Assisted GPS solution in cellular networks

Gidon Lissai

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Assisted GPS Solution in Cellular Networks

By

Gidon Lissai

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Telecommunications Engineering Technology

November 2006
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Objectives

The ‘Wireless Enhanced 911’ rules, which were issued in 1996, state that the position of a mobile device should be sent to Public Safety Answering Point (‘PSAP’) once a 9-1-1 call takes place from it. The rules imposed the cellular carriers to integrate a technology into their networks so that the mobile device location can be transferred once a 9-1-1 call is made. One of the chosen technologies was the Global Positioning System (GPS). The solution suggests integrating a GPS receiver into every cellular device. But the GPS receiver, as a stand alone solution, has some major performance limitations in regards to the Wireless Enhanced 911 requirements.

The Assisted GPS (A-GPS) technology improves the GPS receiver performances. It reduces the time it takes the receiver to calculate its location. It also enhances the receiver’s reception sensitivity and improves the calculated position accuracy. With the A-GPS technology, the GPS receiver solution becomes compatible with the rules requirements. Two of the four large wireless carriers in the U.S. had chosen the A-GPS as their location solution in their networks.

The A-GPS technology became an important part of the cellular industry. The intention of the thesis is to explore the A-GPS solution and to show its necessity in today’s GPS-based solutions. The following aspects are reviewed in the thesis – how the A-GPS solution works, how it improves the GPS receiver performances, the technology that is being used to implement it, and how it integrates to the cellular network.
Another A-GPS related aspect that is reviewed in the thesis is the integration of location-based applications in cellular networks. The location-based applications service is a new and growing market in the cellular industry as a result of the deployed location solutions.
Chapter 1 – Global Positioning System
The Global Positioning System (GPS) is a satellite-based navigation system. The satellite network has twenty four dedicated satellites that broadcast signals towards earth. Those signals enable the GPS receiver to calculate its three dimensional location (latitude, longitude, and altitude) at any place in the world. The GPS position calculation is based on measuring the distance from the GPS receiver position to the precise locations of the GPS satellites.

1.1. History of the GPS System

The GPS system was developed by the United State Department of Defense (DoD) in order to meet military requirements. But even before the system was operational, it was already opened for civilian use. This chapter presents an overview of the GPS system development from its beginning to the present day.

1.1.1. Transit, Timation, Secor, and 621B

Beginning in the early 1960’s, the DoD was looking for a global navigation system that would be continuously available and would allow a wide spectrum of users to get location information. The global solution requirement was also to be highly accurate so that every possible user will be able to know where he/she is. The U.S. Navy and Air Force began studying the concept of using radio signals transmitted from satellites for positioning and navigation purposes. These studies developed concepts and experimental
satellite programs, which became the building blocks for the Global Positioning System\textsuperscript{1}.  

The U.S. Army also worked on its own solution.

The U.S. Navy came up with two different navigation systems – Transit and Timation. Transit was the first operational navigation system based on information from satellites. It provided two-dimensional positioning and required long observation time before the location was determined. The position was determined by the Doppler shift of the received satellite signal. It was used by the Navy to locate maritime vehicles, ballistic missiles, etc. Transit demonstrated that worldwide accurate navigation was possible from space. Its operational constellation of satellites in circular polar orbits is still in use today\textsuperscript{2}.

The Timation system based its location calculation on timing information that came from the satellites. This approach is also implemented in the GPS solution. The Timation system provided two-dimensional position (latitude and longitude). It was based on two experimental satellites that were launched at 1967 and 1969 (See pictures 1.1 and 1.2).

The U.S. Air Force designed and implemented the 621B system. The system provided continuous service and three-dimensional positioning. Its satellite signal (for ranging purposes) was based on pseudorandom signal (PRN).

The U.S. Army presented the SECOR (sequential correlation of range) system: Each SECOR satellite was linked to four ground stations — three at geographical points where the coordinates had been accurately surveyed and a fourth at the location whose
coordinates were to be pinpointed. Radio waves were sent from the ground stations to the satellite and returned by a transponder. The position of the satellite at any time was fixed by the measured ranges from the three known stations. Using these precisely established positions as a base, ranges from the satellite to the unknown station were used to compute the position of the unknown station.


Picture 1.2 - Thor-Agena vehicle (the name of the orbital launch vehicle). The satellite was launched into a 500 nautical mile polar orbit.
By the late 1960s, the U.S. Navy, Air Force, and Army were each working independently on radio navigation systems that would provide all-weather, 24-hour coverage and accuracies that would enhance the military capabilities of their respective forces\(^1\). In 1973 the Deputy Secretary of Defense decided to merge the proposed solutions to a single satellite navigation system. By the end of that year, the DoD approved to proceed with the development of the proposed system. The system, which named NAVSTAR Global Positioning System (NAVSTAR GPS), was based on the 621B and Timation solutions.

1.1.2. Implementation and testing

The GPS system divides into three segments: Space segment – the satellites constellation in space and their orbital planes. Full constellation has 24 satellites, which are placed in six orbit planes (four per each); Control Segment – stations on earth that track the GPS satellites and provides them with periodic updates; User Segment – the GPS receiver that calculate its user location.

During the years 1974-1979 the GPS plan was tested. The space segment was tested at the beginning with two refurbished Timation satellites. In 1977, user segment tests were performed. Transmitters were installed on the earth’s surface in order to simulate the satellites’ role in the GPS system. The final segment of GPS—a prototype ground control system—was located at Vandenberg AFB, CA, during this period\(^1\).
In 1978 the first GPS satellite was launched and tested. The first group of satellites was from Block 1 type (Usually marked as ‘Block I’. See picture 1.3). From 1978 to 1985 11 Block I satellites were launched from California, each having a weight of 845 kg. None of those still operates today. Their lifespan was supposed to be 4.5 years and all of them exceeded this lifespan by about another 5 years\(^4\). The Block I satellites were used to demonstrate and test the feasibility of the GPS system.

Picture 1.3 - GPS Block I satellite\(^5\)

The GPS program was initially designed to have 24 satellites. Due to a decision to have major cuts in the FY81-FY86 budget, the program was restructured to have only 18 satellites. Block II satellites (the next satellites generation) development was dropped.

In 1983 a civilian airplane of the Korean Airline was shot down by the Soviet Union. The reason was that the plane (flight 007) had gone lost over Soviet territory. Following the incidence, the United State President, Reagan, offered to open the GPS service (free of charge) for civilian aircraft use. This marked the beginning of the spread of GPS from military dedicated use to civilian global use.
Another setback for the GPS program was the accident of the space shuttle ‘Challenger’ in 1986. The Challenger was planned to be the launching vehicle for the second generation GPS satellites (Block II). Due to the shuttle loss, the satellites launching schedule was delayed two years. The replacements for the shuttle were the Delta II rockets, which were intended for transportation in the first place (See picture 1.4).

Picture 1.4 - Delta Rocket Launches

In February 1989 the first Block II satellite was launched. It became operational a few months later. Up to October 1990, nine satellites of block II were launched to space. Block II satellites were designed to provide 14 days of operation without contact from the control Segment. They also had automatic detection of certain error conditions and anti spoofing capabilities. Selective Availability (SA) was another feature which was introduced in these satellites. SA was a technique implemented by the DoD to
intentionally degrade the information that arrive from the satellites. SA was used to protect the security interests of the U.S. and its allies by globally denying the full accuracy of the civil system to potential adversaries. Block IIA (the ‘A’ stands for ‘advanced’). See picture 1.5) satellite had major improvement: it can operate up to 180 days without contact from the control segment. An additional improvement in the second generation satellites was the accuracy of the clocks the satellites used. Accuracy is a necessary requirement for the GPS system. The location calculation is time based and it is mandatory for the satellites clocks to be accurate and not to go out of synchronization very often (See section 2 in this chapter - ‘How does GPS work?’). Block II and Block IIA satellites are equipped with two rubidium and two cesium atomic clocks with a clock stability of at least $10^{-13}$ seconds. The design lifetime of the Block II/IIA satellite is 7.3 years. The Block IIAs satellites were launched from November 1990 through November 1997.

The Block IIR (the ‘R’ stands for ‘Replenishment’) model was the satellite’s generation that followed the Block IIA satellites. They can work 180 days without contacting the control segment. But unlike the Block II, they maintain full accuracy during that time using a technique of ranging and communication between the other Block IIR satellites.

The next generation, Block IIF satellite, is planned to provide a second frequency for civil use, allowing position determinations with even higher precision. These Block IIF satellites will be equipped with hydrogen maser clocks instead of atomic clocks due to their even higher precision. However these satellites will only be available some time after 2005. Block II satellites have a couple of further features which are not related to
the GPS system. For example they are equipped with sensors capable of detecting atomic explosions\(^4\).

For more information about the launches of Block II/IIA/IIR satellites see Appendix A. Appendix B contains additional information about currently activated satellites.

