth and channel characterization make the detection of these multiple peaks with conventional time-domain cross-correlation processing a futile exercise. Because the analog AMPS standard does not dictate the use of a precise pulse-shaped digital waveform, the construction of a signal replica for use in the cross-correlation may be inexact and lead to additional error.

One of the first solutions for the location of AMPS mobiles was developed by TruePosition, a subsidiary of the Associated Group of Bala Cynwyd, Pennsylvania. TruePosition has designed a TDOA system that works as an overlay to existing cellular systems. The system is virtually self-contained and requires only access to signals from the base station antennas. The TruePosition system consists of four major subsystems: the signal collection system (SCS), the TDOA location processor (TLP), the application processor (AP), and the network operations center (NOC).

The SCS consists of a wideband digital receiver that monitors all 21 reverse control channels and stores a precisely time-stamped segment of the incoming mobile signal in a circular buffer. The control channels are monitored in the frequency domain, and when an incoming call is received, a threshold detector directs the SCS to grab a sample of the corresponding control channel. Once the control channel signal is stored, the signal is demodulated and examined to determine if the incoming call needs to be located; mobiles can be located based on called number (e.g., 911), mobile ID number, or any other information contained on the reverse control channel.

If the call is determined to require a location estimate, the SCS at the receiving base station sends a request for other base stations in the vicinity to save a copy of the same control channel signal (hence the need for buffer of stored signal). These signal copies are then passed to the TLP for location processing.

At the TLP, the time-stamped copies of the target call signal are cross-correlated using special high-resolution algorithms, and the resulting correlation peaks that estimate the difference in TOA of the call signal are used to compute the latitude and longitude of the caller. In addition, the signals from each base station can be analyzed for Doppler shift to estimate the speed and bearing of the caller to assist in tracking a moving caller.

Finally, the latitude, longitude, speed, and bearing information is passed to the AP database where the data on call locations can be accessed by appropriate authorities. For security and network convenience, the TLP is typically located within the mobile switching center, and the AP is typically located at the convenience of the carrier, remotely connected to the TLP. The NOC monitors the operation of the location system.

In a large-scale field trial conducted in the first few months of 1997 on the southern 50 mi of the New Jersey Turnpike/Interstate 295 corridor, the TruePosition system was deployed at 24 cell sites covering portions of four counties. Over 3000 actual 911 calls as well as over 80,000 test calls were handled during the trial period with average location errors of just over 600 ft. Based on the results of the trial, the participants were optimistic that the technology exists to successfully deploy Phase II location services for AMPS cellular systems [6].

Another known provider of FCC Phase II location systems is Grayson Wireless, a division of Allen Telecom. In support of this effort, Allen Telecom acquired Signal Science Inc. in 1996, and the Raytheon E-Systems Geometrix™ system in 1997.

Grayson Wireless is developing a geolocation system using the network overlay model. Location sensors, typically located at the base stations, measure the radio signal under control from a central location processor. Grayson has chosen to offer location sensors with a range of optional capabilities to cost-effectively meet the challenge of providing the required location accuracy in the presence of varying degrees of multipath interference. Lower-cost sensors provide the measurements required for TDOA location from two or four element diversity receive antennas of a base station. Greater antenna diversity allows spatial processing algorithms to mitigate the multipath interference. Finally, if the antenna elements are arranged in a phased array, AOA measurements are available to supplement the TDOA measurements. The combination of AOA and TDOA with spatial processing offers the capability to provide accurate locations in demanding environments.

