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Geolocation technologies and applications for third generation wireless

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Summary

Wireless Service Providers have become increasingly interested in developing position location services for commercial application of the evolving Third Generation (3G) communication systems. The initial and driving force behind this interest is a regulation in the United States promulgated by the Federal Communications Commission, requiring wireless carriers to be capable of delivering the position of a wireless device (or mobile station) making an emergency call to emergency authorities by October 2001. Similarly in Europe, the 1999 Communications Review (COM 1999/539) set the date of 1 January 2003 for the carriers to make location information available for emergency authorities. The cellular mobile station geolocation problem can be solved using either network-based methods or handset-based methods. A hybrid position location method that combines measurements from the communication system's forward and/or reverse links with measurements from the Global Positioning System (GPS) can improve position service availability. Given the ability to accurately determine a user's location means that position location service applications can and most certainly will provide value-added features such as navigation, fleet management, real-time traffic updates, location sensitive billing, etc. In this paper we present different geolocation technologies, list some of the important applications, and review the status of the location services in the 3G Standards Development Organizations. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS
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1. Introduction

Mobile location technologies open the door for new wireless services and applications. No doubt, the catalyst application is government mandated user location emergency services (e.g. E911 in the United States and E211 in Europe).

In January 1968, a three-digit telephone number, 9-1-1, (or '911') was introduced throughout the United States for use as a 'universal emergency number'. Upon receiving a 911 call, the dispatchers alert medical, fire, and/or police for assistance as required. In March 1973, the 911 service was further enhanced (E911) to provide 'automatic' location and calling telephone number information to the Public Safety Answering Point (PSAP). This improvement enables the PSAP to provide emergency services even if the person making the call is unable to give location information. In a series of orders since 1996, the Federal Communications Commission (FCC) has taken action to improve the quality and reliability of 911 emergency services for wireless phone users by adopting rules to govern the availability of basic 911 services and implementing E911 for wireless services [1]. The PSAP operators have to rely on the location information given by the caller before they can respond to emergency requests. Problems arise because routing is not exact and can cross PSAP jurisdictions. In addition, serving cells often encompass several square miles thus making it much harder to determine the exact location of the caller in distress.

Two pieces of information were missing in the wireless networks: Automatic Location Identification (ALI) and Automatic Number Identification (ANI). ALI is used to determine the geographical location of the caller. ANI is used to call the user back if the original call is disconnected. Wireless emergency calling (E911) services will significantly improve as new FCC rules governing wireless call-origination tracking go into effect.

FCC rules regarding wireless E911 consist of two phases. Under Phase I, as of April 1998, wireless carriers were required to provide to the PSAP the telephone number of the originator of a 911 call and the location of the cell site or base station receiving a 911 call. Under Phase II, the wireless carriers are required to provide ALI as part of Phase II E911 implementation beginning 1 October 2001, as detailed below. Originally, the FCC's rules envisioned that carriers would likely deploy network-based technologies to provide ALI. In the past several years, there have been significant advances in location technologies that employ new or upgraded handsets. As a result, in September 1999, the FCC revised its rules to enable carriers to use handset-based location technologies to meet the Phase II requirements. In addition, the FCC established separate accuracy requirements and deployment schedules for network-based and handset-based technologies. In August 2000, the FCC made minor adjustments to the deployment schedule for handset-based technologies [2]. The current mandate (revised in November 1999) requires 67 per cent of callers to be located with a maximum error of either 50 m or 100 m depending on whether the positioning technology is respectively handset-based or network-based. For 95 per cent of calls, these numbers are relaxed to 150 m and 300 m.

The continuous growth of the Internet will fuel the demand for wireless multimedia services beyond the capabilities of the Second Generation (2G) wireless networks. These current First and Second Generation air-interfaces are inadequate for satisfying the higher data rates required for such services. Several standards bodies throughout the world submitted proposals to the International Telecommunications Union (ITU) for consideration for International Mobile Telecommunications in the year 2000 (IMT-2000). In Section 2 we will describe the development process for these third generation (3G) wireless systems.

In Section 3 we introduce the performance goals for any position location technology. Different approaches to providing position location include terrestrial (network and/or handset)-based methods and Global Positioning System (GPS) methods. The coverage areas of the terrestrial signals and the GPS signals complement each other. For example, in rural and suburban areas the Mobile Station (MS) may not see more than one Base Station (BTS) because the BTSs are far apart, but a GPS receiver can see four or more satellites because of unobstructed view of the sky. Conversely, in dense urban areas and inside buildings, GPS receivers may not detect enough satellites to obtain a position fix, but an MS can see two or more BTSs. The above observations prompted engineers to develop hybrid approaches that combine both terrestrial and GPS measurements. Indeed, 3G Standards Development Organizations (SDOs) have developed hybrid position location solutions that combine measurements from the network, handset and GPS to take advantage of the complimentary coverage areas of all the solutions.

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This hybrid technology provides benefits such as improved sensitivity, high availability, high accuracy, and low cost.

Since nearly all 3G standards-based radio geolocation techniques measure propagation time of radio signals and then translate these time measurements into distances, time synchronization of signal sources (clocks) becomes an important issue. In Section 6, we address some techniques to synchronize different nodes in the wireless network which do not rely on GPS.

Finally, the introduction of wireless position location-based applications and services bring new and heightened privacy risks for wireless users that must be addressed. In Section 9, we discuss the privacy issue and its relation to position location.

2. Third Generation Wireless Communication Systems

2.1. Historical Perspective

The First Generation (1G) analog mobile phone systems included the Advanced Mobile Phone System (AMPS), Nordic Mobile Telephone (NMT), and Total Access Communications System (TACS). The AMPS system has major network deployments in North America, the Asia/Pacific region, and Central and Latin America. NMT and TACS first deployments were primarily in Europe—NMT in Scandinavia and TACS in the United Kingdom, with other substantial network operations in the Asia/Pacific region. These 1G analog systems for mobile communications saw two key improvements during the 1970s: the invention of the microprocessor and the digitization of the control link between the mobile station and the cell site.

The 2G systems digitized not only the control signal but also the voice signal. The new systems provided better quality and higher capacity at lower cost to consumers. 2G systems consist of IS-95 or cdmaOne™, the Global System for Mobile Communications (GSM), IS-136 or Digital AMPS (DAMPS), and Personal Digital Cellular (PDC). IS-95 uses code division multiple access (CDMA) as its air-interface whereas GSM, IS-136, and PDC uses Time-Division Multiple Access (TDMA). All the 2G standards are deployed globally but not uniformly. IS-136, IS-95 and GSM are in operation in North America, with other major installations throughout Central and South America and the Asia/Pacific region. IS-95 is the predominant 2G system in South Korea, GSM is the predominant standard in Europe while PDC is currently only in operation in Japan.

First and second generation wireless networks have proven capable of providing voice and low-rate data services; however, their current air-interfaces are inadequate for satisfying the higher data rates that have been specified by the ITU for IMT-2000. In order to satisfy advanced 3G requirements, GSM networks are planning to initially add GPRS/EDGE technology to existing systems and ultimately utilize a new air-interface based on 'wideband' CDMA using a spreading rate of 3.84 MHz. The IS-136 networks migration path is less clear, with the most advertised path today being to join the GSM path by upgrading first to GPRS and/or EDGE, and later provide higher data rates through WCDMA. Cdma20001x, using a spreading rate of 1.2288 MHz, will provide the migration path for existing IS-95 networks, by improving the existing air-interface. As such, cdma2000 and IS-95 systems will be able to coexist on a common channel.

All 3G systems promise increased voice capacity and faster communication services, which include circuit switched and packet data with direct Internet access and anytime and anywhere with seamless global roaming.

The key features of IMT-2000 are:

- high degree of commonality of design worldwide;
- compatibility of services within IMT-2000 and with the fixed network;
- high quality;
- small terminals for worldwide use;
- worldwide roaming capability;
- capability for multimedia applications and a wide range of services (e.g. video-teleconferencing, high speed Internet, speech and high rate data).

The ITU's IMT-2000 global standard for 3G is expected to enable innovative applications and services (e.g. multimedia entertainment, infotainment and location-based services, among others).

The major standards body in Japan, the Association for Radio Industry and Business (ARIB), was one important force behind the development of wideband CDMA (WCDMA). In Europe, the European Telecommunications Standards Institute (ETSI) developed a very similar version of WCDMA. ETSI and ARIB have managed to merge their technical proposal into one WCDMA standard air-interface, with some small differences between the Japanese and

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European versions. In the United States, the Telecommunications Industry Association (TIA) had proposed two air-interface standards for the 3G, one based on CDMA and the other based on TDMA. Technical committee TR45.5, within the TIA, proposed a CDMA-based air-interface, referred to as cdma2000, which maintains backward compatibility with the existing IS-95 system. The second proposal came from TR45.3, which adopted the Universal Wireless Communications Consortium's (UWCC) recommendation for a 3G air-interface that builds off of existing IS-136 networks. The South Korean Telecommunications Technology Association (TTA) supported two air-interface proposals, one similar to WCDMA and the other to cdma2000.

The Operators Harmonization Group (OHG) has agreed to a harmonized Global 3G (G3G) CDMA technical framework, based on the prior agreement of the TransAtlantic Business Dialog (TABD) Group. The harmonized G3G CDMA standard consists of the following three modes:

- CDMA-Direct Spread (DS) or WCDMA/UMTS;
- CDMA-Time Division Duplex (TDD), or TD-CDMA;
- CDMA-Multicarrier (MC) or cdma2000 (1X and 3X).

In the technical framework, specific recommendations have been made on Chip Rate, Pilot Structure and Synchronization Method for these three modes to ensure a harmonization of the two main CDMA-based IMT-2000 Radio Transmission Technology (RTT) proposals: Wideband CDMA (WCDMA) and cdma2000.

The ITU, SDOs and 3GPPs have all agreed to implement the OHG agreement and have taken appropriate actions to implement the OHG recommendation in the desired timeframe. Specifically, the hooks and extensions, as defined in the G3G CDMA framework, are in the process of being specified in detail so that the three radio access modes (MC, DS and TDD) can be adapted to the two core networks (ANSI-41 and GSM MAP).