**Picture 1.5 - Block IIA satellite\(^9\)**

1.1.3. Activation of the GPS system

The SA (selective availability) of the satellites was deactivated during the Gulf War (1990-1991). The purpose of it was to allow all the allied forces to use the GPS technology. It was the first time that the GPS was used under combat conditions. The GPS usage during the war was successful and proved to be operational. At the end of the war (July 1991), the SA was activated again.
In September 1991 the United States offered to make the GPS available to international and civil usage as soon as the system becomes operational. The offer promised free of charge usage of the GPS system for at least 10 years. The following year, the United States extended the offer for the foreseeable future and also pledged to provide at least six years notice prior to termination of GPS operations or elimination of the GPS SPS (Standard Positioning Service).

On December 8, 1993 the Initial Operational Capability (IOC) of the GPS system was announced. The system was no longer considered as under development and was capable of providing location with 100 meters accuracy.

On July 17, 1995 Full Operational Capability (FOC) was announced by the Air Force. Full Operational Capability status means that the system meets all the requirements specified in a variety of formal performance and requirements documents.

On May 1, 2000 the use of SA (Selective Availability) was discontinued by the order of the President of the United States. The immediate result was a major improvement in the GPS receivers’ accuracy - from 100 meters to around 20 meters.

The GPS management from the beginning has been under the responsibility of the DoD. A join task force to the DoD and the DoT (Department of Transportation) was established in 1993 due to the future increase in civil use of the GPS. One of the JTF recommendations was to have civil participation in managing and developing the GPS system. This was the starting point of making the GPS a more civil oriented system.
In September 2005, President Bush updated the nation’s Global Positioning System policy. The new policy gives the DoT authority equal to that of the DoD on the committee that manages GPS technology and spectrum. The change in governance reflects the fact that GPS is now used in more civilian applications than military ones\textsuperscript{11}. The revisions in the policy update military and homeland security roles for GPS and designate it as a component of the critical infrastructure.

1.2. How does GPS work?

The GPS receiver uses the signals from the satellites in order to calculate its location. It measures the distance from the satellites using the travel time of their radio signals. To measure the travel time, the GPS system needs timing synchronization. Knowing the distance from the satellites is not enough, the receiver also needs to know exactly where the satellites are in space.

1.2.1. Satellite orbits

The GPS satellites network design requires twenty four satellites in order to achieve a complete coverage all over the world. Currently there are twenty eight functioning GPS satellites in the sky (See Appendix B). Twenty four of them are the primary satellites, which are used for location calculation. The rest serve as backups.
The GPS satellites orbit the earth over a period of 12 hours (speed of 800 meters per second). The height of the satellites is around 20,200 km from earth (10,900 nautical-miles). The satellites orbit the earth at a speed of 3.9 km per second and have a circulation time of 12 h sidereal time, corresponding to 11 h 58 min earth time. This means that the same satellite reaches a certain position about 4 minutes earlier each day. The satellites are arranged in six planes. Each plane has four slots so four satellites can be arranged equidistantly within it. The arrangement guarantees that the signals of at least four satellites can be received at any time all over the world. The planes have a 55 degree inclination angle towards the equator. Figure 1.1 shows the orbits of the GPS satellites.

**Figure 1.1 - Orbits of the GPS satellites**

1.2.2. Trilateration

The GPS system is based on the trilateration concept. The trilateration concept states that in order to know your exact location you need to have at least three references i.e. places
that you know their exact locations. The intersection of the distances from the references
to you is your location. The GPS system uses destinations from satellites as the distances.
Similar concept is triangulation. Triangulation uses angle measurements, together with at
least one known distance, to calculate the subject’s location. Occasionally people tend to
confuse between the two concepts. However, trilateration is the concept the GPS system
is based on.

An example of two dimensional trilateration (which gives a two dimensional location)
can be: The given data is that your location is 238 miles from Cleveland, OH, 339 miles
from Boston, MA, and 250 miles from New York, NY. Given the fact that you know the
exact locations of those cities, your location is Rochester, NY. Figure 1.2 schematically
shows the distances intersection.

Figure 1.2 - Schematic illustration of distances intersection
The GPS receiver calculates a three-dimensional location (latitude, longitude, and altitude). The calculated distance between the GPS receiver and a satellite is the radius of a sphere that the satellite is its center. Calculating the current location is done by figuring out where the spheres intersect. Getting location information from three satellites leads to two points in space where the spheres intersect (See figure 1.3). In order to decide which one is the true location, a fourth measurement should be made. Usually one of the points is too far from earth and therefore can be eliminated.

Figure 1.3 - Three spheres intersection\textsuperscript{13}

A fourth measurement is still necessary due to the nature of the spheres intersection - Ideally, these spheres would intersect at exactly one point, causing there to be only one possible solution to the current location, but in reality, the intersection forms more of an oddly-shaped area. The GPS receiver could be located within any point in the area, forcing receivers to choose from many possibilities\textsuperscript{14}. Figure 1.4 shows the area that can be created from three satellites. The calculated location in the figure can be any point in the grey-colored area. More information about the GPS accuracy can be found in section 2.6.3.
1.2.3. Measuring distance from a satellite

In order to calculate the distance of a GPS receiver from a satellite, we use the simple equation: Velocity x Time = Distance. As mentioned before, the satellites broadcast signals that can be received and analyzed by the GPS receivers. The velocity of an electromagnetic ray in space is the speed of light (approximately 299,792.5 kilometers per second/186,200,000 miles per second). Hence, the missing parameter for the distance calculation is the time it takes the signal to travel from the satellite to the receiver.

The travel time measurement is achieved by timing the signal. It works in the following way: the satellite begins transmitting a digital pattern (Pseudo Random Code – see section 1.2.3.1) at a particular time. At the same exact time the receiver begins running an identical digital code. When the signal arrives to the receiver, its pattern will lag behind the receiver’s pattern. This delay is the time it takes the signal to travel.
1.2.3.1. Pseudo Random Code (PRC)

The pseudo random codes (often called ‘pseudo random noise’ (PRN) or ‘pseudo noise’ (PN)) are the signals the satellites send. Each satellite has a different PRC so the GPS receiver can differentiate between them. It means that each satellite is defined by its code. The selected codes that are sent from the satellites are ‘Gold codes’. Gold codes have the characteristic of a weak cross correlation among each other. The GPS receiver can then have low interference when it tries to correlate with one of the satellites signals. The gold codes also guarantee that the receiver won't accidentally pick up another satellite's signal. Hence all the satellites can use the same frequency without jamming each other. The gold codes make it more difficult for a hostile force to jam the GPS system. In fact the Pseudo Random Code gives the DoD a way to control access to the system\(^{15}\).

There are 32 PRCs in the GPS system. The GPS receiver has all the satellites’ PRCs in its memory so it can search for signals from all of them.

1.2.3.2. C/A and P-Code

Two different codes are sent from the GPS satellites, C/A (coarse acquisition) code and P code (The ‘P’ stands for ‘precise’). The C/A code is used for civil GPS receivers. The P code is for military use. Information about the C/A code generation can be found in Appendix C.
The C/A code is a 1023 “chip” long code, being transmitted with a frequency of 1.023 MHz. A “chip” is the same as a “bit”, and is described by the numbers “one” or “zero”. The name “chip” is used instead of “bit” because no information is carried by the signal. 1023 chip long code with a frequency of 1.023MHz means that every 1msec the PRC is repeated (1023/1.023M = 1msec) and that 1,023,000 chips are generated in a second from the satellite. If we divide the number of chips per second by the velocity (speed of light) we can see that the length of one chip can be calculated as 300 meters.

The timing measurement is done according to the delay of the pseudo random code from the satellite. The delay is measured with how many chips are needed to be shifted in the receiver’s code in order to correlate with the satellite’s code. Since one chip is equal to 300 meters, we can get distance accuracy of 300 meters. This is not a good accuracy. The GPS receiver is much more precise. Modern GPS receivers are capable of calculating the signal shift as precise as 1 % of one chip. Therefore the distance to the satellite can be calculated with a precision of 3 m. Additional information on runtime measurements can be found in section 1.2.3.3.

Designed for military users, the P-code is a week-long pseudorandom number (PRN) sequence, approximately $6 \times 10^{12}$ bits long, with a bandwidth of 10.23 MHz. The long length of the code makes it hard to acquire and difficult to spoof. The P-code is more accurate than the civilian code and is more difficult to jam because of its wider bandwidth. To ensure that unauthorized users do not acquire the P-code, the United States can implement an encryption segment on the P-code called anti-spoofing (AS).
The P-code with AS, designated as the ‘Y-code’, is available only for users with the correct deciphering chips\textsuperscript{18}.

1.2.3.3. Runtime measurement of the satellites’ signals

As previously mentioned, each satellite transmits PRC that is known to the GPS receiver. The algorithm that is used to calculate the difference between the satellite’s PRC to the receiver’s PRC is cross correlation. In signal processing, the cross-correlation (or sometimes "cross-covariance") is a measure of similarity of two signals, commonly used to find features in an unknown signal by comparing it to a known one. It is a function of the relative time between the signals. For discrete functions $f_i$ and $g_i$ the cross-correlation is defined as

\[(f \ast g)_i \equiv \sum_j f^*_j \, g_{i+j}\]

The sum is over the appropriate values of the integer $j$ and an asterisk indicates the complex conjugate\textsuperscript{19}.