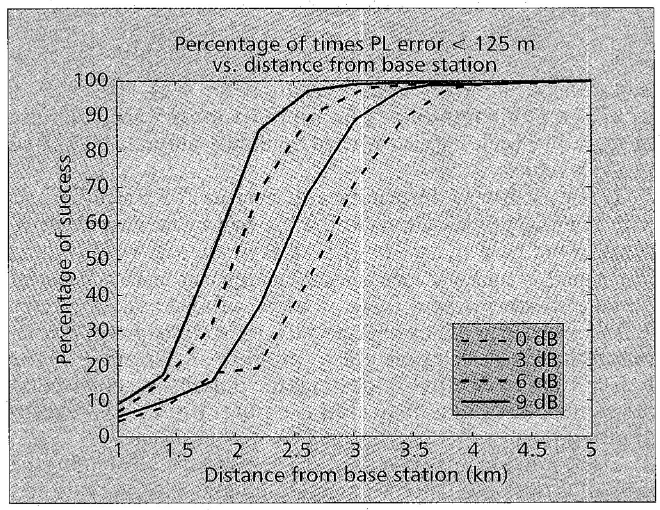
The resulting geolocation system uses an antenna array to spatially filter out multipath as well as calculate the AOA of the earliest arriving signal (corresponding to the shortest signal path). The CAPITAL geolocation system was one such system that performed joint TDOA and AOA to optimally geolocate narrowband AMPS signals [5]. Average position error for this system was approximately 108 m in semi-hilly suburban terrain. As a result of the recent acquisition of the technology by Grayson Wireless from Raytheon E-Systems, variations of the CAPITAL system are currently under development. Grayson will perform major in-network trials of these products in 1998.

CDMA

IS-95, the current air interface standard for digital code-division multiple access (CDMA) systems in much of the world, incorporates a combination of relatively wide signal bandwidth with data transfer capabilities, which makes CDMA an excellent platform from which to develop and provide location services for mobile terminals.

The Challenges of CDMA

In principle, the wide bandwidth of CDMA systems serves to increase the accuracy of location estimates, but the use of TDOA techniques within a CDMA system presents several challenges. First, the signals must be cross-correlated with the desired code sequence in addition to each other to separate the signal from the multiple access interference. Second, the location accuracy decreases as the mobile unit moves nearer to one base station and away from other base stations making TDOA measurements. This decrease in accuracy is exacerbated by the use of power control, which decreases signal power as the mobile unit approaches a base station. In this case, the signals received by the other base stations become extremely weak, resulting in the reduced performance.



■ **Figure 1.** *Location success in a CDMA system as a function of distance from controlling cell site for different mobile transmit power levels.*

One obvious solution to this problem is to allow the mobile unit to override the normal power control operation when a position estimate is desired. For the duration of the observation interval, the desired signal might increase the power level to the maximum mobile unit power. Although overriding power control for the desired user enhances location accuracy, it leads to a near-far situation, which greatly degrades the performance of other users whose signals are received at much lower power levels. While the system could withstand an occasional frame error in an emergency situation, the number of cellular E-911 calls is rising rapidly. Furthermore, if nonemergency services such as navigation and traveler information are to be implemented, there must be a way of obtaining accurate position location fixes without impairing the performance of other users in the network. One alternative to power control is the use of interference cancellation to cancel the strong interfering mobile user.

Reverse Link Location for IS-95

Reverse link geolocation approaches for IS-95 terminals are based primarily on TDOA techniques. The idea is to listen for a known signal from the mobile on the reverse link (uplink) at a number of time-synchronized base stations and cross-correlate the received signals from receiving base stations to estimate the differences in TOA. These time differences can be used to estimate the location of the mobile transmitter. The reverse link approach has the advantage of locating the mobile without requiring active participation by the mobile itself other than to transmit a known signal. The relatively wide (1.25 MHz) bandwidth of the IS-95 signal creates sharp correlation peaks, allowing for accurate location. The disadvantage of reverse link geolocation in IS-95 is that the ability to detect the mobile's signal at multiple base stations is limited by the system's normal power control operation.