The global standard for 3G wireless communications is now defined most generally as IMT-2000. This standard remains under control of the ITU and is defined by a set of interdependent ITU recommendations. But, presently driving the standards development are two Third Generation Partnership Groups, 3GPP and 3GPP2, which are seeking to develop and deploy three related, but not identical, modes of CDMA for 3G, as shown in Figure 1.

If position location was the only concern, differences between the two primary 3G standards (WCDMA and cdma2000) are relatively minor, with one major exception. WCDMA is asynchronous, and cdma2000 is synchronous. This has made a difference in the way their position location techniques have evolved from their 2G beginnings. While these systems are similar in that they are both a form of direct sequence CDMA, they each have a different history.

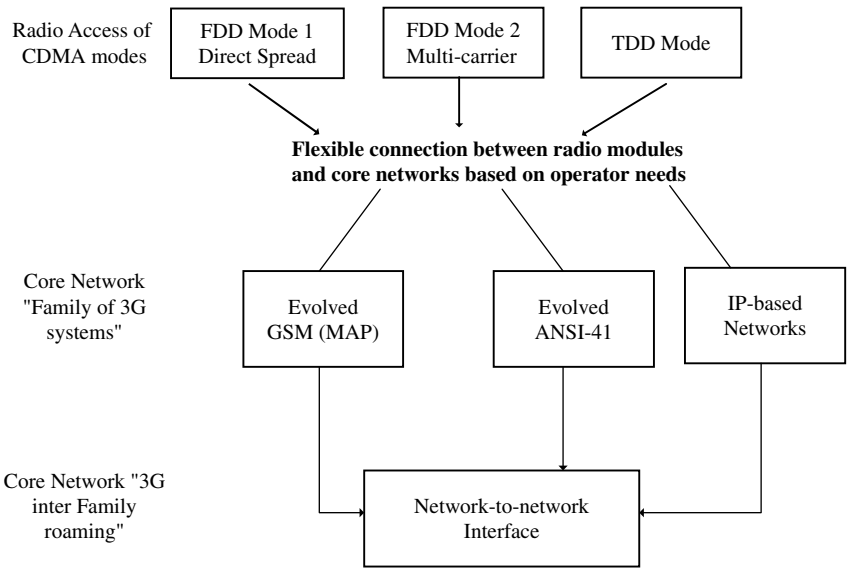

Fig. 1. IMT-2000 harmonization.

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2.2. cdma2000

Position location related standards are divided into position location air-interface standards and position location network standards. The network standards apply to all wireless (e.g. CDMA, TDMA, Analog) technologies and also to all position location technologies (e.g. network-based, handset-based) technologies. On the other hand, air-interface standards are wireless technology specific and are most applicable to handset-based position location techniques. Location standards, which have relevance to the cdma2000 family of standards, will be discussed in the next few paragraphs. WCDMA standards follow in Section 2.3.

2.2.1. Air-interface standards

Air-interface Standards describe messaging and procedures to be used by the mobile stations and network, including the BTSs. The first CDMA position location standard was TIA/EIA/IS-801, 'Position Determination Service Standard for Dual-Mode Spread Spectrum Systems', developed by TR45.5 and published in October of 1999 by the TIA. The 'Dual-Mode' term indicated the intention to include the Analog air-interface specifications to be used in the Analog (AMPS) overlay network. The Analog position location standard, however, was developed separately. To ensure positioning operation while roaming, a common core Analog position location standard, TIA/EIA/IS-817, 'A Position Determination Service Standard for Analog Systems', was developed by TR45.1 and published in July 2000 by the TIA. The Analog standard is incorporated in IS-801 only by references to IS-817. IS-801 was also intended to contain point-to-point, as well as broadcast procedures. However, due to time pressures, the broadcast methods were not incorporated.

The features of IS-801 are:

- compatible with both E911 and commercial services requirements;
- supports both MS-based and MS-assisted operating modes;
- provides wireless assistance to improve both acquisition time and receiver sensitivity;
- supports mobile authentication and user privacy;
- data burst message transport is used; the position location data can be multiplexed with voice traffic;
- either the common channels or the dedicated channels can be used; a position location session doesn't necessitate establishing a voice or data call;
- supports multiple simultaneous position location sessions in the MS.

An Addendum, IS-801-1, containing various bug fixes and clarifications, was published in February of 2001 by TIA. The actual development of the Addendum took place in the Position Location Ad Hoc of TSG-C in 3GPP2.

At the time of developing the original IS-801, the CDMA 2000 standard was not completed. However, because of backward compatibility, IS-801 is still applicable to CDMA 2000.

The following is an excerpt from IS-801, explaining this relationship: 'References in this document are to TIA/EIA-95-B. This standard is equally applicable to TIA/EIA/IS-2000. Except where explicit references are made to TIA/EIA/IS-2000, the reference to TIA/EIA-95-B can be converted directly to TIA/EIA/IS-2000 usage.'

Nevertheless, an update for fully adopting cdma2000 will be necessary in the form of a new release of IS-801. The development of Release-A is scheduled to start at the end of 2001. Other Release-A work items include support for broadcast mode and optional IP-based message transport.

An Addendum for IS-817, the Analog position location standard, was published in 2001.

Standardized position location test procedures have been developed by Standards bodies. The recommended minimum performance specification for IS-801-1 is published as C.S0036-0 and TIA-916.

Future test standardization work items include:

- Position Location Interoperability Test Specification;
- Position Location Protocol Compliance Test Specification.

2.2.2. Network standards

The following network standards are published or being developed for cdma2000:

- TIA/EIA J-STD-034, 'Enhanced Emergency Services', published in October 1997;
- TIA/EIA J-STD-036, 'Wireless Enhanced Emergency Services Phase II' published by TIA in July 2000, Addendum 1 published in December 2000, and Addendum 2 to be published in July 2001;

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- PN-4747, 'Location Services Enhancements' to be published as TIA/EIA/IS-881 by TIA in August 2001.

PN-7474 addresses commercial services related aspects beyond the scope of J-STD-036, such as user privacy.

2.3. WCDMA

WCDMA evolved primarily from within the GSM community, with major input from NTT in Japan. In terms of position location, the standard has developed along the following path.

In 1996 ETSI initiated the creation of the T1P1.5 LCS (Location Services) SWG (Sub Working Group which is part of the US-based T1 Committee) to LCS standards, therefore defining the operation of LCS on a GSM network; and for the U.S. market, the interface with Public Service Answering Points (PSAPs). As was the case for IS-95, the GSM LCS standards initiative was originally triggered by the FCC 911 mandate. The European Telecommunications Standards Institute (ETSI) finalized the GSM standards for LCS, and in 1Q2000, T1P1.5 LCS SWG handed over responsibility for WCDMA to 3GPP, which has now completed most of the LCS standards applicable to WCDMA.

3. Positioning Location Performance Goals

The most common measure of position location performance is accuracy. The FCC requirements, as stated in the FCC Report and Order [1,2], have set specific targets for the accuracy of position location. Accuracy is relatively easy to measure and has traditionally been considered indicative of the quality of the solution. It is essentially the key parameter specified by the FCC. But, accuracy is only one of several important performance parameters. The location technology must also produce the location information reliably, quickly, and with consistent performance across different networks and spatially diverse geographies. In fact, more important than any individual performance requirement is the broader requirement that they all be achieved simultaneously. Only then will performance be adequate for most location applications. A minimum set of performance goals that must be considered when developing alternative solutions for commercial services are:

- service availability or blocking: measure of location determination failures or unacceptable inaccuracy;
- accuracy: measure of the area of uncertainty (e.g., 125 m rms);
- delay: measure of minimum time required to calculate a fix (delay) also known as Time to First Fix (TTFF);
- capacity: measure of number of requests and location update rate;
- coverage: measure of service area where the location service is provided;
- reliability: measure of availability of the system;
- signaling complexity: measure of signaling mechanism to report a location to PSAP;
- administration: complexity and costs associated with operation.

Accuracy, yield, consistency, and time to first fix are given high priority when comparing different geolocation technologies. A brief description is given below:

- **Accuracy:** Many location services require better accuracy (10–100 m) than the 911 requirements if they are to be useful to the end user. This is because there today exist services based on standalone GPS devices, which provides 10-meter accuracy, although not inside buildings. Many consumers have come to expect this level of accuracy.
- **Yield:** Any position location system should provide results, even in difficult locations. The positioning yield should be at least 75 per cent to 99 per cent, depending on the application. In-building results are highly desirable.
- **Consistency:** The location fixes should be uniform across different environments and different networks. Inconsistent performance creates doubt in the users mind and may also make the location service requested impossible to deliver.
- **TTFF:** Once requested, a location solution should be produced quickly, within 2 to 20 s if it is to be viable. This time should include delays added by the network, since the end user is only concerned with the total delay. Note that the FCC 911 mandate does not include a TTFF requirement. (FCC Bulletin OET71 mentions <30 s.)

These measures of performance are highly correlated, in that techniques to improve accuracy, such as averaging, may increase response times.

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A final decision on what technique to choose is based on even more factors, as discussed in Section 5.

4. Measurement Accuracy

Locating an MS using network measurements requires the following: measuring some aspects of the received signal, either Time of Arrival (TOA) or Angle of Arrival (AOA), and then using a triangulating mechanism from a minimum of two sources. A strong signal and clear line of sight are required for an acceptable performance. All terrestrial measurements obtained with AOA, TOA, and TDOA methods suffer from multipath and weak signal conditions. In order to study the performance of each technique, one needs to study the characteristics of the radio channel and the impact of sources geometry.

4.1. Role of Radio Sources Geometry

The geometry of the radio sources plays an important role in determining the positioning accuracy. Three sources almost on a straight line with respect to the MS, for example, produces a poor estimate of the location compared to three sources forming three vertices of equilateral triangle whose center is the MS. The geometry dependent factor is called Geometric Dilution of Precision (GDOP) [3–7]. GDOP is a metric used to determine what constitutes a good radio sources geometry. Other dilution of precision parameters include position DOP (PDOP), horizontal DOP (HDOP), vertical DOP (VDOP), and time DOP (TDOP).