Figure 1.5 demonstrates cross correlation: The two signals in the two upper rows are multiplied with each other. The lowest row is the result of the multiplication. The sum of the signal in the result row, is the cross correlation of the two signals. The green pulse represents the beginning of the signal. If we shift the upper row three chips to the left, the cross correlation result will be 25.
There is a clear maximum value when the two signals are correlated. This is how the GPS receiver knows that the timing measurement is done and that the number of ‘shifts’ that were made until then is the number of chips that indicates the time.

1.2.3.4. Data transmission from the satellites

The data from the satellites is modulated onto a carrier signal before it transmitted. The carrier frequency has some constrains:

- Frequencies above 2 GHz require beam antennae for signal reception.
- For frequency ranges below 100 MHz and above 10 GHz, there are large Ionospheric delays.
- The speed of propagation of electromagnetic waves with low frequencies in media like air deviates from the speed of light (in vacuum). For low frequencies the runtime measurement is falsified\(^\text{16}\).
- The PRCs require a high bandwidth. The C/A signal, for example, requires a 20 MHz bandwidth.
- The signal propagation should not be influenced by difficult weather conditions.
The chosen frequencies, one for C/A code and the other for P-code, are marked as L1 and L2. The L1 band transmits both the C/A and P-codes at a frequency of 1575.42 MHz; the L2 band transmits the P-code only at a frequency of 1227.6 MHz\(^{18}\). The signals are modulated using the binary phase shift keying (BPSK) modulation scheme.

Figure 1.6 shows the composition of signals that are transmitted from the satellites. Explanation about the ‘navigation system data’ channel can be found in section 1.2.5.2. The ‘Modulo 2 Sum’ is equivalent to the XOR Boolean operation (0+0=0; 0+1=1; 1+0=1; 1+1=0).

Figure 1.6 - Composition of signals from GPS satellites\(^{16}\)
1.2.4. Timing synchronization

Timing synchronization is a crucial point in the GPS system. The system is based on measuring the travel time of a radio signal. Therefore, the satellites’ clock and the receiver’s clock must be synchronized.

Satellites use atomic clocks for timing. Atomic clocks are very precise clocks that consider keeping time better than any other clock. Each satellite has four atomic clocks. The clocks types that are in use are Cesium and Rubidium. Atomic clocks are very expensive ($50K to $100K). That fact excludes them from being integrated into the GPS receivers. This would make the receiver non-affordable technology for the average customer.

Standard quartz clocks are used for timing on the GPS receivers. The way to keep the receiver’s clock synchronized with the satellites’ clock is to constantly reset it according to timing measurements from the satellites. For this operation, the receiver must get pseudo random codes from at least four satellites.

The receiver uses the measurement from the fourth satellite in order to find the ‘correct time’. The four (or more) location measurements from the satellites can intersect only at one point. The times that are used in order to calculate the point are based on one ‘current time’. This time value is the one the satellites use. The receiver resets itself to this time. The result of this ongoing procedure is that the GPS receiver presents atomic clock accuracy. For more details of how the synchronization procedure works see Appendix D.
1.2.5. Satellite positions

Due to the time synchronization, the GPS receiver can calculate its exact distance from the satellites it receives signals from. But in order to use the distances for trilateration, the receiver must know exactly where the satellites are.

Figure 1.7 - Position of the monitor stations

1.2.5.1. Control Segment

The Department of Defense stations on earth, which monitor the GPS satellites 24 hours a day, are called the control segment. The five stations (See figure 1.7 for their locations in the world) check the satellite’s position, speed, and altitude. Errors can also be detected in the satellites’ orbits. These errors are caused by gravitational pulls from the moon and sun and by the pressure of solar radiation on the satellites. On the control segment, the real satellite location is measured and then transmitted to the satellite. The
information is also called ‘ephemeris’. The data transmission, which includes other information than the ephemeris, occurs once or twice a day.

1.2.5.2. System data

In order for the GPS receiver to know exactly where the satellites are, the information that is sent from the control segment, must find its way to it. This is done by the system data signal.

A 50 Hz signal, which contains satellite status, clock correction, satellite orbits, and additional information, is constantly transmitted from each satellite. From this data stream the GPS receiver gets mandatory parameters like date, time, and of course the satellite’s position.

The transmission rate of the signal is 50 bits per second. The complete data signal consists of 37,500 bits which means it takes 12.5 minutes to get the complete signal. The signal is divided into 25 frames of 1500 bit (interval of 30 seconds for transmission). Each frame has 5 sub frames, 300 bits each: clock correction data information (sub frame 1), ephemeris data (sub frames 2 and 3), and support data (sub frames 4 and 5). Figure 1.8 shows the frame structure.

1.2.5.2.1. Clock Correction

The GPS receiver works according to GPS reference time. The satellites’ clocks are not synchronized with that time. In order to know the exact time the PRC was transmitted in GPS reference time, the receiver uses time parameters that are sent in the clock correction
field. The receiver corrects the time received from the satellite with the equation (in seconds)
\[ t = t_{sv} - (\Delta t_{sv})_{L1} \]
where
\[ t = \text{GPS system time (seconds)}, \]
\[ t_{sv} = \text{effective SV PRN code phase time at message transmission time (seconds)}, \]
\[ (\Delta t_{sv})_{L1} = \text{SV PRN code phase time offset (seconds)}^{22}. \]

SV stands for ‘Space Vehicle’, which is a common alias for the GPS satellite.

1.2.5.2.2. Ephemeris data

From the ephemeris parameters on sub frame 2 and 3, the GPS receiver can calculate the current position of the satellite from which it obtained the data signal. The ephemeris data also gives detailed instructions on where the satellite will be in the next few hours. Therefore, a set of ephemeris data is valid for several hours.

1.2.5.2.3. Almanac data

Almanac data is part of the support data sub frames. The almanac is a subset of the clock and ephemeris data, with reduced precision\textsuperscript{22}. Unlike the ephemeris sub frame, which includes information only from the sending satellite, the almanac includes information on every satellite in the GPS constellation. It allows the GPS receiver to view which satellites are available for it. The GPS receiver can then correlates with the signals from the available satellites and calculate its position. This part is crucial when there is a need
for a quick fix in location after the receiver is turned on. Appendix E explains more about the almanac parameters.

Figure 1.8 - Structure of one data frame

1.2.6. Errors in the GPS system

In the GPS system, the most vulnerable component to errors is the signal that is transmitted from the satellites. It is the GPS receiver’s task to take into account the possible errors the signal carries.
1.2.6.1. Signal’s velocity

When calculating the distance from the satellite, the velocity of the signal was estimated
to be the speed of light. But the speed of light is constant only in a vacuum. On the way
from space to earth, there are some atmospheres that cause propagation delays to the
signal. In other words, the signal’s velocity is different than the speed of light while it
crosses those atmospheres. The ionosphere is the layer of the atmosphere ranging in
altitude from 50 to 500 km. It consists largely of ionized particles which can exert a
perturbing effect on GPS signals. While much of the error induced by the ionosphere can
be removed through mathematical modeling, it is still one of the most significant error
sources\(^\text{23}\). The troposphere layer, which is closer to earth, also has an influence on the
signal propagation.

One way to minimize the errors is to predict the atmospheric delay of the GPS signal.
This approach is called ‘modeling’. A different approach is the ‘dual frequency’ that by
comparing the two carriers from the satellite (L1 and L2) the atmosphere influence can be
calculated.

1.2.6.2. Multipath error

Multipath error occurs when the antenna receives the same signal in two or more paths.
The error is caused when the signal is reflected from terrestrial objects, such as
mountains and buildings. The GPS receiver should ignore the other signals that are not
the direct signal it already received.
1.2.6.3. GDOP

GDOP, Geometric Dilution of Precision, happens when the satellites’ distance circles (see figure 1.2), which define the receiver’s position, cross each other at a very shallow angle. It occurs when the GPS receiver chooses satellites that are close to one another. That increases the error margin around a position. If it picks satellites that are widely separated the circles intersect at almost right angles and that minimizes the error region. It is up to the GPS receiver to pick the satellites that will cause the lowest GDOP.