Detection of a mobile signal at three or more base stations is a basic requirement to obtain a useful position fix for the mobile 911. One proposed solution to this "hearability" problem has been to add a "power-up" function to the IS-95 standard, which allows a mobile to transmit a short burst at high power so that its signal can be detected at multiple base stations. Figure 1 shows the percentage of successful locations (within 125 m) for a CDMA system with 10 users/cell and a nominal signal to noise ratio of 10 dB as a function of mobile distance from its controlling cell site when the mobile transmit power is increased by 3, 6, and 9 dB from its nominal level [7]. The results of overriding the power control operation are dramatic. Although there is still a threshold effect, it occurs at a much closer distance to the base station. It is reasonable to believe that through a combination of overriding the power control and increasing the observation interval, FCC location requirements could be satisfied in most instances. Although a single strong signal could be canceled, multiple simultaneous requests for location might lead to system instability.

FORWARD LINK LOCATION FOR IS-95

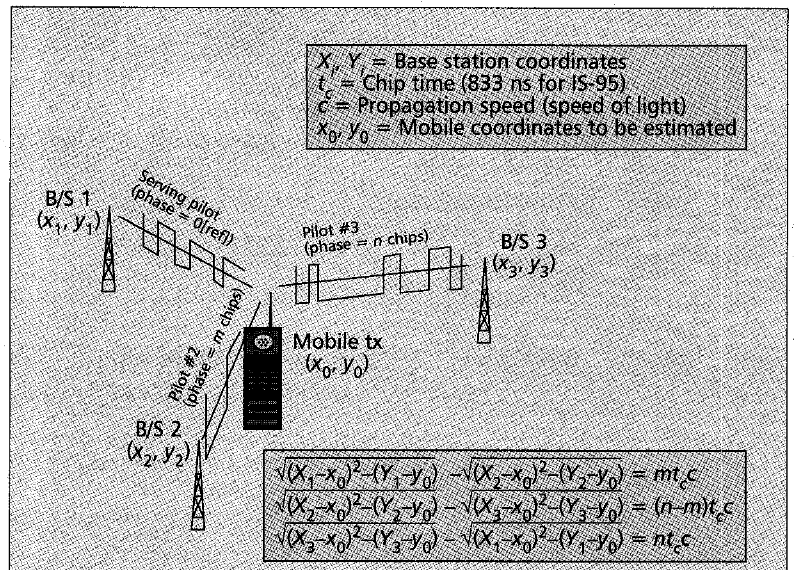
The IS-95 interface provides a way to obtain location information from signals on the forward link while avoiding the power control issues associated with reverse link geolocation [8]. Reception on the forward link is performed coherently. To maintain coherence, the mobile searches for and locks onto a pilot psuedonoise (P/N) sequence. Every base station sector broadcasts the pilot P/N sequence with a unique known offset. The base stations are synchronized, allowing the mobile to identify the signal originating from a particular base station sector.

A typical IS-95 mobile terminal has four rake receiver fingers, three of which are used to receive an incoming signal and one to search for multipath signals and handover candidates. While it is active in the system, an IS-95 terminal keeps track of the strongest pilots in its vicinity. When requested by the base station through a pilot measurement request order (PMRO), the terminal will report all of the pilot signals it receives above a given threshold.[1] The message sent back to the base station includes the magnitude of each pilot in the candidate set and the P/N phase of each pilot, relative to the offset of the base station transmitting the pilot tone.

Using the pilot of the serving base station as a phase reference and knowing the P/N offsets of the pilots transmitted from nearby base stations, it is possible to construct TDOA estimates for the mobile using nothing more than standard control messages that already exist within the IS-95 standard. As long as the mobile can detect, lock onto, and report the phase of at least three pilot tones from three different base stations, it is possible to perform a location estimate for the mobile receiver.

The main sources of error in estimating the location of the mobile using the forward link pilots are synchronization timing errors in the base stations. These errors result from crude P/N phase resolution (limited to whole chips in current IS-95) and multipath or non-line-of-sight propagation of the received signal. Synchronization and chip resolution errors are relatively easy to characterize. The IS-95 standard requires that base stations be synchronized only to within about 3 μs, which is generally inadequate to perform meaningful location. However, in practice, IS-95 base stations often reduce synchronization errors to tens of nanoseconds by exploiting a precision GPS time base. Location errors due to multipath propagation tend to depend on the particular environment and are more difficult to characterize.