4.2. Role of Signal-to-Noise-Ratio

One estimate of the time-of-arrival accuracy in the absence of the multipath environment is obtained from the Cramer–Rao Bound [8]. The rms error in estimating the time-of-arrival of a radio signal is upper-bounded by the following expression.

$$\sigma = \frac{\tau_{\mathrm{rms}}}{\sqrt{\mathrm{SNR}}}, \tag{1}$$

where τ_{rms} is reciprocal of the rms bandwidth of the waveform used to measure the time of arrival and is defined as

$$\tau_{\mathrm{rms}}^2 = \frac{\int_{-\infty}^{\infty} |F(\omega)|^2 \mathrm{d}\omega}{\int_{-\infty}^{\infty} \omega^2 |F(\omega)|^2 \mathrm{d}\omega} \tag{2}$$

where $F(\omega)$ is the Fourier transform of the transmitted waveform. As can be seen from Equation (1), signals with higher bandwidth exhibit smaller rms time error for the same signal-to-noise ratio.

5. Geolocation Technologies

In this paper, position means a point on earth that can be described by coordinates, such as latitude and longitude, while location in this document means an area. Location may be the area covered by a given cell site or sector, the area served by an MSC, a paging or location area, the area served by a particular emergency services agency, or the area associated with a particular street address. This definition may be at odds with other forum, but it is consistent with the usage of terms used in wireless mobility management protocols such as TIA/EIA-41 and GSM. Positioning or geolocation is the process of determining the coordinates of an object on the surface of the earth. The wireless geolocation problem can be solved using either terrestrial (network-based or handset-based) solutions or Satellite (GPS)-based solutions. In the network–based methods, measurements are normally made by the existing network receivers (BTS) or by an overlay network of special purpose receivers.

Network-based solutions rely on the signal transmitted from an MS and received at BTSs or vice versa. This can be accomplished by two general methods: Angle of Arrival (AOA) and Time of Arrival (TOA) techniques, as explained below.

In the case of AOA, the position of the mobile is estimated based on the intersection of multiple Lines of Bearing (LOB) calculated by direction finding antenna arrays. The arrays are located on nearby BTSs of exact known location. Accuracy of position estimate depends upon the angular resolution and transmitter location relative to the BTSs. The best estimate usually results when LOBs are at right angles to one another. References [9–11] provide details on this non-standards-based approach, which in many cases can provide adequate location fixes, and have the attractive feature in that they do not require any change to the MS. This feature has to be traded against the need for directional beams at all the BTSs. In the case of TOA, when only using network-based measurements, the position of the mobile is estimated based on the timing of signals arriving at multiple BTSs. The mobile will lie at the intersection of several hyperbolas, each hyperbola being defined by the difference in time of arrival of the same signal at a pair of BTSs. Accuracy of the position estimate depends on accurate synchronization

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and signal structure (bandwidth, etc.), and also on the geometrical layout. The best estimate results when the MS is at the geometric center of the BTSs' configuration.

Network-based position location solutions are vulnerable to multipath propagation, which is typical in terrestrial communications systems [25]. Not only can multipath propagation cause large errors in the estimated location of the MS, but can also create signal attenuation conditions that lead to situations where the location of the MS cannot be found.

This paper addresses only standards-based location technologies for the 3G Family. As such it ignores many viable techniques such as AOA, or pattern recognition techniques. Methods that do not require standards development can be found in References [12–19]. Included in this section are 2G, 2.5G and 3G methods to illustrate how these are evolving, since at this time, no one method has been selected as the final, or only choice. The list includes the following.

- **Cell-ID (and Cell-ID variants):** standards support in GSM, GPRS and WCDMA;
- **E-OTD:** Enhanced Observed Time Difference, standards support only in GSM/GPRS;
- **OTDOA:** Observed Time Difference of Arrival, standards support only in WCDMA;
- **A-GPS:** Wireless Assisted GPS, standards support in GSM, GPRS and WCDMA and cdma2000;
- **Hybrid:** Some combination of A-GPS and Cell-ID, E-OTD or OTDOA, standards support in GSM, GPRS, WCDMA and cdma2000.

For consistency, when describing these techniques, we will hereafter refer to BTS and MS as the two primary system elements. In 3GPP, the BTS is referred to as Node B and the MS is referred to as the UE (user equipment). In the literature, the MS is also referred to as a handset, subscriber unit, wireless device, access terminal and wireless terminal.

5.1. Cell-ID

Cell-ID is supported in GSM, GPRS, and WCDMA networks. It is the simplest way to locate an MS, and determines the user's position simply as being within the area covered by the cell.

The technology requires the network to identify the BTS with which cell phone is communicating and the location of that BTS. If this information is available, the Cell ID Location Server (LS) identifies the MS location as the location of the BTS and passes this information on to the location service application.

Since the MS can be *anywhere* in the area defining the cell, the accuracy of this method depends on the cell size, and is therefore poor in many cases since a typical GSM cell is anywhere between 0.5 Km to 20 Km in diameter. Further reducing the cell area by specifying cell sector is typically done to improve the accuracy.

Positioning is more accurate in urban areas with a dense network of smaller cells than it is in rural areas where there are fewer cells. If micro-cells are utilized, the cell size may be reduced significantly to the range of a few hundred meters. The diversity in cell site size, density, and operational characteristics across a network makes the accuracy of this technology inconsistent and by itself Cell-ID cannot meet the FCC E911 requirements.

5.2. Cell-ID with TA or RTT

Including the technique of Time Advance (TA) for GSM/GPRS networks or round trip time (RTT) for WCDMA networks can enhance Cell-ID. The TA approach exploits existing information normally used to avoid collisions of MS transmissions arriving at a BTS. Both TA and RTT use time offset information sent from the BTS to adjust an MS's relative transmit-time to correctly align the time its signal arrives at the BTS. For position location purposes, the TA and RTT provide a range estimate between the MS and the BTS. As an aid to Cell-ID, these measurements are used to reduce the position error of the basic Cell-ID technique. Unfortunately, this information is available only for the call in progress, so the MS must handoff from BTS to BTS if the technique were to be used as a standalone range determination system.

Even with these enhancements, this technology remains inconsistent and is the least accurate of the technologies discussed here. It is an inexpensive approach to implementing a very coarse location solution. Generally the yield and TTFF are very good, but the accuracy is poor and the consistency of the solution varies dramatically depending on cell site density. It is particularly poor in rural areas where cells are widely spaced. It supports roaming to the same interface networks without major modifications, is easy to maintain, and is not a major cost expenditure to expand the network. Unfortunately, despite

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these advantages, the basic accuracy performance is so poor that it would not support the many location services in a majority of locations, and does not meet the FCC E911 requirements.

5.3. E-OTD

Enhanced Observed Time Difference (E-OTD) is a time difference of arrival method based on MS measurements and is designed for GSM and GPRS networks. For GSM and GPRS, the MS monitors the transmission bursts from multiple neighboring BTSs and measures the time differences between the arrivals of the GSM frames from the BTSs. These observed time differences are the underlying measurement of the E-OTD radio-location method and are used to trilaterate the position of the MS.

The accuracy of the E-OTD method is a function of the resolution of the time difference measurements, the geometry of the neighboring BTSs, and the signal environment. The MS must measure time differences from at least three BTSs to support two-dimensional (no altitude) position determination. Because TOA is the basis of the location measurement, E-OTD requires knowledge of the BTS timing reference. For GSM and GPRS, this is solved through the addition of Location Measurement Units (LMUs). The number of LMUs has been estimated to range from one LMU per three to five BTS sites [18].

This deployment constraint comes from the requirement for each one of the BTS in the network to be observed by at least one LMU. E-OTD also requires software modifications to the MS.

E-OTD location technology measures the times at which signals from a BTS arrive at two separate locations: the MS and the LMU. The MS's position is determined by comparing time differences between the two sets of measurements.

E-OTD solutions offer improved performance relative to Cell-ID, and can provide accuracy in the 50–150 meter range, but require the use of LMUs to do so. Adding LMUs increases the cost and complexity of the overall system. And because the MS must receive signals from at least three BTSs (deployed for communication, not radio-location purposes) and utilize terrestrial TOA measurements to derive a position estimate, this leaves the technology vulnerable to accuracy degradation from multipath and signal reflections. For roaming, E-OTD requires global modifications since the 'roamed to' network must also have LMUs. This is true even if only one subscriber wants to roam into a network.

Since the U.S. FCC mandated that all calls from mobile phones to emergency services include highly accurate information about the caller's location, E-OTD has emerged as the preferred choice for GSM network carriers to meet E911 regulations. It is expected that E-OTD will become the method used by GSM operators in the U.S. and that a modification of this method will be used by WCDMA.

5.4. Observed Time Difference of Arrival (OTDOA)

OTDOA is a TOA-based approach designed to operate on WCDMA networks. The OTDOA LCS estimates the position of a handset by referencing the timing of the downlink pilot signals as they are received from a minimum of three BTSs. Similar to E-OTD, LMUs are used to calibrate these downlink measurements. Considering these similarities, OTDOA can be viewed as a WCDMA version of E-OTD. As such, it has the same type weakness as E-OTD (absolute time accuracy drives need for LMUs, no yield in areas without at least three visible BTSs, poor accuracy along linear networks, multipath degradation, and compatibility with only one network).

In addition, OTDOA has an added characteristic that results in performance inherently inferior to that of E-OTD. Because the WCDMA network is based on CDMA, all BTSs share the same downlink frequency, and the MS's ability to 'see' and use multiple downlinks is reduced from the number that can be seen in a GSM system, where different frequencies are assigned to neighboring BTSs. This severely impacts OTDOA's accuracy, but more importantly, impacts yield to the point that OTDOA's overall performance is uniformly worse than E-OTD. A study in Germany showed that a BTS density equivalent to the current GSM base station deployment supports BTS visibility for 2-D positioning between 22 and 36 per cent of locations, a statistic that would suggest OTDOA as a standalone positioning technology is not viable.