1.2.6.4. Doppler shift

Doppler shift is defined as the change in frequency of a wave caused by movement of the source relative to the observer. The frequency increases when the source and observer approach each other and decreases when they move apart. The source’s motion causes a real shift in frequency of the wave. The observer’s motion results in only a small shift in the frequency. Due to the constant movement of the satellites, the GPS signals arrive at the GPS receiver with a different frequency/wavelength than the one they had when they were transmitted. It requires the GPS receiver to search for the signal in different frequencies than the carrier frequency. The frequency shift that the Doppler Effect creates can be calculated. Taking into consideration the satellites’ velocity and the earth movement, results in a range of frequency shift of ±4200 Hz. The maximum Doppler shift is considered to be 5 KHz.
Figure 1.9 shows an example of Doppler shift calculation. The equation is as follow: If the moving source is emitting waves through a medium with an actual frequency $f_0$, then an observer stationary relative to the medium detects waves with a frequency $f$ given by:

$$f = f_0 \left( \frac{\nu}{\nu + v_{s,r}} \right)$$

Where $\nu$ is the speed of the waves in the medium and $v_{s,r}$ is the speed of the source with respect to the medium (negative if moving towards the observer, positive if moving away), radial to the observer.$^{25}$

Figure 1.9 - Example for Doppler shift calculation$^{26}$
1.2.7. User segment

The user segment in the GPS system is the GPS receiver. Figure 1.10 presents a block diagram of the multi-channel GPS receiver. The received signals are filtered, pre-amplified and converted from analog to digital. Samples are then addressed to the digital signal processor (DSP) section, which contains N parallel channels to simultaneously track carriers and codes from N satellites. Each channel includes code and carrier tracking loops to perform code and carrier phase measurements and demodulation of the navigation message data.\(^{27}\)

The code tracking loop measures the delay between the arriving PRC to the locally generated PRC. In each channel in the DSP, the generated PRC, which related to a selected satellite from the constellation, tries to lock on the correlation peak with the arriving signal (See section 1.2.3.3). Thanks to the properties of the code sequences (C/A code), the signals coming from satellites other than the one under consideration can be discarded.\(^ {27} \) The loop sometimes uses a delay-lock loop (DLL) which delays the signal until the two PRC codes are aligned. If the time result is multiplied by the speed of light we will get the distance measurement, called pseudorange. However, the distance result will be not accurate since it doesn’t take into account the propagation delays of the signal and the clock synchronization between the satellite and the receiver.

The Carrier tracking loop uses phase-lock loop (PLL) in order to match the phases of the locally and the received carriers. The phase changes are due to the Doppler shift. Once
the oscillator locks onto the satellite signal, it will continue to follow the variations in the phase of the carrier as the range to the satellite changes\(^{18}\). The pseudo-delta-range measurement is based on integrated carrier-phase measurements. It is an addition range to the pseudorange which could not be detected from the PRCs, but from the phase correction. The pseudorange, pseudo-delta-range, integrated Doppler (the measurement of Doppler shift frequency of phase over time), together with the demodulated navigation message, are sent to the navigation/receiver processor.

It can be concluded that there is a search over the possible code-delays and frequencies in order to acquire the GPS signal for a specific channel.

Figure 1.10 - General Block diagram of the GPS receiver\(^{27}\)
1.2.8. Differential GPS

Differential GPS (DGPS) was designed in order to improve the accuracy the GPS receiver provides. The inaccuracy factors the DGPS deals with are the timing delays caused by the atmospheres layers, multipath, and satellite and receiver clocks. It does it through a nearby reference receiver that measures the timing error of all the satellites in range and broadcasts the information to all the DGPS receivers in the area.

The DGPS relies on the fact that a satellite’s signal has the same timing delay for the reference receiver and for all the other DGPS receivers that are a few hundreds miles away. The reason for it is that the area is very small in relation to the travel distance of the satellite’s signal. Therefore the timing delays are the same within that area.

The reference receiver calculates the timing delay by using ‘backwards’ calculation, i.e. it uses its known position in order to calculate the timing delays. Since it knows its location, it knows what the travel time of the signals should be. The timing error is the difference between the arrived timing to what it should be.

The reference receiver broadcasts the message in a known frequency. The DGPS receivers receive the message and handle the timing delay of the received GPS signals. The only problem with the DGPS concept is that the reference receiver can work only for each specific area and there need to be multiple reference receivers in order to cover a large area.
References – chapter 1


Chapter 2 – Wireless Enhanced 911
The emergency phone number in the U.S. is 9-1-1. The Basic 911 phone system routes all the 9-1-1 calls to a Public Safety Answering Point (‘PSAP’). PSAP is a facility that is staffed and equipped to receive 9-1-1 calls. The Enhanced 911 (‘E911’) phone system provides improved service to the 9-1-1 callers. When a person dials 9-1-1 from a landline phone it guarantees the following: 1. the location of the caller will be transferred to the PSAP; 2. the call will be routed to the relevant PSAP. It means that the PSAP, which has responsibility for the area that the phone call comes from, will receive the call.

In the early nineties, when the usage of cellular devices increased, there was a concern regarding wireless 9-1-1 calls. Unlike landline calls, which come from a set phone that its location is known to the system, there is a problem to provide the caller’s location when it comes from a cellular device. The wireless Enhanced 911 rules seek to apply the E911 actions to a 9-1-1 call that comes from a cellular device.

2.1. Regulation history of the Wireless E911

On June 12, 1996 the Federal Communications Commission (FCC) adopted a Report and Order that creates rules to govern the availability of basic 911 services and the implementation of Enhanced 911 (E911) for wireless services. According to the rules, the deployment of the E911 for wireless calls was divided into two phases. Phase I required the wireless carriers to provide the PSAPs the location of the cell site that the call was routed from, i.e. the cell the user that made the 9-1-1 call is physically in (See section 2.3.1 for more information about ‘cellular cell’). It also required a call back
number. Phase II states that the location of the mobile station must be provided to the PSAP in two dimensions (latitude and longitude), with accuracy within a radius of 125 meters in 67 percent of all cases.\footnote{1}

Phase I was scheduled to begin on April 1\textsuperscript{st}, 1998. Beginning at that date, PSAPs could request from the wireless carriers to be compatible with the rules. Phase II was scheduled to begin on October 1\textsuperscript{st}, 2001.

The deployment schedule and the accuracy demands were changed by the commission on October 6, 1999, when it published the ‘third report and order’. One of the reasons for the changes was the development of handset-based location technology. Handset-based solution means that the handset takes the measurements that are used for the location calculation. On a network-based solution the measurements and the location calculation are done by the network (more information about location solutions can be found in section 2.3).

The new accuracy demands determined to be: For network-based solutions: 100 meters for 67 percent of calls, 300 meters for 95 percent of calls; for handset-based solutions: 50 meters for 67 percent of calls, 150 meters for 95 percent of calls.\footnote{2}

The new schedule was divided into two:

- For handset-based solution - once a PSAP request is received for a Phase II implementation, within six months of the request or by October 1, 2001, whichever is later,
• The wireless operator needs to ensure that 100 percent of all new mobile stations activated are ALI-capable.

• The wireless operator needs to implement any necessary network upgrades to ensure proper operation.

• The wireless operator needs to begin delivering to the PSAP the location information that satisfies the Phase II requirements.

Within two years of the request or by December 31, 2004, whichever is later, the wireless operator needs to strive for 100 percent penetration of ALI-capable mobile stations in its total subscriber base. The term ‘ALI-capable’ refers to the mobile station ability to send the latitude and longitude location information to the PSAP.

• For network-based solution – the FCC replaced its previous plan, which required that implementation be fully accomplished within 6 months of a PSAP request, with a revised rule requiring the carrier to deploy Phase II to 50 percent of callers within 6 months of a PSAP request and to 100 percent of callers within 18 months of such a request.

The commission also directed the wireless carriers to report their plans for implementing E911 Phase II, including the technology they plan to use to provide caller location, by October 1, 2000.

In September 2000, the FCC made some adjustments to the rules. Two of them were regarding the handset penetration: The first was to extend from December 31, 2004, to
December 31, 2005, the date for carriers to reach full penetration of ALI-capable handsets in their total subscriber bases. The second was to modify the operational definition of full penetration from "reasonable efforts" to achieve 100 percent penetration of ALI-capable handsets to a requirement that 95 percent of all handsets in a carrier's total subscriber base be ALI-capable⁴.

On July 2002, the FCC reluctantly granted non-nationwide Tier II (mid-sized regional carriers) and Tier III (small carriers) temporary, limited relief from the Phase II implementation deadlines⁵. For the six nation wide carriers - AT&T Wireless, Cingular Wireless, Nextel Communications, Sprint PCS, Verizon Wireless, and VoiceStream Communications (called ‘T-mobile’ today) – the requirements stayed the same.

The E911 rules had more revisions over the years. Most of them were regarding Tier II and III carriers. The main requirements stayed the same for the Tier I carriers.

One major addition to the E911 rules is the E911 requirement for IP-Enabled service providers. The commission published an order on June 3rd, 2005 stating that it adopts rules requiring providers of interconnected voice over Internet Protocol (VoIP) service to supply enhanced 911 capabilities to their customers⁶.

2.2. Technical description of the 911/E911 systems
The following section discusses the wireline and wireless E911 network configuration. It shows how the 9-1-1 call is routed to the right PSAP and how the PSAP receives the location information of the call.