[1] This feature was originally included to support soft handover.



From three (or more) IS-95 pilot signals, a TDOA position estimate can be made for the mobile based on the received pilot P/N chip phase. The estimate is calculated by minimizing a vector functional based on the TDOA ranging equations similar to those shown above.

■ **Figure 2.** *IS-95 forward link location.*

A preliminary investigation was performed by Lucent Technologies in 1997 to characterize the ability to detect multiple pilot signals in an IS-95 system. The areas examined included suburban areas in northern New Jersey and the outer boroughs of New York City. Given only the ability to receive three pilot signals from three independent base stations and using standard IS-95 control messages, location errors of several hundred feet have been observed. Although these preliminary results are inadequate to conform with FCC Phase II location requirements, they are on par with other preliminary location trials reported and require no additional system hardware.

However, there is some difficulty in using the forward link for location. To maximize system capacity in an interference-limited environment, a given mobile should receive one strong pilot signal to maintain reception coherence and receive little pilot signal energy from nearby base stations until the mobile is ready to be handed over to another base station. Minimal "pilot pollution" from other base stations reduces capacity-limiting interference and conserves network resources by minimizing the amount of time the mobile terminal is in the soft handover mode. On the other hand, for the positioning mode, reception of multiple pilot signals is essential. A trade-off results between the ability to perform location on the forward link and the minimization of pilot pollution.

GSM

The Global System for Mobile Communications (GSM) and its upbanded versions, DCS 1800 and PCS 1900, have been embraced by most countries in the world. The air interface is based on time-division multiple access Gaussian minimum shift keying. GSM has the capability of frequency-hopping multiple access to mitigate the impact of interference. GSM bandwidth is 200 kHz, making it wider in bandwidth than AMPS and IS-136, and thus potentially more accurate than these standards, particularly for TOA- and TDOA-based systems. In addition, timing measurements are inherent in the GSM standard as a way of ensuring proper slot framing.

While it is possible to provide an appliqué for AMPS and potentially USDC with little if any interaction with the mobile

Location service	Function	Application
Mobile-originated request for positioning	Mobile station requests its location from the network	Aid for driver navigation
Positioning allowed on a per-service instance	Mobile station grants an external application a temporary allowance to position the mobile for the sake of delivering a specific service	Mobile yellow pages, e.g., find the nearest hotel to my location
Network-originated request for positioning	Network requests the position	E-911 location service or location-dependent billing
Positioning without mobile station identification	Positions the mobile without mobile station identification	Traffic incident detection of cellular hot spot activity locator
Position with mobile station identification	Provides the position of the mobile in a defined area with mobile station identification	Used to detect mobile units in a high security region
Positioning within a closed group	Allows for special rights in determining position	Fleet and asset tracking

■ **Table 1.** *Summary of location services proposed for GSM.*

switching center, this is not feasible for GSM because of the dynamic use of time and frequency slots. Thus, a change in standards may be required to ensure compatibility among different equipment vendors and seamless operation between various service providers.

Committee T1 (subgroup T1P1) of the Telecommunications Industry Association (TIA) in the United States is working in cooperation with the European Telecommunications Standards Institute (ETSI) to develop the necessary technical specifications for location monitoring services. This ongoing process is being carried out in three stages. The first stage is defining the requirements and features of the location monitoring service, the second is defining the network architecture and positioning mechanism, and the third is defining the protocols.[2]

Location services (LCS) in GSM allow a user to be positioned with a certain quality of service (accuracy, periodicity, and response time) depending on the needs of the application [9]. Positioning may be initiated by the subscriber, the network, or an external party and is subject to various restrictions based on capability, security, and service profiles that lead to different classifications of LCS. Table 1 summarizes the classes of location services currently being discussed in the T1 standards body.