This has led to modifications to OTDOA, namely, IPDL, TA-IPDL, and OTDOA-PE [26]. The basic premise with IPDL (Idle Period Downlink), is that BTSs will pseudo-randomly disable their downlink for a short period during which time the MS will be able to 'see' the neighbor BTS signals. In TA IPDL, these blanking periods are synchronized (within 30 μs) among the BTSs. In OTDOA-PE, positioning elements are added which synchronize

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with the nearest BTS and transmit a short pulse. Since the PEs are at known locations, this enables the MS to use these signal as inputs to the OTDOA solution. Simulations suggest that these techniques will enable OTDOA to meet FCC E911 requirements, but there is no large-scale field test to support this argument.

One other point of note: as WCDMA networks are deployed, it is possible that many will be time-synchronized or designed so that they can be time-synchronized at a later date by adding timing equipment to appropriate network elements. This can be done by using special GPS-based timing receivers throughout the network or done 'virtually' by LMUs. Section 6 will further discuss a possible process in which to accomplish this.

5.5. The Global Positioning System (GPS)

Many of the proposals for 3G positioning employ GPS receiving functions located in the MS. This section provides an overview of this worldwide navigation system, and provides an aid to the understanding of how this resource is being used by 3G standards in a variety of ways. The sections that follow describe these methods and provide details on one particular hybrid method.

The space segment of the GPS consists of a constellation of 24 satellites (plus one or more in-orbit spares) circling the earth every 12 hours. The satellites are at an altitude of 26 000 km. Each satellite transmits two signals: L1 (1575.42 MHz) and L2 (1227.60 MHz). The L1 signal is modulated with two PN codes: the protected (P) code and the coarse/acquisition (C/A) code. The L2 signal carries only the P code. Each satellite transmits a unique code, allowing the receiver to identify the signals. Civilian navigation receivers use only the C/A on the L1 frequency.

The idea behind GPS is to use satellites in space as reference points to determine location. By accurately measuring the range from three satellites, the receiver 'triangulates' its position anywhere on earth. The receiver estimates the range by measuring the time required for the signal to travel from the satellite to the receiver and by knowing the speed of light, converts this propagation time to a range estimate. However, the problem in measuring the travel time is to know exactly when the signal left the satellite. To accomplish this, all the satellites and the receivers are synchronized in such a way that they generate the same code at exactly the same time. Hence, by knowing the time that the signal left the satellite, and observing the time it receives the signal based on its internal clock, the receiver can determine the travel time of the signal. If the receiver has an accurate clock synchronized with the GPS satellites, three measurements from three satellites are sufficient to determine the position in three dimensions. Each pseudorange (PR) measurement gives a position on the surface of a sphere centered at the corresponding satellite. The GPS satellites are placed in a very precise orbit according to the GPS master plan. GPS receivers have a stored 'almanac' which indicates where each satellite is in the sky at a given time. Ground stations continuously monitor GPS satellites to observe their variation in orbit. Once the satellite position has been measured, the information is relayed back to the satellite and the satellite broadcasts it as part of the 'ephemeris'. The ephemeris is similar to the almanac but is of a much higher precision, and represents a shorter term curve-fit prediction. The ephemeris also contains satellite clock correction information. The ephemeris is broadcast by the satellite as part of the navigation message. For more detail on how GPS works see Reference [3]. For commercial purposes it is too expensive to have an accurate clock at the GPS receiver. In practice, GPS receivers measure time of arrival differences from four satellites with respect to its own clock and then solve for user position and clock bias with respect to GPS time. This involves solving a system of four equations with four unknowns given the PR measurements and satellite positions (satellite data). Another way of looking at this process, due to receiver clock error, is that the four spheres will not intersect at a single point. The receiver then adjusts its clock such that the four spheres intersect at one point.

The time required by a conventional GPS receiver to obtain a position fix depends upon the state of the GPS receiver. Typically, there are three common states.

- **Cold Start State:** In a cold start state the GPS receiver has no GPS almanac, or it has no approximate knowledge of current time and location. The GPS almanac gives an approximate satellite ephemeris. Almanac data permits the user to select the best set of satellites or to simply determine which satellites are in view. It takes the receiver 12.5 min to download the almanac of the entire GPS constellation. Without an almanac, the GPS receiver must search all 24 satellites and must conduct the widest frequency search to acquire the

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first satellite. The width of the search window is determined by satellite Doppler and receiver local oscillator offset.

- **Warm Start State:** In this state, it is assumed that the receiver has a GPS almanac and a rough estimate of location and time, which will reduce the search in the frequency domain (using approximate location and time, the satellite Doppler is computable from the almanac). The time required to generate a position is determined by the time to receive clock correction and ephemeris data for each satellite. The ephemeris is broadcast every 30 s and is valid for approximately 2 h. Hence, a GPS receiver that starts in this state will be able to determine a position in about 30 s.
- **Hot Start State:** In this state, the receiver is assumed to have ephemeris and clock corrections for all satellites in view. The receiver needs to do two steps: measure PRs to all detected satellites, and compute the position using PRs and satellite data. It is possible to determine a position fix in less than 1 s if the search algorithm uses information from the first acquired satellite to calibrate its own local oscillator frequency error.

5.5.1. Limitations of GPS-only solution

Problems associated with wireless phone location techniques that rely only on GPS are listed below:

- need to add a full GPS receiver to the MS;
- limited visibility in dense urban areas;
- unaided GPS acquisition time is unacceptable;
- different antenna system is needed;
- poor performance in tunnels, subways and indoor locations;
- additional power consumption which will impact talk and standby time;
- added computational complexity, data storage capability which impacts size, weight and cost.

5.6. Assisted GPS

Assisted GPS (also known as Wireless Assisted GPS or WAG) operates on GSM, GPRS, WCDMA and cdma2000 networks and seeks to combine the location accuracy of GPS with the communications capability of the handset [20]. A-GPS still uses GPS satellites as reference points in the location determination, but also adds aiding processes aimed at simplifying MS operation and design.

Accurate position (and time) can be derived directly from GPS satellite signals using standalone GPS receivers, but this requires demodulating low rate data from the GPS satellites and also requires that the satellite signals be at relatively high signal strength. To address these limitations, an A-GPS receiver utilizes 'aiding' data from an A-GPS location server that gives the A-GPS receiver the information it would normally have to demodulate, as well as other information to increase sensitivity by as much as 25 dB, and reduce start times to approximately 5 s (independent of network latency). This approach eliminates long start times and allows the A-GPS receiver to operate in difficult GPS signal environments, including indoors. A-GPS yield only drops in environments where the satellite signals are severely blocked.

There are two primary modes of assisted operation, MS-Based and MS-Assisted. In MS-Assisted mode, the A-GPS receiver in the MS obtains a small set of aiding data from the A-GPS LS, then recovers only pseudoranges from the satellite signals (distance measurements to the satellites in view), sends this information back to the A-GPS LS which then calculates the position of the MS. In MS-Based mode, the position calculation is made in the MS, which requires an extended set of assistance data.

A-GPS provides much better accuracy than CELL-ID, E-OTD, and OTDOA and operates on synchronous as well as asynchronous networks without the need for LMUs (though LMU information can be used if it is available). An A-GPS implementation has minimal impact on the infrastructure and easily supports roaming. A-GPS requires message exchanges with an A-GPS LS in the infrastructure, but there is flexibility with how this is handled and the messages are small. Means to support the required messages are defined by the various location standards.

To speed up satellite acquisition in the time/frequency domain, the receiver needs to know the GPS almanac, its approximate location, and approximate time of the day. Finally, to calculate position, the receiver needs to collect ephemeris of satellites in view. A GPS receiver is working in aided mode if one or more of the above pieces are sent to it using the basic communication link

5.7. Hybrid Design Considerations

A-GPS based hybrids can operate on all networks, though compatibility depends on the other location technology used with the A-GPS technology. Hybrid location technology combines A-GPS with other location positioning in a way that allows the strengths

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of one to compensate for the weaknesses of the other to provide a more reliable and robust location solution [21]. Because A-GPS is air-interface independent, it can be combined with any of the other technologies discussed to best suit the network plan and service offering, rollout plans, and other restrictions of the Operator. Hybrid solutions are typically designed to use the best information available from A-GPS or terrestrial sources, either individually or in combination, to provide accurate and reliable positioning even where independent network solutions and unassisted GPS solutions fail.

The simplest implementation of Hybrid technology for GSM, GPRS, WCDMA and cdma2000 networks is to combine A-GPS with Cell-ID. This improves yield in areas where A-GPS cannot produce position information, but provides the accuracy of A-GPS in all other cases. A-GPS coverage and accuracy is typically excellent in outdoor locations, degrading only deep inside buildings or in dense urban areas where Cell-ID may still be able to produce a position. Typically, these are areas where cell density and Cell-ID will be at the more accurate end of its accuracy range, though not as accurate as A-GPS. The combination of A-GPS and Cell-ID also has the roaming advantages defined for both Cell-ID and A-GPS.

A more sophisticated hybrid solution is A-GPS combined with E-OTD or OTDOA. This approach requires only spot deployments of E-OTD or OTDOA. A-GPS could be used throughout the majority of the network to provide the basis for most location information. The Hybrid approach generally improves yield and allows the location technology performance to gracefully degrade in a way that supports most location services in most locations.

An even more sophisticated implementation of Hybrid technology is when the A-GPS and the terrestrial measurements are used simultaneously in the navigation solution. In other words, the A-GPS and terrestrial measurements are used as complements instead of alternatives.

Tight integration of GPS with a CDMA phone results in a considerable reduction in the complexity of the MS in hardware, computational load, and memory allocation, while improving the overall performance over that of a standalone GPS receiver. In the section that follows, we describe in detail one particular hybrid solution, termed gpsOne, which is being deployed in cdma2000 networks in Korea and Japan, and has demonstrated performance well within that specified by the FCC mandate.