2.2.1. Wireline E911

Wireline 911 system simply routes the 9-1-1 calls to a PSAP. The system has two major limitations that were mentioned earlier: 1. the origin of the call is unknown; 2. the call is not necessarily routes to the PSAP that served the geographic location of the caller. The limitations make the 911 system inefficient and problematic: the operator cannot call back the caller in case the 9-1-1 call was disconnected, valuable time is wasted on collecting the caller’s location and identification, the call can be routed to the wrong PSAP and it would take time for the appropriate forces to get details about the call. The Wireline E911 system resolves the two limitations.

ANI (Automatic Number Identification) is a feature that identifies the telephone number of the caller. The feature was introduced for billing purposes so that long distance calls can be properly billed. The caller phone number is transferred through the signaling network. ALI (Automatic Location Identification) is a database that contains a subscriber’s name, address, and telephone number. In case the system has the caller’s telephone number, this database can provide the address and name that is associated with it. The ANI and ALI are utilized by the E911 system. The equipment at the PSAP – known as Customer Premises Equipment or “CPE” – is connected to the ALI database
over a separate data circuit\textsuperscript{7}. When the E911 call is received at the PSAP, it uses the calling number to send a query to the ALI. The ALI then returns the caller’s name and address.

The Selective Routing is the functionality in the E911 system that routes the 9-1-1 calls to the proper PSAP. The E911 Control Office is a tandem switch that is in charge of this functionality (often called ‘Selective Router’). The 9-1-1 call is routed to the E911 Control Office from the Central Office. The E911 CO then uses the ANI information to find the street address that associate with the phone number. For that action, the Selective Router uses its own database. According to the address, the call is routed to the proper PSAP.

The following is a description of the 9-1-1 call flow in a wireline E911 system: a 9-1-1 call is placed from a wireline telephone and sent to the local central office that serves that specific telephone. The central office recognizes the call as 9-1-1 and forwards the call to a specialized switch, referred to as a selective router. The selective router routes both the voice and the caller’s telephone number (ANI) to the appropriate PSAP. The PSAP’s Customer Premise Equipment (CPE) uses the ANI to retrieve the caller’s Automatic Location Information (ALI) by querying the ALI database\textsuperscript{8}. Figure 2.1 shows the described call flow.
2.2.2. Wireless E911 – phase I

The MSC (Mobile Switching Center) is the component in the wireless system that routes the calls to and from the base stations. It bridges between the cellular network and other networks (PSTN, internet, etc). So when there is a 9-1-1 call from a cellular device, it is routed from the base station to the MSC.

In the NCAS* solution, the MSC has dedicated pseudo telephone numbers (also called Emergency Service Routing Key (ESRK)) per each cell. When a MSC receives a 9-1-1 call, a processor associated with the switch knows the cell site/sector where the call is

* There are several phase I solutions which are implemented today: Call-path Associated Signaling (CAS), Non-Call-path Associated Signaling (NCAS), and Hybrid-CAS (HCAS). The NCAS uses separate data path between the MPC and the ALI
coming from and selects an unused pseudo telephone number from the set associated with the cell site/sector\(^7\). In some networks, the processor that picks the ESRK can be the MPC (Mobile positioning Center). The processor (or MPC) is also in charge of ‘pushing’ the ESRK, callback number, and location information to the ALI database. The ‘pushing’ is done through a separate data link. The call is forwarded from the MSC to the Selective Router with the pseudo telephone number. The Selective Router Data Base contains information that associates the pseudo telephone number (and its associated cell site/sector) with a particular PSAP\(^7\). It finds the proper PSAP the call should be routed to and forwards the call with the pseudo telephone number. The PASP queries the ALI with the pseudo telephone number and gets the call back number and the cell site that is associated with it. Figure 2.2 displays the call and information routing.

Figure 2.2 - 9-1-1 call flow in wireless E911 Phase I system (NCAS Solution)\(^8\)
2.2.3. Wireless E911 – phase II

The flow of the 9-1-1 call in phase II is similar to the one in phase I, but because the required location information is different (longitude and latitude) it becomes more complicated to send it to the PSAP’s ALI. First, it may take more time to make the necessary computations to locate the wireless caller than it does to transmit the voice data to the PSAP. Second, the amount of information transmitted is greater. Finally, the information may need to be refreshed one or more times to improve accuracy or to maintain a continuous location on a moving caller (such as when the call is made from a car).

Phase II implementation requires two additional components in the wireless network – PDE and CRDB. The PDE (Position Determination Equipment) determines the location of a wireless handset. As mentioned in section 2.1, there are two types of PDE technologies - handset based and network based. The CRDB (Coordinate Routing Data Base) receives the handset location from the MPC and returns the information necessary to forward the call to the proper E911 Control Office.

The call flow (NCAS solution) uses the ESRK as an identifier for the call (similar to phase I solution). The MPC sends the ESRK to the MSC, which sends it to the Selective Router. Based on the ESRK, the SR forwards the call to the appropriate PSAP. The PSAP then queries the ALI with the ESRK. The ALI queries the MPC for location. The MPC, which gets the location information from the PDE, sends the caller’s latitude and longitude to the ALI. The ALI forwards the information to the PSAP. The location

* The NCAS description is for illustration purposes. There are other phase 2 solutions which are implemented today.
information of the caller can be refreshed during the call. The data link between the MPC to the ALI, which is TCP/IP based, is used for this purpose. Figure 2.3 presents the call and information routing in wireless E911 phase II system.

Figure 2.3 - 9-1-1 call flow in a wireless E911 Phase II system (NCAS Solution)

2.3. Location solutions for E911 phases

2.3.1. Phase I location solution

Wireless E911 Phase I required the wireless carriers to provide the cell site/sector location that the 9-1-1 call was made from.
When a call is made from a cell phone (sometimes referred to as UE (User Equipment) or MS (Mobile Station)), it communicates over wireless channels with a base station. The base station is the cellular network component that is in charge of receiving the cell phone signals and routes the calls to and from it. The area the base station is in charge of in terms of network reception is called ‘cell’. The cellular network is built in a way that if a cell phone is active, the network knows what base station is ‘in charge’ of it. It makes the cellular carrier job very easy since the location information they are required to provide is already known and available.

In phase I, there is a well known accuracy issue: the cell size is large (typically 2km to 20 km diameter) and there is no indication of exactly where the 9-1-1 caller is, in the cell. In urban areas with a dense network of smaller cells the positioning is generally more accurate than in rural areas where there are fewer base stations and the cells are large\textsuperscript{10}. Some cells are divided into areas called ‘sectors’. Information about the caller’s sector location gives better indication about the caller’s location but still provides an area and not exact location. The sector information can be transferred to the PSAP.

2.3.2. Phase II location solutions

Phase II location requirements forced the wireless carriers to come up with new technological solutions and integrate them into their network and/or their cellular devices. There are two approaches for phase II solution: network-based solution and handset-based solution.
Network-based location solutions use location equipment within the network to determine the location. Methods that use the network to provide location are TDOA (Time Difference of Arrival), AOA (Angle of Arrival), TOA (Time of arrival), and Multipath Analysis. More about the network based location solutions can be found in section 2.3.3.

Handset-based location solutions use technology within the mobile handset to determine the location. Usually, the solutions require network modification as well. Methods that use the handset in order to provide location are A-GPS (Assisted GPS), AFLT (Advanced Forward Link Trilateration), OTDOA (Observed Time Difference of Arrival), and E-OTD (Enhanced Observed Time Difference). More about the network based location solutions can be found in section 2.3.4.

Within the handset-based solutions there is also the hybrid approach. The approach suggests combining the A-GPS method with another handset/network-based solution. The motivation behind this approach is that each solution will compensate the other. More information about hybrid solutions can be found on section 2.3.4.4.

2.3.3. Network-based solutions

In networked-based solutions the signals measurements and the location calculation are done by the network.

The cellular device is capable of sending and receiving signals to and from other base stations that are not ‘in charge’ of it. While it has primary connection to the cell’s base station, there are secondary connections from base stations that are in charge of the cells
nearby. The cellular network uses those communication channels to get information from nearby cells. With this information it calculates the cell phone location. There are few methods of how to calculate location using information from nearby base stations.

One, which is not very common, is Time of Arrival (TOA). In this method, the base stations calculate the arrival time of the signal from the cell phone and pass it to the network location server. The server needs at least three measurements in order to determine the exact location (according to the trilateration concept). It means that three base stations would need to be involved in the process and send the time measurement of the cell phone.

A more common method is Angle of Arrival (AOA). With this method the server requires only two measurements. The base stations measure the angle (or direction) of the received signal from the cell-phone. The location server analyzes the measurements and calculates the location.

2.3.3.1. U-TDOA

The network-based solution that some of the Tier I carriers decided to integrate into their networks as phase II solution is U-TDOA (Uplink Time Difference of Arrival). The solution can be integrated into all types of cellular networks - GSM, GPRS, CDMA, and UMTS networks. The ‘Uplink’ is in order to differentiate the method from a handset-
based method, which called OTDOA (Observed Time Difference of Arrival). The OTDOA uses the same measurement and calculation concepts but does it on the handset.