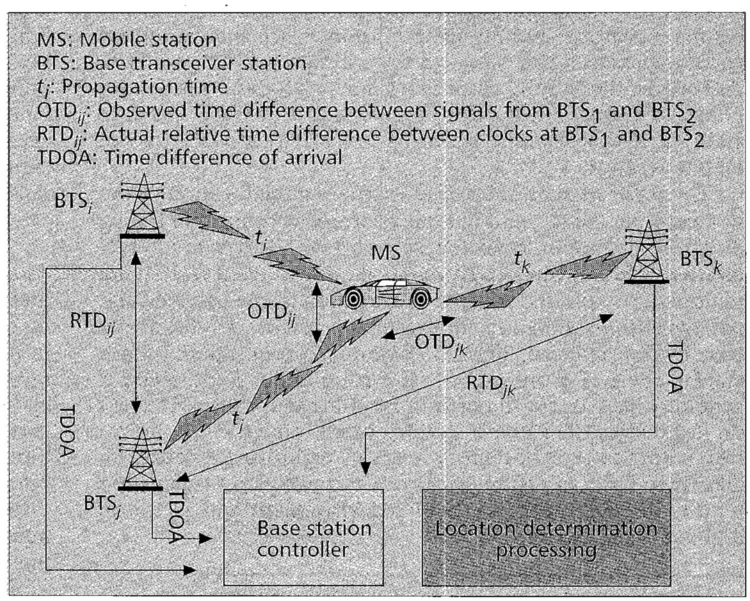
Various proposals for location determination procedures are under review by T1P1. Three of these proposals from major GSM equipment suppliers are discussed below. Proposals for incorporating location information within the GSM architecture, either mobile-assisted or network-based approaches, are provided in [10, 11].

Observed Time Difference Positioning

One proposal, illustrated in Fig. 3, is based on enhancements to the pseudo-synchronization scheme available as an option in GSM for improving handovers [12]. This procedure works by using the mobile to make observations of time difference (OTDs) between base transceiver stations (BTSs). This information is known in both the idle and communication modes. When communicating, the mobile station also knows the propagation delay with the serving BTS. Thus, it is possible for either the mobile or base to determine the mobile station location. If two OTDs are passed to the network (determined from different base stations) and the real time difference (RTD) values are known, the network can calculate two additional absolute propagation delays. Three propagation delays are sufficient to locate the position of the mobile station. The mobile station can compute its position in the idle mode by using pseudo-synchronization. In this case, the infrastructure broadcasts the various RTD between the operating BTSs and the position of the BTSs, sufficient information to determine the location. Modifications in the base station and mobile station are likely to improve the precision of the timing estimates and to support overhead messages to and from the mobile station. The advantage of this approach is that it uses the existing GSM architecture. A disadvantage to this procedure is that it requires the current GSM handset to be modified. The performance of the procedure would depend on manufacturers being consistent in the production of their handsets to meet the stringent timing requirements, a feat that may be difficult to ensure in practice.

Time Advance Positioning

Another proposal makes use of the slot time advance information. This feature is present in the existing GSM system and is used to control the timing of the user's transmission burst. In practice, a GSM base station tells the mobile user how to advance the frame timing to ensure proper frame synchronization. After performing two forced handovers, three time advances are known, providing sufficient information for locating the user. Additional handovers can improve the posi-



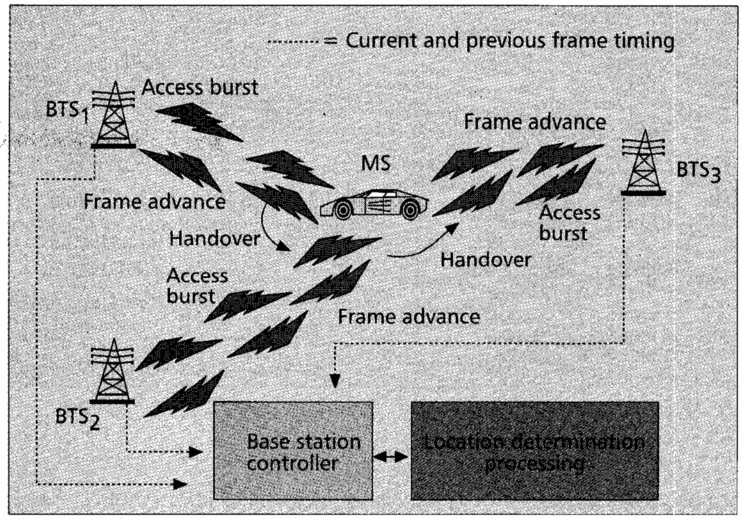
■ **Figure 3.** *Observed time difference location positioning.*