The cdma2000 3G System operates with time-synchronous BTSs. This means that the pilot timing on the forward link of each sector in all the BTSs is synchronized with GPS system time (which is itself simply an offset version of UTC). By using GPS time as a reference, this has resulted in all the network elements of the hybrid gpsOne system using one common time reference. The MS does not have an accurate clock, and its time reference is defined as the time of arrival (as measured at the MS antenna connector) of the earliest arriving usable multipath component being used in the demodulation. The MS time reference is then also used as the transmit time of the reverse traffic and access channels in IS-95, plus the reverse pilot channel in cdma2000.

The hybrid solution will have the following advantages:

- Allows computation of MS position when fewer than four satellites are visible.
- Provides better availability, since it merges and expands the coverage areas of infrastructure-based and GPS-based approaches.
- Improves receiver sensitivity permitting operation of the system in urban canyons and high-rise buildings. In addition, this may result in lower antenna subsystem cost.
- Takes advantage of the CDMA phone's knowledge of time.
- Allows for the use of the serving BTS location and the round trip delay (RTD) between the BTS and the wireless phone in determining the latter's position.
- Allows for the use of mobile measurements such as pilot strength and pilot phase.
- Gives differential correction capability.
- Uses existing hardware correlators and software searchers already implemented in the CDMA MS.
- Uses a small search window to reduce search time in the code domain.
- Narrows the search window in the frequency domain since the CDMA wireless unit is continuously tracking the BTS frequency.
- Reduces the impact on battery drain because the GPS signal can be acquired very quickly (because of small search space).
- Eliminates the need for additional server functionality since the PDE functionality could be provided by the base station controller (BSC).
- Allows continuous tracking after initial position is obtained using a hybrid technique. During tracking only a few and infrequent GPS measurements are needed.

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As shown in Figure 2, the mobile uses the received time reference from the serving BTS as its own time reference. Accounting for its own hardware and software delays, the MS transmits its signal such that it is received back at the serving BTS delayed by a total of 2τ, assuming reciprocity of forward and reverse links. The total delay is measured at the BTS by correlating the received signal from the MS with the referenced signal at time T_{sys}. The measured RTD corresponds to twice the distance between the mobile and reference BTS. RTD to other BTSs can be measured also in the same manner, but as shown in Figure 3, these RTDs do not correspond to twice the distance between the mobile and other BTSs. Recall these other BTSs are measuring the RTD with respect to their own clock, which is not the reference used by the MS.

The MS is continuously searching active and neighboring pilots. In the process it measures the PN code phase difference (delay) between each pilot and the reference (earliest arrival) pilot. Clearly, this pilot pseudo-noise (PN) phase difference is the same as time difference of arrival (TDOA) of the two pilots from the two BTSs as shown in Figure 4.

The proposed hybrid approach merges GPS and network solutions to meet not only the FCC E911 mandate, but also other location-based service requirements. The MS collects measurements from the GPS constellation and the communication system and sends the information back to an entity in the network that fuses the measurements together to produce an accurate 3D position. A 3D position is made possible by the inclusion of GPS measurements into the process. This is not possible in any system using only terrestrial measurements.

With the hybrid approach, 3D positioning can be accomplished with one, two, or three satellites. As shown in Figure 5, since the MS is receiving CDMA

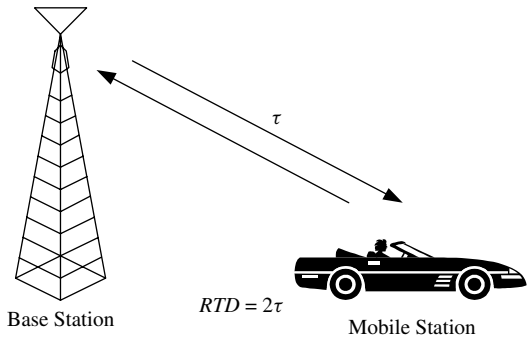

Fig. 2. Round trip delay measurements.

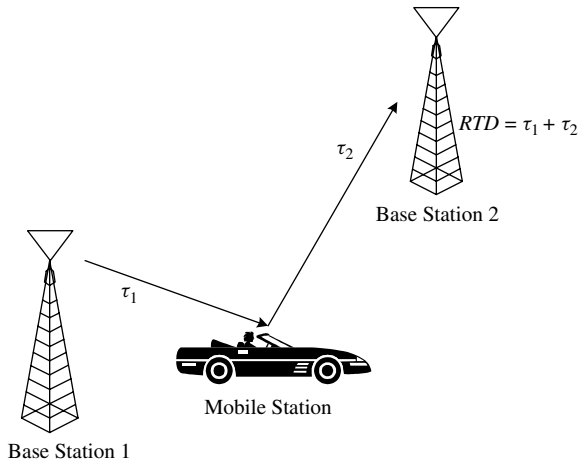

Fig. 3. RTD to other base stations.

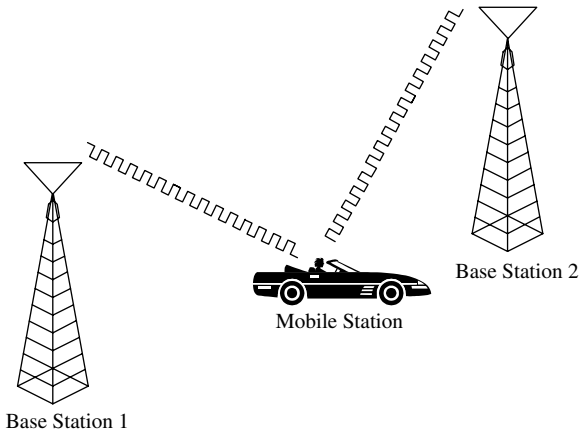

Fig. 4. Pilot code phase difference.

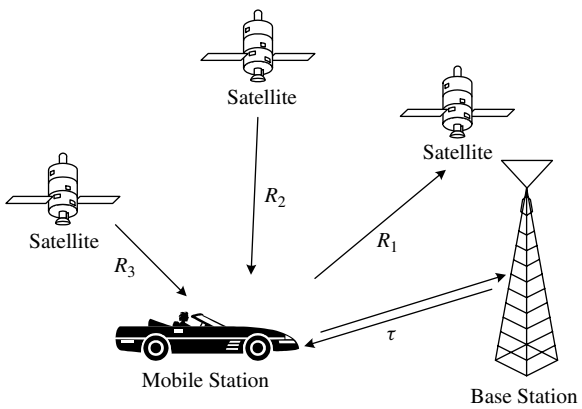

Fig. 5. 3D positioning with three satellites.

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signals from at least one BTS, it will acquire system time. Its sense of system time is delayed with respect to true system time at the serving BTS by the propagation delay τ between the MS and the BTS. Once the MS tries to access the system or is on the traffic channel, the propagation delay τ is estimated by the BTS to be [RTD/2]. This estimate is used to adjust the mobile system time to correspond to 'true' GPS time. Once the MS's clock is synchronized with GPS time, only three measurements from three satellites are needed to determine a 3D location. Note that multipath does not impact the performance of the time estimate because the mobile system time is shifted from GPS time by τ regardless of whether the signal takes a direct path or a reflected path.

In addition to using the RTD to the serving BTS for timing, it can also be used for ranging as shown in Figure 6. The distance to the serving BTS is given by $R_3 = C\tau$, where C is the speed of light, although multipath here will impact on positioning accuracy. Note that under certain geometry scenarios, one may obtain two ambiguous solutions. The ambiguity can be resolved by using either sectorization or forward link information. For example, pilot PN phase difference of a neighboring pilot can be used to resolve the resulting ambiguity.

3D positioning with one satellite is possible. In this scenario, the proposed approach requires one additional measurement from the wireless network. This additional measurement could be either a second RTD measurement, or a pilot phase offset on the forward link as shown in Figure 7. To reduce the impact of multipath on the calculated position, the phone is asked to report only the pilot phase of the earliest arriving path.

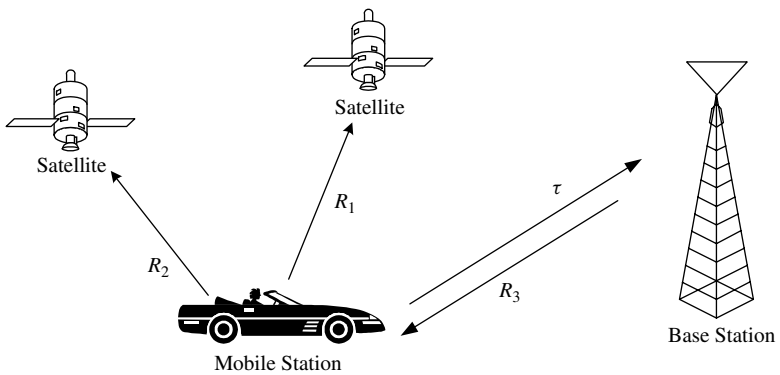

Fig. 6. 3D positioning with two satellites.

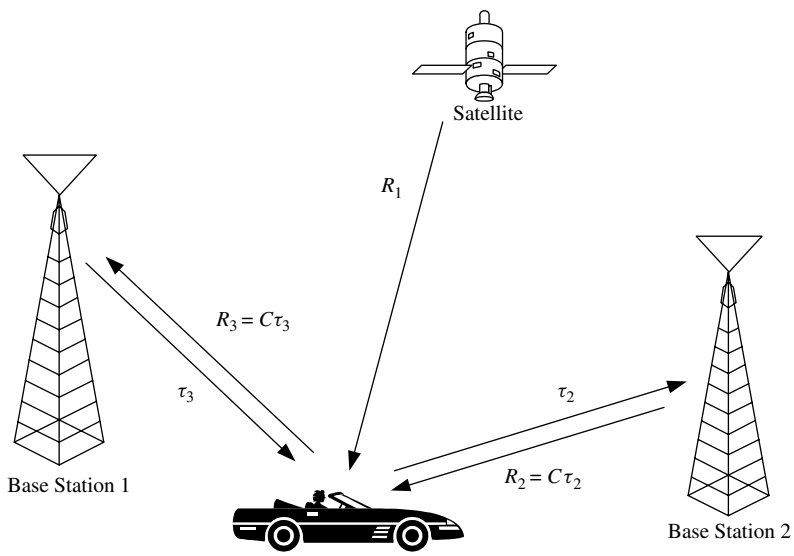

Fig. 7. 3D positioning with one satellite.