The U-TDOA method compares and calculates the difference in time required for a mobile's signal to reach different BTS (base stations) sites\textsuperscript{11}. The mobile device transmits a signal that is received by different base stations. Since the mobile's signal travels at a constant speed (the speed of light), when the arrival time of the signal is compared for any two sites (for example, site A received the signal at time X, site B received at time Y, the difference being $|X - Y|$), it is a straightforward calculation to determine the mobile's relative position to each site. When plotted, this relationship describes an imaginary hyperbola (a broad curve) in space. The mobile is located somewhere on this curve, although additional information is required to determine precisely where. When the same calculation is made involving measurements from a third base station site, calculating the difference of arrival times between either sites A and C or between sites B and C, an independent, positional hyperbola can be described. The point at which the two hyperbolas (A-B and B-C) intersect is the location of the target mobile\textsuperscript{12}.

The network component that measures the signal and transfers the measurement to the location server is LMU (Location Measurement Unit). The LMU is usually placed in the base station. The LMUs must be synchronized with each other. Otherwise comparing the measurements would lead to a wrong location calculation.
As mentioned above, the location server needs measurements from at least 3 LMUs in order to calculate location in two dimensions. See Appendix F for more information about the U-TDOA method.

2.3.3.2. Network-based solution - Pros and cons

The approach of network-based solution is sometimes inaccurate and inefficient. The major reason for this is the limitation of having at least two (or three) connections to base stations in order to get the location of the handset. In urban areas the cells’ sizes are small and usually the handset will be able to connect to nearby base stations. However, in rural areas the cells’ areas are usually large and it is sometimes impossible to connect to nearby base stations. The network won’t be able to provide the cell phone location. The network-based solutions also face a number of difficulties other than base station availability like multipath propagation and diffraction of signals, weak signal conditions, and expensive upgrades. Propagation delay of the signal leads to false calculation of the position in U-TDOA method. Diffraction of signals can happen due to static objects. In the AOA method it can lead to a wrong angle measurement and hence to false location calculation.

The advantage of a network-based solution is that the cellular system modifications are done only on the cellular network side and not on the handset. Unlike handset-based solutions that rely on specialized technology in the handset to calculate the location, network technologies rely entirely on equipment placed within the wireless network to do
the location calculation. Because of this, network technologies are not limited by the processing capacity of the phone and have the ability to devote substantially greater processing power to the calculation of a location\textsuperscript{14}.

2.3.4. Handset-based solutions

In handset-based solutions the signals measurements are done by the handset. The location calculation is sometimes done by the handset and sometimes by the network.

2.3.4.1. E-OTD (Enhanced Observed Time Difference)

The E-OTD is a ‘time difference of arrival’ (TDOA) technique that uses the handset for measurements and calculations. In this method, the phone measures the difference in the time of arrival signals from different base stations. Essentially, the phone triangulates its position using signals from the base stations\textsuperscript{15}, and then reports the position back to the network. The method operates only on GSM and GPRS networks. The OTDOA, which was mentioned earlier, is considered a UMTS version of E-OTD.

As indicated, the E-OTD compares and calculates the difference in times required for a synchronized burst signal from BTSs to arrive to the handset. The burst from the base stations must be synchronized i.e. the signal must be sent at the same time. Since the GSM networks are unsynchronized there is a need for an additional component in the network that will synchronize the base stations. The LMU (location measurement unit)
has an accurate timing source and it provides system-wide base stations synchronization. LMUs must be deployed on the entire cellular network in order to cover all base stations. When the handset receives the burst from its serving and neighbor base stations, it compares the arrival times of 2 or more pairs of base stations. The time difference between pair of base stations creates hyperbola curve that mark the possible location of the handset. The intersection of the created hyperbolas is the location of the mobile. Figure 2.4 shows the principle of the E-OTD method. The clocks represent the LMUs.

The E-OTD method has some disadvantages. It demands handset and network modifications. Each handset should support E-OTD and LMUs must be part of the network. The implementation is therefore considered expensive. The position method also demands connection to at least three base stations from the handset, in order to calculate the location. As previously mentioned, achieving it in areas with large size cells
is sometimes impossible. The most problematic part in the E-OTD is the accuracy. As a handset-based method, the E-OTD had proven to not be accurate enough for the phase II requirements. More about the accuracy issue is explained in section 2.3.5.

2.3.4.2. AFLT - Advanced Forward Link Trilateration

The AFLT location technique is used on CDMA networks. It uses the TDOA technique that is also used by E-OTD and U-TDOA methods. The CDMA networks are synchronized and therefore there is no need for LMUs. In order to determine location in AFLT solution, the phone takes measurements of signals from nearby cellular base stations and reports the time/distance readings back to the network, which are then used to triangulate an approximate location of the handset\(^\text{17}\). In the network, the calculation is done by the location server.

The big advantage of the method is that it doesn’t require major changes in the cellular network. It also provides good accuracy in dense areas. However, in rural areas it provides accuracy which is not sufficient for the E911 demands. Therefore the technology cannot be used as the only method to find the handset location in a cellular system.

2.3.4.3. A-GPS – Assisted Global Positioning System
As explained in Chapter 1, the GPS system provides location in three dimensions to its receivers. Integrating the GPS receiver to each handset can therefore be a good solution for the E911 requirements. But the GPS has two major limitations in regards to phase II requirements.

The first is reception issue. In order to receive signals from the satellites, the GPS receiver must have direct view to them. Inside buildings, malls, parking lots or other RF-shadowed environments the GPS receiver cannot function properly. The location calculation cannot be processed since there is not enough data to do so. The second problem is the TTFF (time-to-first-fix). For a GPS receiver that has just been turned on (‘cold start’) it takes between 30 seconds to several minutes to acquire the first location fix (this time period is called time-to-first-fix). In an urgent event when lives are in danger, every second counts. If the GPS can’t provide the location quickly, it can’t fulfill the purpose of the E911 rule.

The Assisted GPS technology concept claims that with more information, the GPS receiver can operate better. The solution is a combination of a stand alone GPS, which is integrated to every handset, and information that sent from the network to the GPS receiver. The information assists the GPS receiver in the following aspects: it shrinks the time-to-first-fix to a few seconds, it enhances the reception sensitivity to satellites signals, and it improves the position accuracy.

The network component that sends the information to the handset is the location server (or ‘A-GPS server’). It is connected to the cellular infrastructure and consists of GPS receivers that can detect GPS signals continuously and monitor the satellite constellation
in real time\cite{18}. It sends information about the satellites to the handset so the GPS receiver on the handset can use it when it demodulates the GPS signals. Figure 2.5 shows the concept of the A-GPS solution. More information about the Assisted GPS solution can be found in chapter 3.

Figure 2.5 - A-GPS concept\cite{19}

2.3.4.4. Hybrid solutions

As mentioned before, hybrid solutions combine the A-GPS solution with another handset/network-based solution. The methods can compensate one another. For example: in dense urban environments, GPS signals undergo shadowing or blockages, whereas these environments are the best for TDOA positioning methods, since there is the highest density of base stations\cite{18}. In open sky spaces the GPS receiver has good satellite signal reception, while for other handset-based and network-based methods, the low density of BSs does not allow one to achieve high accuracy\cite{18}. Hybrid solutions are more robust than
a regular solution. It provides good accuracy and has the ability to calculate the handset location in any type of environment.

Some of the hybrid solutions are: A-GPS/E-OTD, A-GPS/OTDOA, A-GPS/AFLT, and A-GPS with Cell-ID.

2.3.5. Tier I carriers - chosen solutions for phase II

With wireless location technologies, there are two primary performance measurements: accuracy and yield. Accuracy relates to the ability of the location technologies to pinpoint a caller or location devices (usually an average measure in meters), while yield is a measure of the ability of the technologies to actually calculate a location (usually measured as a percentage of successful locations per 100)\(^{14}\). The carriers were looking for the best solution in terms of accuracy and yield that would fit their network.

In 2001 there were six tier I carriers. Their chosen solutions were as follow\(^{20}\):

- AT&T Wireless – E-OTD (for their GSM network)
- Cingular Wireless - E-OTD (for their GSM network)
- Nextel - A-GPS
- Verizon Wireless - A-GPS/AFLT
- Sprint PCS - A-GPS/AFLT
- Voice Stream - E-OTD
Today there are only four tier I carriers. Three big mergers had occurred – Cingular and AT&T Wireless merged and became ‘Cingular Wireless’; Sprint PCS and Nextel merged and became ‘Sprint’; Voice Stream and Powertel merged and became T-Mobile. Tier I solutions today are as follow:

Cingular Wireless - U-TDOA
Verizon Wireless - A-GPS/AFLT
Sprint - A-GPS/AFLT
T-mobile - U-TDOA

The most important change between 2001 and today is the replacement of the E-OTD method with the U-TDOA. Both methods are based on the same location calculation technique (time difference of arrival). But E-OTD is a handset-based solution while U-TDOA is a network-based solution. Phase II requirements are stricter with the handset-based solution. The E-OTD platform proof itself as not compatible with the phase II requirements and as a result, the carriers moved away from it.