[2] *The working documents for the T1P1 subcommittee can be found at http://www.t1.org/index/0509.htm.*

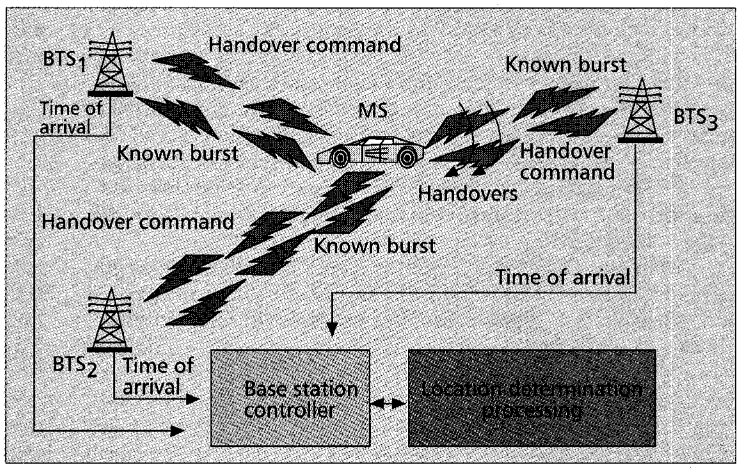
tion estimate. The process is illustrated in Fig. 4. An advantage of this technique is that it can be accomplished with the current generation of GSM handsets.

Time of Arrival Positioning

Another approach that may offer better accuracy is TOA positioning. In this approach, a mobile sends a burst of known data (likely the access burst[3]) to a receiving base station. At least two other base stations determine and record the TOA. The base station instructs the mobile to hand over within the same base station. Again, the known data is transmitted to this base station, and the TOA is calculated. The process is repeated as needed. Determining the TOA at the base station requires sophisticated digital signal processing (DSP) algorithms for finding the direct path (or earliest arriving component) in the presence of multipath. The process is illustrated in Fig. 5.



■ **Figure 4.** *Time advance positioning.*



■ **Figure 5.** *Time of arrival positioning.*

Common Challenges for All Standards

All the infrastructure techniques and the handset solutions suffer from RF channel imperfections, particularly multipath time dispersion and interference. This problem is compounded for the network-based approaches since the locations of the base stations may not be suitable for a particular mobile location. The lack of base stations (three or more for TDOA and two or more for AOA) prohibits location estimates from being made in sparse or poor coverage areas, especially rural environments. Hybrid location techniques that use a combination of AOA and TDOA information are particularly effective in these locations. Experience gained from military systems has shown that fusion of AOA and TDOA data with other information such as signal strength, multipath distortion, or Doppler shift history can lead to improved estimates. Since most emergency calls are placed on the roadway, fusing road map information with measured signal strength data, AOA estimates, and TDOA estimates may be particularly useful for providing position estimates in sparse coverage areas.

Although not explicitly required by FCC regulations, it is desirable to convey information on the reliability of the position determination in addition to providing accurate location information. This information impacts the way the emergency call is handled. A low certainty level would facilitate the emergency operator asking the caller for identifying landmarks, and it may also impact the way an emergency vehicle approaches the caller's location.