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5.7.1. GPS receiver sensitivity enhancement in hybrid systems

The specification for the GPS signal level under clear view of the sky is −130 dBm, but building penetration, shadowing, and foliage losses can degrade the signal by more than 20 dB.

Conventional GPS receivers typically integrate coherently over 1 ms (one period of the CA code) and non-coherently for 6 ms. As a result, a conventional GPS receiver can only acquire signals above about −136 dBm. Weaker signals require more processing gain (longer integration) for successful acquisition. Knowing 'true' GPS time at the mobile and the approximate range to the satellite enables the phone to integrate over 20 ms (one navigation bit period). Furthermore, if the network predicts the bit sequence for some parts of the navigation message, the bit polarity pattern can be sent to the MS to help with integrating over multiple bits. In addition to the sensitivity enhancement, knowing 'true' GPS time at the MS reduces the time required to acquire the GPS signal for a given satellite by reducing the search window dramatically. To do this, the serving BTS sends information regarding the search window center and the search window size to the MS. Therefore, the MS needs only to search a small window in the time domain rather than the whole code space. For an MS at four miles distance from the BTS, the search window size for a satellite with a 60° elevation angle is only 20 chips. This would reduce search time per satellite by a factor of 50.

5.7.2. Position update using only infrastructure information

Once an accurate position fix is obtained, infrastructure information alone can be used to update the location of the MS. This 'free wheeling' concept is useful in tracking modes because it reduces the amount of time the MS is away from the communication channel while measuring the signal on the GPS channel. This way there is a very small degradation to either data delivery rate or voice quality.

An initial and accurate position is determined using information from both the GPS constellation and infrastructure as discussed earlier. Afterwards, and until it is decided that the 'free wheeling' solution is no longer reliable, the MS uses only infrastructure measurements to update its position. It can be shown that forward or reverse link information from two BTSs is enough to update the 2D position of the MS. Because of the inherent channel impairments, the update will degrade with time and eventually a fresh GPS constellation-based solution will be needed.

6. Synchronization Methods

All 2G and 3G location solutions defined in standards, except for the Cell-ID only solution, are based on TOA techniques. These include Cell-ID with TA or RTT, E-OTD, OTDOA, standalone GPS, A-GPS, plus hybrid solutions that extract range data from the communication links. All can be improved if the BTS time references operate time-synchronously. In cdma2000 all BTS clocks are synchronized with respect to a common time scale specifically chosen to be the GPS time scale. The GPS time scale was selected for IS-95 since it is traceable to the global standard time scale (i.e. UTC, and is available worldwide via a variety of methods at no cost for the service). The GPS time scale differs only from the UTC time scale in that leap second adjustments are not used by GPS, which eliminates a periodic time jump in the GPS (and cdma2000) system time reference. Today, GPS time leads UTC time by 13 s, which is the total of all leap seconds that have occurred since 6 January 1980.

cdma2000 specifies that all Base Station Transmissions (measured as transmitted pilot phase) must be within +/−10 μs of GPS time, but does not require the use of GPS to provide the time reference. For situations where GPS signals are not available, there are alternate sources for UTC time but none are as accurate as GPS. As a result, the most common method of time distribution is to locate a GPS receiver at every BTS.

WCDMA is designed to operate asynchronously, with each BTS (referred to as Node B in 3GPP) permitted to have its own, independent time reference. The MS (referred to as the User Equipment, UE, in 3GPP) has no prior knowledge of the clock state of any BTS. Even though the WCDMA system has been designed to operate asynchronously it is quite feasible, as well as beneficial, to synchronize all the BTS clocks. In fact, the WCDMA standard provides explicit signaling methods to inform the MSs about relative BTS timing and the accuracy of their synchronization.

An important point to note is that there is no technical disadvantage to synchronizing BTSs. That is, a system operating designed to be asynchronous but is running synchronously using accurate external

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timing sources is never worse than the basic asynchronous system, even if the external timing sources are unavailable for an extended period of time. Any attempt to synchronize BTSs can only improve performance.

Some advantages that made time synchronization worth pursuing for IS-95 and which are now retained for cdma2000 are as follows:

- Faster initial acquisition for the mobile, since a common pilot sequence can be used by all BTSs.
- Each sector is identified by the time shift assigned to each sector's pilot sequence. Thus, an MS only searches the one sequence to test for all sectors.
- Faster Handoffs, since the BTSs know where (in time) to look for incoming MS transmissions.
- Reduced MS wake-up time when in idle mode, since pages can be synchronized. This in turn reduces battery power and increases standby time.
- Increased reliability of common channels, since these can use soft handoff.
- More options for accurate location-based services, since it adds the capability of TOA techniques.

The accuracy required of the clocks for position location is far tighter than the requirement for communication (approximately 50 ns or better is needed). There are three methods that can provide this better accuracy:

- GPS plus BTS calibration;
- Location Measurement Units (LMUs);
- Self-Synchronization using inherent CDMA attributes (described next).

6.1. Non-GPS Method for Synchronizing BTSs

IS95 and cdma2000 base stations are generally synchronized using GPS receivers located at every BTS, and this method could as well be used for synchronizing WCDMA BTSs. Alternatively, both networks could be 'Self-Synchronized' using the schemes proposed in References [22] and [23]. The method is inherent with CDMA operation, and is briefly described here in terms of cdma2000 operation. WCDMA could use a similar, but not identical, method since it is based on soft handoff procedures used by both systems. During soft handoff an MS is connected simultaneously to multiple BTSs, which (by adding diversity) greatly enhances call reliability. To initiate soft handoff in cdma2000, an MS sends information on relative pilot strengths and arrival times in the Pilot Strength Measurement Message (PSMM) [22]. Based on this information, soft handoff is enabled to those links that will provide 'adequate' diversity gain. Since the MS reports on all pilots above a rather low threshold, many reported links will provide little diversity gain and are not useful in soft handoff. But relative pilot timing information from those links is still contained in the message and this information can be used to estimate time differences between BTSs.

As required by cdma2000, an MS sets the first arriving pilot used for demodulation as a time reference and reports on all other pilots with respect to this reference. And since the MS's transmitted signal is transponded with respect to the reference pilot, the reference BTS can estimate the propagation distance to the mobile by noting the time difference between the BTS's transmission time and the time the MS signal is received back at the BTS. This RTD can be combined with the relative delays reported in the PSMM as an aid to acquisition at the new BTS. The interesting point is that once a call is established, this same process can be used to estimate the difference between the two BTS clocks.

To see how this can be accomplished, first define the time for the signal to propagate to the MS from the two BTSs as $T1$ and $T2$, respectively. At the MS, the signal from BTS2 arrives a time ΔT after the signal arrives from BTS1. The mobile reports ΔT in a PSMM, with the sense that later arrivals have a positive sign. Assume for the moment there is no clock error (i.e. $Te = 0$) at BTS2 with respect to BTS1, and that the difference between the MS transmit and receive time is MSTO. The reference BTS measures RTD1, which is $2^*T1 +$ MSTO since the return propagation time is the same in almost all cases. Similarly, as measured at BTS2, RTD2 (the time for the signal to propagate to the MS from BTS1 plus the time for the signal to propagate from the MS to BTS2 plus the MS's internal delay) is equal to $T1 + T2 +$ MSTO. Since $T2 = T1 + \Delta T$, BTS2 should expect the mobile's reverse link at RTD2 $= 2^*T1 + \Delta T +$ MSTO $=$ RTD1 $+ \Delta T +$ MSTO. If there is a time error (Te) at BTS2, then the measured Round Trip Time RTD2 will be different from the expected RTD2. Given the measured round trip delays, RTD1 and RTD2, plus ΔT, one can easily compute the time error, Te, of BTS2 as:

$$Te = (\text{RTD1} - \text{RTD2} + \Delta T)/2.$$

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This is now a direct measure of the time difference between BTS1 and BTS2, made at every soft handoff. Note that Te is not dependent on the value of MSTO. During normal operation, there are multiple PSMMs sent from every MS in soft handoff. And for each MS in soft handoff, there can be multiple RTDs from every BTS in the MS's active set. This mutual RTD information, when combined with the delay measurements in the PSMM messages, can be used to measure the time difference between any two BTSs in the active set. And as demonstrated in field tests, the accuracy of the estimate is good enough to support position location using the CDMA signals. Reference [22] describes an experiment with a demonstrated error in the time error of 42 ns obtained from a 40-min test.

In the case of WCDMA, time synchronization can be accomplished using a common clock source such as GPS or using self-synchronization schemes similar to cdma2000. In WCDMA the MSs are aware that the BTSs are clock-synchronized (through the System Information Broadcast messages). Within WCDMA, different levels of synchronization are feasible. The current 3GPP specification [24] supports time synchronization to an accuracy of 2560 chips (666 us), 256 chips (66.6 us) and 40 chips (10.4 us), which, unfortunately, is inadequate for positioning. However, there is also an 'SFN–SFN measurement type 2' message that has a resolution of 1/16 of a (WCDMA) chip, which is quite satisfactory for position determination.

This description for self-synchronization is indicative that precise time-synchronization between WCDMA BTSs can be accomplished using existing mechanisms specified by 3GPP. Generally, BTS synchronization using GPS receivers is the most cost effective way to gain all the benefits of synchronous deployment, but other methods are viable. LMU or MS-based synchronization can be used if availability of GPS receivers at the BTS is in question.

7. Network Reference Model

For location services network, as in any other network, it is important to define a reference model (i.e., network architecture) in which a set of functional entities and interfaces between them are identified [13,15]. A network reference model defines a set of network entities and interfaces between them. A set of messages is also defined to transfer information and requests between the network entities. Communication paths or reference points between the network entities are also defined to indicate where information can be exchanged. These network reference points allow specific interfaces to be discussed and defined. Once the network reference model is developed, the next step is to define the information that must be passed from one network entity to another. Information that can be passed at the same time is collected together to form messages. The network reference model has messaging that occurs between wireless network entities; between wireless network entities and emergency services network entities; and between MSs and wireless network entities.