In December 2002, the following news was published: The FCC's rejection of Cingular Wireless' request for more time to install E-OTD E911 location technology has pushed the carrier to switch gears in favor of the rival Uplink Time Difference of Arrival Technology. Cingular has told the FCC that after completing field trials involving TruePosition's network-based U-TDOA technology, it was moving away from E-OTD, a platform that has resulted in E911 delays - and financial penalties - for several
carriers. The company also told the FCC it would file yet another request to implement U-TDOA\textsuperscript{21}.

On March 2003, T-Mobile USA notified the FCC that it plans to switch technologies for meeting the commission's E911 mandates for locating wireless users who call 9-1-1. The company had already started deploying E-OTD technology, but switched to TDOA technology\textsuperscript{22}. On July 2003 T-Mobile adopted the U-TDOA technology.
References – chapter 2


Chapter 3 – Assisted GPS technology
The Assisted GPS (A-GPS) idea was initially proposed in 1981. The A-GPS concept is to provide the GPS receiver with information that will help to reduce the time it takes the receiver to calculate its location. But the A-GPS technology became relevant and needed only after the wireless Enhanced 911 mandate was issued.

The GPS was one of the technologies that were chosen in order to follow the mandate requirements. But the GPS receiver, as a stand alone solution, has some major performance limitations in regards to the E911 phase II requirements. With the A-GPS technology, the GPS solution becomes compatible with the phase II requirements.

3.1. GPS receiver limitations

The wireless E911 rule requires the carriers to provide the caller’s location at any time and from any place the 9-1-1 call takes place. Integrating the GPS receiver into the cellular device as a solution cannot answer these demands. There are several scenarios where the GPS receiver cannot provide the cellular device location.

3.1.1. Time to first fix

The time it takes the GPS receiver to calculate its position when turned on is called ‘time to first fix’ (TTFF). There are three different states the receiver can be at when it is powered on – cold start, warm start, and hot start. The start times depend on the acquisition sensitivity of the receiver, the number of visible satellites, the signal strength.
of the individual satellites, the constellation of the satellites in the sky, and the receiver’s view of the sky\(^1\).

Cold start is when the GPS receiver is powered on after it has been turned off for an extended period of time and no longer contains current ephemeris data. In cold start scenario, the receiver has no knowledge on last position, approximate time or satellite constellation\(^2\). The TTFF in cold start is the longest startup time for a GPS receiver. It can take from 30 seconds to more than a minute. Warm start is when the receiver has approximate GPS time, its last position, and almanac. The ephemeris data is either not up to date or cleared. The existed information is used when the receiver tries to get a position fix. Warm start is usually 5-15 seconds shorter than a cold start. Hot start takes only a few seconds. The receiver has up to date ephemeris data and all other necessary parameters.

The GPS receiver consumes a lot of power from the handset’s battery when it is activated. In order not to force the user to charge the cell phone battery a few times a day, the GPS receiver should be turned off unless it’s needed. The solution most users pick in their cell phones is to trigger the GPS only when a 9-1-1 call is made. It means that in most cases the 9-1-1 call will be made when the GPS receiver is off. That will result in a cold start.

As mentioned before, the TTFF in a cold start can take from 30 seconds to more than a minute. In regards to the E911 mandate, this is an unacceptable performance. For
example, there is a possibility that the 9-1-1 call is shorter than the TTFF. Then the PSAP will not get location indication. The urgent nature of a 911 call demands that the location of the caller will be sent within the first seconds of the call. With a stand-alone GPS this requirement cannot be fulfilled.

The A-GPS technology provides a solution for the long TTFF problem.

3.1.2. Weak signals

The position calculation of the GPS receiver is based on signals that come from the GPS satellites. Hence, a clear view to the sky increases the receiver ability to have good signal reception. Indoor locations like malls, offices buildings, covered parking lots, elevators etc, are problematic for GPS receivers since the GPS signals are further attenuated as they propagate through the buildings. That results in signals which are too weak to detect. Without the signals the GPS cannot calculate its position. In other words, in RF-shadowed environments, where the GPS receiver does not have a direct view to the atmosphere, the GPS receiver has difficulties in providing the phase II location requirements.

According to revision D of the IS-GPS-200 specification of NAVSTAR GPS, the GPS coarse acquisition (C/A) code signal at L1 is designed to arrive on the ground at not less than -158.5 dBW (-128.5dBm) power level. Indoor signals can be attenuated to power levels of -160dBW to -200dBW, which makes the GPS receiver task impossible. There
are some GPS receivers today that can work with minimum received power of lower than -160dBW, but this is not enough.

The A-GPS helps the GPS receiver to deal with weak GPS signals.

3.2. A-GPS solution

The A-GPS idea is to assist the GPS receiver by sending it information. The information includes parameters that help the GPS receiver with signal acquisition and fast location calculation.

3.2.1. A-GPS concept

The Assisted GPS technology concept is shown in figure 3.1. The cellular device (referred in the figure as ‘Mobile Station’ or ‘User Equipment’) has a GPS receiver integrated into it that picks up the signals from the satellites. The A-GPS server has a reference GPS receiver. It has clear view to the sky and it monitors the same satellites the cellular device monitors. Each A-GPS server is in charge of multiple base stations. It has exact knowledge about the GPS signals that are available for the cellular devices in the cells it’s in charge of. The A-GPS is connected to the mobile switching center (MSC). Through the cellular network, the A-GPS server sends information to the cellular device. The information includes the satellites that their signals are available in that area. The
device utilizes the information and as a result improves its location providing performances. The messages from the A-GPS server can also be IP based and not go through the MSC and BSC. More about the subject is explained in section 3.2.4.

**Figure 3.1 - Structure of A-GPS**

![Diagram of A-GPS structure](image)

### 3.2.2. A-GPS and the receiver limitations

#### 3.2.2.1. Doppler shift

The long TTFF problem is caused by the search the GPS receiver performs in order to acquire the satellite signals. In conventional GPS receivers, the phase of acquisition of GPS satellite signals is practically a search over the whole possible frequency and code-
delay space\(^4\). The reason for having more than one possible frequency for the incoming signals is the Doppler shift.

The Doppler shift has three different sources: The satellite motion, the GPS receiver motion, and the local oscillator at the GPS receiver. The satellite motion itself adds ±4.2 KHz of Doppler shift, thus there is a frequency uncertainty of greater than ±4.2 kHz on the observed GPS signal\(^5\). The receiver has to search the entire space of possible frequency offsets and code delays - (Doppler shift) x (1023) - in order to acquire one GPS signal. Figures 3.2 and 3.3 show the GPS signal search space (frequency/delay space). Figure 3.3 also shows the correlation peak with the GPS signal.

**Figure 3.2 - Frequency/Delay search space**\(^4\)

Usually there are 40 frequency bins (small frequency ranges where the correlation with the PRC is searched) in the possible frequency offset. There are 1023 delays that need to be tested in each frequency bin. Each delay, at the receiver’s PRC, needs to be cross correlated with the arriving signal. GPS receivers have been designed to dwell for at least
one millisecond in each delay, taking approximately 1 second per bin \((1\text{msec} \times 10^3)\).
Hence, the search for the entire freq/delay space takes approximately 40 seconds.

**Figure 3.3** - Frequency/Delay search space and correlation peak

One of the A-GPS server’s major tasks is to provide the approximate Doppler shift of the GPS signals. The A-GPS server has a reference GPS receiver, which knows the Doppler shift of the signals from the satellites. The A-GPS server transfers the information about the Doppler shift according to the coarse position of the mobile device, which is usually the cell ID of the device. With the aiding information, the GPS receiver on the handset can reduce the search space. The space can now include only a few frequency bins. Hence, the TTFF is dramatically reduced to only a few seconds (considering the GPS signals are not highly attenuated). Figures 3.4 and 3.5 show the frequency/delay search space when assisted information is sent from the A-GPS server.
Both CDMA and GSM protocols have standards for minimum operational performance of A-GPS handsets: 3GPP2 C.S0036-0 (TIA 916) for CDMA and 3GPP TS 25.171 for GSM. The requirements for the maximum respond time (i.e. maximum TTFF) are 16
seconds for CDMA and 20 seconds for GSM. As previously mentioned, if the receiver is not in an indoor environment, the requirements can be easily followed.

3.2.2.2. Integration period

In the GPS receiver’s search over the ‘frequency - code delay’, in each one of the frequency bins, all the code delays (1023) of the PRC are examined to see the correlation of the GPS signal with them. The time it takes to search each code delay is called ‘integration period’. For strong signals, an integration period of 1ms (i.e. the C/A code repetition time) is sufficient, since the correlation peak values appear above the noise level of the incoming signals. For weak signals, however, the correlation period must be extended to improve the signal-to-noise ratio at the correlator output$^3$.

Due to the A-GPS information about the Doppler shift, the number of frequency bins is reduced. Therefore the GPS receiver can increase the dwell time (integration period) in each bin. That increases the receiver sensitivity since it can detect weak signals when the dwell time is longer. However, increasing the integration period leads to several problems.