Hearability and Nonideal Base Station Locations

Hearability, that is, the ability of a sufficient number of base stations to simultaneously receive the signal at a sufficient power level, is a major concern in network-based location techniques. In the summer of 1996, the MPRG performed a series of measurements to gain a better understanding of the hearability issue by monitoring the forward control channel (FC) power level of AMPS base stations while driving the I-95 corridor, a transportation region that parallels Interstate 95 and spans the east coast of the United States. AMPS is used as an example here because it has the most fully developed network within the United States, but the hearability problem is common to all standards.

Data was recorded for the entire drive path. For simplicity, three distinct cellular environments have been identified and evaluated from the drive test data. Hearability has been analyzed as a function of environment type. The first environment considered is a rural area that has large separations between cell sites (e.g., 5 mi) and uses higher FC transmit powers. The second environment considered is semi-urban, which typically has cells spaced closer together (e.g., 2 mi). The final environment analyzed is urban, consisting of mostly sectorized cells transmitting at reduced FC power levels. Both A and B side carriers in the three regions were recorded and analyzed.

A Grayson Wireless *CellScope*™ was programmed to take continuous scans along the entire path, but the analysis has concentrated on three particular areas: the mountainous terrain of I-81 North in Virginia, the heavily traveled urban area from just south of Washington, DC, to just north of Baltimore, Maryland, and the flat semi-urban areas along the New Jersey shoreline.

The *CellScope*™ was set to continuously scan the 21 FCs and find any channel sensed to have an instantaneous power greater than –115 dBm. It was set to lock onto such a channel for 100 ms, sampling the received signal strength indicator (RSSI) amplitude at 400 Hz, producing 40 samples over a track of approximately nine wavelengths. These 40 data samples were linearly averaged by the *CellScope*™ and recorded as one entry. The *CellScope*™ contains two AMPS receivers,

3 Handover triggers the access burst with a large known sequence.

				Percentage of scans of FC with at least *X* base stations received by CellScope™ above threshold									
				Threshold = –100 dBm					Threshold = – 85 dBm				
Area	Terrain description	Total	Carrier	*X* = 1	*X* = 2	*X* = 3	*X* = 4	*X* = 5	*X* = 1	*X* = 2	*X* = 3	*X* = 4	*X* = 5
Rural area	Mountains I-81	5950	A-side	98.3	86.3	57.1	33.8	16.7	68	19.1	4.9	2	0.7
		5982	B-side	96.6	72.2	49.6	33.3	18.2	60.4	17.8	4.3	1.2	0.1
Semi-urban	New Jersey Coastal	3003	A-side	91.9	80.9	69.2	56.7	44.1	60.7	30.6	11.8	5.3	2.7
		3012	B-side	94.9	81.2	67.1	50.6	36.1	61.9	27.8	7.8	2.3	0.7
Urban corridor	Washington Baltimore	1677	A-side	100	96.8	92.4	85	76.2	77.8	52.1	35.9	25	17.8
		1623	B-side	100	98.1	94.5	89.5	82.1	81.6	58.4	38	28.5	20.9

■ **Table 2.** *Percent of base stations exceeding –100 dBm or –85 dBm.*

which enabled the simultaneous measurement of both A and B side carriers. It is also equipped with a GPS receiver, which provides a time stamp as well as the latitude and longitude coordinates once every second. The antenna used was a quarter-wave monopole mounted on the roof of the vehicle.

The tabulated results given in Table 2 show the percentage of scans that were above a given threshold in each geographic region. The thresholds presented here are –100 and –85 dBm measured by the *CellScope*™. By making assumptions about the antenna gains, FC transmit power, and reciprocity of the channel, the signal-to-noise ratios (SNRs) expected at the base station for the reverse control channel are approximately 14 dB and 29 dB at the base station for these threshold values.

The bar graphs of Fig. 6 and their respective signal strength thresholds clearly show that the coverage in rural areas is much less than in urban areas. For example, the likelihood of finding three base stations with RSSI stronger than –100 dBm is only 35 percent in rural areas, whereas it is about 84 percent in urban areas. The signal strength of the first base station is stronger in the rural areas than in semi-urban areas, which indicates that the transmit power of the FC in the rural area is stronger than the semi-urban area sampled.