Phase-I emergency services requires the passing of the location of BTS, cell site or sector serving an emergency services caller. This information is passed as Emergency Services Routing Digits (ESRD) during call setup as the called number, as an ISDN User Part (ISUP) Generic Digits Parameter, or both. Position may be used in emergency services networks for two basic purposes: to route the Emergency Services Call (ESC) for proper handling and to aid in resolving the emergency situation.

The position information may be delivered to the emergency services network in two basic ways: with the call as part of the call setup information or through a separate data service. The former is known as Call Associated Signaling (CAS) since the position information is delivered in the call signaling. The latter is Non Call Associated Signaling (NCAS) and the messages delivered by the data service must be correlated with the call by parameters carried in the message.

With CAS, the wireless network pushes the position information to an Emergency Services Network Entity (ESNE). With NCAS, an Emergency Services Message Entity (ESME) pulls the position information from the wireless network.

If call setup is sent in a CAS push or used for routing, then call setup may be delayed while position information is being determined. The maximum period of time that a call will be held up is provisionable on a per system basis.

Figure 8 describes a functional network model of a system for determining the location of an MS in a wireless network.

7.1. Network Entities

This section describes the functionality of the network entities of the network reference model. Message routing and transmission facilities are considered to be outside of the network reference model, even though they provide essential services.

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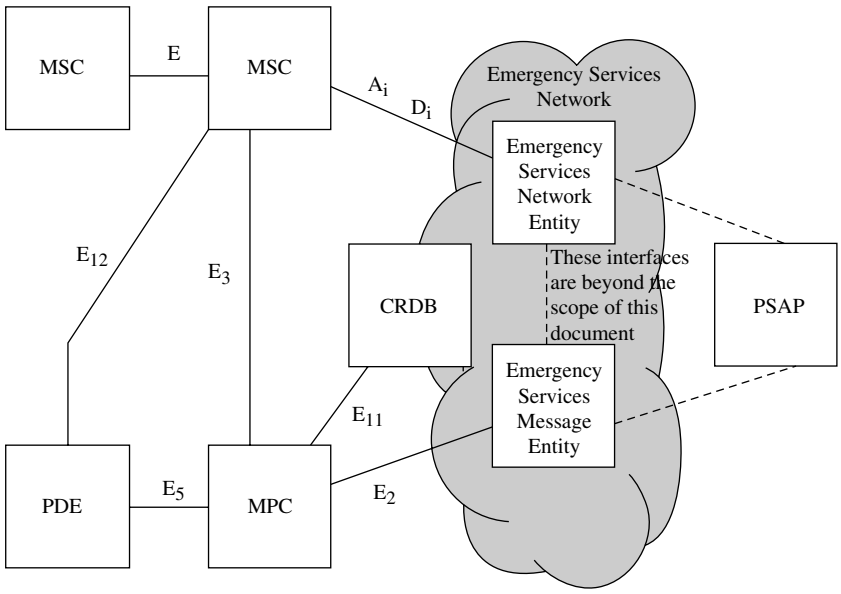

Fig. 8. Network reference model.

7.1.1. Coordinate routing database (CRDB)

The CRDB provides a translation between a given position expressed as a latitude and longitude and a string of digits identifying an Emergency Services Zone (ESZ).

7.1.2. Emergency services message entity (ESME)

The ESME routes and processes the out-of-band messages related to emergency calls. This may be incorporated into selective routers (also known as Routing, Bridging and Transfer switches) and Automatic Location Information (ALI) database engines. The structure of the Emergency Services Network is beyond the scope of this paper.

7.1.3. Emergency services network entity (ESNE)

The ESNE routes and processes the voice band portion of the emergency call. This is composed of selective routers (also known as Routing, Bridging and Transfer switches).

7.1.4. Mobile position center (MPC)

The MPC selects a PDE to determine the position of an MS. The MPC may restrict access to position information (e.g., require that the MS be engaged in an emergency services call or only release position information to authorized nodes).

7.1.5. Mobile switching center (MSC)

The MSC provides radio contact with MSs making emergency calls. The MSC may hand off the radio control to another MSC, but the emergency call remains anchored with the MSC establishing the first radio contact.

7.1.6. Position determining entity (PDE)

One of the key elements of an emergency services network is the PDE. The proposed architecture is flexible enough to allow the location functionality to be built in a variety of configurations using different radio location technologies.

The PDE determines the position of a wireless terminal when the MS starts a call or while the MS is engaged in a call. Each PDE supports one or more position-determining technologies. Multiple PDEs using the same technology may serve the coverage area of an MPC, and multiple PDEs each using a different technology may serve the same coverage area of an MPC.

7.1.7. Public safety answering point (PSAP)

A PSAP is the terminating end-point of an emergency services call responsible for answering to emergency services calls.

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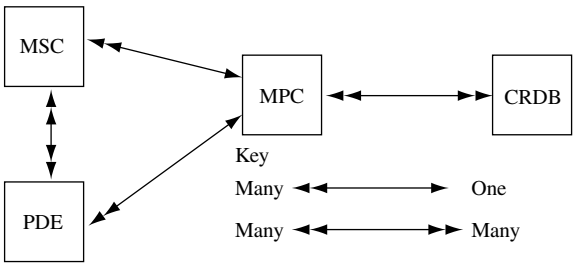

Fig. 9. Entity relationship diagram.

7.2. Network Entity Relationships

Figure 9 depicts network entity relationship. Each MSC is associated with only one MPC, but each MPC may be associated with multiple MSCs. PDEs are associated with only one MPC, but each MPC may have multiple PDEs associated with it.

8. Location Applications

Although initiated as a response to the FCC's E911 mandate, position location information is now recognized as a catalyst for a wide variety of location-based applications. The fact that these applications could be a source of revenue is not lost on the operators, especially since the FCC left it to the Operators to determine ways to recover costs associated with the E911 service.

The technical part of the location process is well underway for 3G and the obtained accuracy will likely exceed the requirements set forth by the FCC. However, the fact that a person's position can now be located means that privacy and marketing issues are to be expected.

Except for standalone GPS, position location information for 3G systems will probably be computed within the network using measurements from either the MS or from the BTSs. This is necessary to simplify the MS design. Non-wireless standalone mapping systems can use stored maps and existing options include CDROMS for in-car GPS systems or PC downloaded maps for handheld GPS receivers. In wireless systems, these maps would have to be stored on location servers with only the region necessary downloaded to the MS as needed. At this time there is no universal solution and there are a variety of vendors offering different ways to minimize the MS's involvement.

Location service for wireless systems is a rapidly growing industry that will have an impact on the way people use handsets, and on the design of the handset itself. Many position services do not need maps displayed to the user, and can be less demanding than those that actually display a map. Location Services that fall into this category are those that provide answers to the following questions:

- Where am I?
- What (entity) is near here?
- Where is (the entity) I asked about?
- How do I get there?

In response to these requests simple text messages can be sent from the network. These can then either be displayed on the MS screen or converted to voice messages.

For map-based services, the user interface and screen size will increase as more of these informational services evolve. How far these map-based services can go depends on the accuracy of the location estimate. Users have become conditioned to the accuracy of GPS, which today runs about 10 meters in good locations. In addition to the FCC mandate, the service providers recognize location service as a value-added feature. Indeed, value added location services present a great revenue opportunity for wireless carriers. A market study from The Strategis Group, Wireless Location Services, 1997, projected that revenues from five wireless location applications have the potential to exceed $8 billion per year in a mature market. Potential location applications include the following:

- **Location sensitive billing:** The wireless carriers can target new market segments by enabling accurate price differential based on the caller location. This enables wireless carriers to compete with wireline carriers by offering comparable rates when the caller is at home or in the office.
- **Location-based information services:** For a monthly fee, a user can call the service center to ask for driving directions or get advice on restaurants, hotels, department stores, and gas stations. The service center can also respond to emergency requests by notifying police/fire personnel or ordering a tow truck in the case of a vehicle breakdown.
- **Network planning:** Statistics from the wireless network operation can be used to plan expansion of an existing network or deployment of an entirely new network.

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- **Dynamic network control:** The collected statistics can be used to dynamically adjust network parameters to accommodate network load change due to callers' behavior.
- **Fraud management:** Fraud can have a devastating impact on wireless carriers by reducing profits and undermining the customer's confidence. Location information helps operators ensure prompt detection and tracking leading to swift apprehension of the culprit.
- **Fleet management and asset tracking:** Asset tracking represents a cost savings that almost equals the value of the asset. It gives the fleet owner the ability to constantly locate company vehicles, to instantly communicate with the driver, or at the push of a button, to update the status of the engine, power train, door locks, etc.
- **Real-time traffic updates:** Information received can be sent to traffic management centers to help reduce traffic jams and speed travel.

9. Privacy

Privacy is important to carriers, vendors and consumers since it adds value to location technology. There is no issue when considering privacy for a 911 call. Anyone requesting emergency assistance is assumed to approve being located in the process. But for other services it is not so clear, and there is a definite concern that the user may not wish to be located under any and all situations. The CTIA has a petition before the FCC seeking rules to safeguard personal privacy for mobile phones, but not all members of the CTIA are in agreement of what to do at this time. The Direct Marketing Association has urged the FCC to allow the industry to regulate itself on privacy, to leave the door open for 'push' services. In 'push' services the user could be contacted based on location, without prior consent.

Wireless location information presents particularly sensitive privacy concerns. The pressure is mounting for the industry and authorities to establish guidelines setting acceptable standards for the protection of privacy for users of wireless devices, which may be located using wireless location technology. It is increasingly apparent that products and services that use location information will soon pervade everyday life. The issue of determining the location of mobile phone users when the phone is connected to the network, and sharing that information with third parties is an extremely sensitive one. Needless to say, this raises a host of privacy concerns. Just about everybody wants a 911 operator to know where they are, but don't necessarily want someone else to know their whereabouts.

In some applications, users will say they are in the vicinity of a certain ZIP code or city to receive weather, restaurant, travel and other information specific to that location. In other models, the information can be sent automatically using several location-detection technologies that are beginning to roll out.

The Carriers must protect the location information by not just automatically forwarding it to wireless advertisers or service providers. Carriers also should not intend to send the information unless users authorize it. Vendors should develop platforms that utilize 'user location privacy filter.' This software would tell each carrier which users want ads or location services, and which do not, on a per service or a per service attempt basis.

In general, control of location information privacy is shared by every entity that has access to either the location data (i.e. the computed user position) or the location measurement data (i.e. the measurement values to be used in the computation of the user position); however, primary control of location information privacy resides with the entity that carries out the measurements to be used in the location computation.

In the case of the network-based positioning method, the fundamental measurements to be used in the position computation are made at the base station. The notation base station here means all elements of the terrestrial network (including the BTS, BSC, MSC, MPC, PDE, etc.). Hence, the location information privacy is controlled solely by the base station.

In the case of the handset-based positioning method, the fundamental measurements to be used in the position computation are made at the MS. Hence, the location information privacy is primarily controlled by the MS. When the MS sends the location data or location measurement data to the BTS, then the BTS also has location information privacy control.

Location information privacy control by the BTS is described in PN-4747 [12]. PN-4747 defines the Location Information Restriction (LIR) service, which allows the subscriber to manage an MS privacy profile. This profile describes a class of applications that are authorized to obtain the location of the MS. Authorization can be on a per-attempt or on a permanent basis (permanent authorizations are also subject

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to change by the user). The standard relevant to location information privacy control by the BTS, in case of emergency calls, is J-STD-036 [13].

The handling of location information privacy control by the MS is described in the various air-interface standards. The requirements of the IS-801-1 [14] are relevant to the handset-based positioning method, even though network-based positioning methods may also use certain messages defined in IS-801-1.

The Target MS Subscriber shall be able to restrict access to the location information (permanently or on a per attempt basis). The LCS Client access shall be restricted unless otherwise stated in the Target MS Subscription Profile (i.e. opt-in). The home network shall have the capability of defining the default circumstances in which the Target MS's location is allowed to be provided, as required by various administrations and/or network requirements. If a target MS supports LCS, the target MS user shall be notified of each location request for which there is no restriction in the MS subscription profile and be enabled to accept or reject it. The default treatment, in the absence of an indication from the MS user, is to accept.

The target MS subscriber may also subscribe to notification for each location request that is restricted in the MS subscription profile and be enabled to accept or reject it—the default treatment in the absence of an indication from the MS user being to reject. Where a target MS does not support LCS, a location request for which there is no restriction in the MS subscription profile shall be denied where required by local regulatory requirements and allowed otherwise. In the latter case, the LCS server may maintain a record of each location request including the result and the identity of the LCS client.

10. Conclusions

In the view of many observers, the most eagerly awaited applications in the wireless industry are mobile location services. No doubt that the Federal Communications Commission's E911 mandate is catalyst and the wireless operators are waiting until they are E911 compliant before launching value-added capabilities. To the average consumer, location services may be just 'another high-tech feature' and could be perceived in the same way cell phones and computers were viewed 10 years ago. Nevertheless, to wireless carriers, location applications have become increasingly important as they look for ways to meet the FCC mandate and to offer new revenue-generating services to their customers.

Location services are expected to play a more important role in third-generation wireless systems. The basic principles for locating mobiles in CDMA systems are identical to those used in the second generation systems, but the greater bandwidth of the W-CDMA signals should allow greater accuracy than with GSM. In addition, the time synchronization feature of cdma2000 makes it more economical to deploy location services based on cdma2000 systems.

A network solution requires carriers to add equipment to their infrastructure that determine caller location and is compatible with existing handsets. If carriers choose handset-based technology, fewer network changes are required. But, they must start offering new subscribers location-enabled handsets soon. The FCC has mandated that 95 per cent of each subscriber base must have location-based handsets by the end of 2005.

For Carriers deploying handset-based technology, GPS is the most popular choice, while a combination of Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) technology is the most popular option for carriers rolling out network-based systems.

GPS and wireless technology have dramatically impacted position location and navigation systems over the past decade. Integration of GPS with wireless devices has significantly reduced time to first fix and improved accuracy. Increased processing power and proliferation of wireless devices has made high performance navigation systems available at a much lower cost.

Hybrid location determination technology combines measurements from the wireless network and the GPS constellation. This hybrid approach is best suited to support the most accurate and highest availability location services. It will improve accuracy and availability in scenarios where infrastructure-based solution only or GPS-based solution only will have reduced performance, since these two techniques tend to have their worst performance in many locations.

All position location techniques can be improved if the BTS time references are synchronized, and this article has outlined a non-GPS method that is introduced to synchronize base stations.

On the issue of privacy, for location services, the target MS subscriber may be able to restrict access to location information used to enhance or support particular types of service. The LCS client access

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will be restricted, unless stated otherwise, in the Target MS subscription profile. For Emergency Services (where required by local regulatory requirements), target MSs making an emergency call may be positioned regardless of the privacy attribute value of the subscriber associated with the Target MS making the call.

For Lawful Interception Services (where required by local regulatory requirements), target MSs may be positioned under all circumstances required by local regulatory requirements. It is noted that in this situation the target MS user shall not be notified of any location attempt.

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Authors' Biographies

Samir S. Soliman (S'80-M'83-SM'88) received his B.Sc. degrees in Electrical Engineering and Applied Mathematics from Ain Shames University, Cairo, Egypt, both with honors in 1974 and 1977, respectively, and M.S and Ph.D. degrees in Electrical Engineering from University of Southern California, Los Angeles, in 1980 and 1983, respectively. From August 1983 to May 1990, he was with the Department of Electrical Engineering, Southern Methodist University, Dallas, Texas. He joined QUALCOMM Incorporated in 1990 and has since participated in developing subscriber stations for wireless local loop, cellular and PCS systems. He also developed the hybrid position location approach to meet the FCC E911 mandate for wireless devices. For the past few years, Dr. Soliman has devoted the majority of his time in optimizing IS-95 and cdma2000 cellular networks and resolving interpretability issues.

Dr. Soliman has served as the Communication Theory technical representative for ICC'90, as a vice chair of the technical program committee for Globcom'89, and Communication Society Chair, San Diego Chapter in 1996. Dr. Soliman's research interests include wireless applications using code division multiple access techniques, coding and synchronization over fading dispersive channels, detection and estimation over non-Gaussian channels, signal classification, Ultra wideband signals, and position location techniques.

Dr. Soliman has over 40 published articles in various journals and conferences, and 17 issued patents related to

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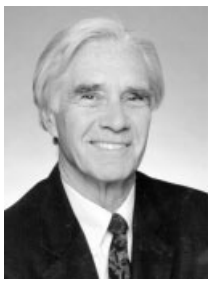
CDMA and position location. In addition, he is the principal author of the book, *Continuous and Discrete Signals and Systems*, published by Prentice-Hall, 1998.



Charles E. Wheatley, III, received the B.S. degree in Physics from the California Institute of Technology, Pasadena, in 1956; the M.S degree in Electrical Engineering from the University of Southern California, Los Angeles, in 1958; and the Ph.D. degree in Electrical Engineering from the University of California, Los Angeles, in 1972. Dr. Wheatley joined QUALCOMM Inc. in 1987, and is presently Senior Vice President - Technology, concentrating about equally on RF hardware design, system design, field verification testing, and standards development.

Since 1989, these efforts have been devoted almost entirely to CDMA as applied to wireless mobile communications. During this period, Dr. Wheatley developed the complete RF design of the first CDMA prototype mobiles and Base Station hardware, used for early system testing; and also contributed to the idea and first mechanized the concept of closed and open loop power control, considered by many to be a key factor in making Mobile wireless CDMA a reality. He was a key member of the TIA TR 45.5 committee responsible for standardization of Cellular CDMA, specifically contributing to three primary physical layer documents for CDMA: IS-95, IS-97 and IS-98; and he was also a key member of the JTC committee responsible for the standardization of PCS CDMA. In addition, he developed a procedure to fairly compare the performance of all the various technology options, and was heavily involved with field verification testing of commercial CDMA systems as compared with initial expectations. Dr. Wheatley is now spending the majority of his efforts on third generation (3G) systems that are designed to support higher data rates with direct Internet access capability.

Prior to 1989 he was responsible for the second generation RF hardware design and the forward link processor used in Qualcomm's OmniTracs System.

Prior to joining Qualcomm, he held the position of Technical Assistant, Vice President at M/A COM Linkabit. During the 5-year period of 1982 to 1987 while at Linkabit, Dr. Wheatley was assigned almost exclusively to Government communication systems.

From 1963 to 1982, Dr. Wheatley was employed by Rockwell International. While at Rockwell, he was part of a corporate task group in charge with the development of an advanced RF terminal that could eventually be applied to a wide variety of government communication systems. For this extremely wide band radio design, he led the group's investigations into specific problems of the terminal's Frequency plan and architecture. One interesting outcome was the design for a fully digital frequency synthesizer using only binary logic elements. This was achieved through the use of time-dither techniques, which are still used in state of the art synthesizers.

While pursuing his Ph.D. at UCLA in 1971, he was involved in the very early developments in surface wave devices (SAWD) as applied to filters and oscillators. As part of his Thesis, he built and tested a 128 tap matched filter and used this to experimentally verify that it could obtain optimum estimates for the time of arrival of direct sequence waveforms.

Dr. Wheatley has published approximately 20 articles in various journals and symposiums, including 'On the Capacity of a Cellular CDMA system', with co-authors Klein Gilhousen, Irwin Jacobs, Roberto Padovani, Andrew Viterbi, and Lindsay Weaver; *IEEE Transactions on Vehicular Technology*, May 1991, voted 1991 Best Paper Award by the Vehicular Technology Society. This paper formed the basic description of what is now known as CDMA for wireless communication

Dr. Wheatley holds over 50 patents on various techniques and devices, all related to the field of communications, and is a senior fellow of the IEEE and a member of AFCEA.

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