Note that while a single base station is often above threshold in the rural areas, the percentage of scans with two or more base stations above threshold drops dramatically due to the large cell sizes used. This trend is less evident in the semi-urban and urban areas, where cell sizes are smaller for increased capacity. It is also possible to use these measurements to obtain a crude estimate of the accuracy of a TDOA location system based on the Cramer Rao lower bound (CRLB) [13–15].

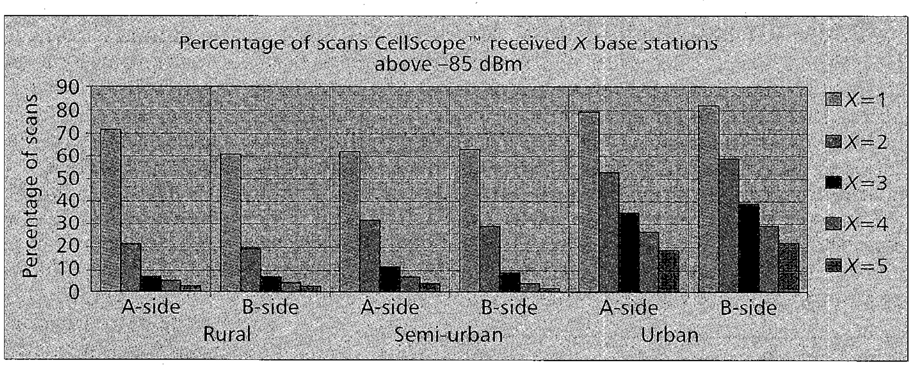
COVERAGE AND PERFORMANCE PREDICTION

The signal strength measurements reported above indicate that hearability is a major concern, particularly for rural environments and even for a system as widely deployed as AMPS. To accommodate location service, system-level adjustments will be necessary. These adjustments might include mapping all traffic routes with measured RSSI, AOA, and TDOA estimates and listing the actual sites that provide coverage. An artificial intelligence algorithm could match a measured response with a large map matrix of measured responses. It may also be necessary to change the tilt, direction, or even height of base station antennas. It may also require cooperation of competing carriers to provide enough locations to ensure hearability. Making these network adjustments requires cell planning tools capable of determining accuracy of location estimates, necessitating the need for developing channel models that represent TDOA and multipath spread. In the event that network adjustments are not sufficient, it might be necessary to use auxiliary receivers to fill in the coverage holes.

CONCLUSION — OVERALL ASSESSMENT OF PROGRESS AND FEASIBILITY

Location technologies have made much progress over the past year, but no systems have been demonstrated to meet FCC requirements under a broad variety of environmental conditions. Most of the efforts so far have focused on location technologies for AMPS, and most are based on TDOA techniques. There are many research and business opportunities in location technologies; additional work is needed to achieve the desired accuracy with all the wireless standards. As the performance of location technologies improves, it is likely that the requirements for the technology will also increase. The FCC has already asked for comments on improving the accuracy of location technologies to 40 m for 90 percent of the measurements [16]. Furthermore, wireless local loop systems necessitate the addition of altitude information in the location estimate to determine the floor for the emergency caller.

The deployment of location technology for wireless systems requires the development of new and unproven technology in a relatively short period of time to meet the regulations adopted by the FCC. Even so, the more challenging and difficult issues may be more institutional in nature. In particular, successful deployment of these emergency systems will require the cooperation of competing carriers, public service answering points, local exchanges, equipment manufacturers, and public utility commissions. Even though the FCC has given PSAPs the authority to request position services by October 1,



■ **Figure 6.** *Percentage of scans above –85 dBm.*

2001, there are numerous financial, political, and institutional issues that must be overcome before these systems can actually be deployed, and many of these problems will be fought again and again at local levels throughout the nation. Certainly, technical approaches to location estimation that minimize the institutional problems are highly desirable.

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