The integration period cannot be extended for too long - if the GPS signal is searched at half chip spacing it would take $1023 \times 2 \times \text{integration period}$ to search the whole code space. For an integration period of 5ms the search time is $1023 \times 2 \times 0.005 = 10$ seconds$^6$. If the integration period is 1 second the search time increases to $1023 \times 2 \times 1 = 2046$ seconds.
The integration period cannot be too short either – if the integration time is increased to 10ms then each extra millisecond of data can be integrated (summed) with the previous results, yielding SNR (signal to noise ratio) gains that approach $\sqrt{N}$ for each extra $N$ milliseconds. Thus the aiding could produce a sensitivity gain that approaches $20\log_{10}(\sqrt{10}) = 10$ dB. But 10dB extra sensitivity is not enough since the indoor signal levels are 20 to 30dB down from the outdoor signal levels.

Two more problems are associated with a long integration period. One is the Doppler range. When the integration period is doubled, the number of Doppler frequencies is also doubled. It happens since the steps between the trial Doppler frequencies are set such that the carrier will drift no more than a quarter period during the integration period. Therefore, doubling the integration period halves the step size, thereby doubling the number of trials required.$^3$

The second problem is the coherent integration. The coherent integration period is limited to less than one navigation message bit (20ms). If not, the probability of bit transitions occurring within integration periods will be high, and excessive random losses will result.$^7$ The solution for the coherent integration limitation is the non-coherent integration. With this integration method the integration period can last for more than 20ms. Figure 3.6 shows a graph of non-coherent integration period for strong to very weak GPS signals.
Fast acquisition and high sensitivity can be achieved by performing integration in parallel at the receiver. High-sensitivity receivers work by performing far more correlations and integrations than a standard receiver in the same amount of time. With enough correlators, all possible delays can be calculated at the same time, and hundreds of milliseconds of convolutions can be integrated to give the required sensitivity for indoor operation.

With more correlators, multiple code delay searches can be performed at the same time. This dramatically reduces the search time for one bin. That enables an extended integration period without long TTFF concerns. For example, some GPS chips now have ‘whole code space’ search engines with 2046 correlator. Therefore, the receiver can search all 2046 half chip spacing in parallel. Today there are receivers with 16,000 and 32,000 correlators.
A different way to achieve fast acquisition and high sensitivity is to use the information from the A-GPS server. The A-GPS can reduce the integration period by sending the approximate chip delay of the received GPS signal at the mobile device. In a typical sector, the uncertainty in the predicted time of arrival of a satellite signal at the mobile is about ±5 µs, which corresponds to ±5 chips of the C/A spreading code sequence. Therefore, A-GPS server can predict to within ±5 chips the phase of the PRC sequence that the receiver should use to de-spread the C/A signal from a particular satellite, and communicate that prediction to the mobile device. The specified code phase range leads to high sensitivity since the dwell time can be increased.

3.2.2.3. Other assisted parameters

Other than the Doppler shift and the code phase, additional assisted parameters are sent to the cellular device: List of available satellites, ephemeris of the satellites, almanac, GPS reference time, and real-time integrity (failed/failing satellite information). These parameters help in the location calculation process and improve the calculated location’s accuracy. More about the assisted parameters can be found in section 3.2.3.

3.2.3. UE-based and UE-assisted solutions

The A-GPS solution can run in either of two modes: UE-based where the location is calculated on the mobile device and transferred to the cellular network; UE-assisted where the UE acquires GPS signals, makes measurements by correlating the locally
generated PRC codes with the received GPS signals, and determines time-stamped pseudoranges that are transmitted to cellular network, which performs the calculation of the UE position\textsuperscript{4}. The UE can support both modes of operations.

The information elements (IE) that transferred between the A-GPS server to the UE and vice-versa are different in each mode.

In UE-assisted mode the following messages are sent\textsuperscript{4}:

From the UE to A-GPS server:
- Location request.
- Coarse position of the UE.
- Time-stamped GPS pseudoranges.

From the A-GPS server to the UE:
- Visible satellite list.
- Satellite-in-view signal Doppler and code phase or, alternatively, approximate handset position and ephemeris.
- GPS reference time.

The UE-Assisted solution requires a short downlink period and uses the network resources for the position determination. That speeds up the position calculation process without loading the network and also does not require additional computing power from the handset. The disadvantages of the solution are the short term validity of the assistance data and the relatively long uplink that includes all the pseudoranges.
In UE-based mode the following messages are sent:\(^4\):

From the UE to A-GPS:

- Location request.
- Coarse position of the UE.
- Calculated position of the UE.

From the A-GPS server to the UE:

- Visible satellite list.
- Precise satellite orbital elements (ephemeris), which are valid for 2–4 hours and extendable to the entire period of satellite visibility (12 hours).
- DGPS corrections.
- GPS reference time.
- Real-time integrity (failed/ failing satellite information)

In UE-based solution, the position calculation on the handset adds to its total memory (RAM, ROM) requirements in addition to extra computing capability such as million instructions per second (MIPS)\(^5\). Another disadvantage is the relatively long downlink assistance data that slow the calculation process and load the network. One of the solution’s advantages is that the handset can be used as a stand alone GPS receiver. This can be useful when GPS applications are used from the handset. Other advantages are the relatively short uplink and the validity of 2-4 hours of most of the assistance data.
It is important to indicate that the information that transferred between the mobile device and the A-GPS server can include part of the messages, which were mentioned above, and not all of them.

The 3GPP2 C.S0022-0 protocol specifies the position determination data messages between the base station (the messages from and to the A-GPS go through the base station) and the mobile device, under the CDMA protocol. The messages types are presented in Appendix G.

3.2.4. Control Plane and User Plane

There are two ways to send and receive assistance information to the cellular device: Control plane, where the messages are sent over the control channels of the cellular network; User plane, where the messages between the UE to the A-GPS server are IP based.

3.2.4.1. Control Plane

The control plane architecture enables highly accurate, widely available location determination immediately on demand within the context of other cellular services, such as voice calls. This approach sends data necessary for performing Assisted-GPS on the control channels, which are an inherent part of a network operator's mobile call distribution system\textsuperscript{10}. Figure 3.7 presents the control plane solution in GSM networks.
Both the CDMA and the GSM communities have developed standards for control plane AGPS messaging. The standards include all the information that transferred from the A-GPS to the mobile station and vice versa. These standards describe how position information from the wireless network can be extracted and used.

The 3GPP2 C.S0022-0 standard (also called TIA/EIA/IS-801-1) defines a set of signaling messages between the mobile station and base station to provide a position determination service in CDMA and CDMA2000 networks. The 3GPP TS 04.31 standard was written for the GSM protocol. The standard contains the definition of the Radio Resource LCS Protocol (RRLP) to be used between the Mobile Station (MS) and the Serving Mobile Location Centre (SMLC) in order to transfer the assistance data. The TS 25.331 standard describes the radio resource control at the WCDMA protocol.

Figure 3.7 - The control plane solution in GSM network
The control plane deployment requires changes in the cellular network: The BSCs and the MSCs must be updated in order to support the assisted messages standard; the network bandwidth must be large enough to handle the additional information that goes through it. The deployment is considered to be expensive and time consuming.

The CDMA and CDMA2000 carriers in the United States (Verizon Wireless and Sprint – which use the A-GPS solution) have adopted the control plane as the solution to transfer assisted information in their networks.

3.2.4.2. User Plane

As previously mentioned, user plane messaging means that the messages between the mobile device and the A-GPS server are IP based. Unlike control plane, the user plane implementation is quick to market, has lower deployment costs, and can be adapted to the carrier's specific needs. Figure 3.8 presents the user plane solution at GSM networks.

User plane deployment was proprietary until recently. In the last two years, two standards were published for the various cellular protocols. The X.S0024-0, which was written by 3GPP2 group, presents a recommended plan for the implementation of IP-Based Location Services. The standard complies with the CDMA and CDMA2000 protocols. The GSM and WCDMA protocols work with the secure user plane location (SUPL) standard. The SUPL can be used for CDMA networks as well. The standard was developed by the
3GPP group: Once the 3GPP community decided it needed a user plane solution, key companies including Vodafone, Ericsson, Nokia, and QUALCOMM led the effort to produce a complete solution\textsuperscript{14}.

\textbf{Figure 3.8} - The user plane solution in GSM network\textsuperscript{1}

The 2.5G and 3G cellular networks (GPRS, WCDMA, and CDMA2000 protocols) enable IP session between the cellular device and external applications. Since the user plane is based on an IP session between the A-GPS server to the mobile device, it is usually implemented in those networks and not in GSM or CDMA.

Control and user plane implementations in CDMA networks, which were designed by Qualcomm (one of the largest A-GPS providers in the U.S), can be found in Appendix H.
3.3. A-GPS deployment

3.3.1. Tier I carriers status

Verizon Wireless and sprint were the tier I carriers who chose the A-GPS as their location solution for the E911 phase II requirements.

In the Verizon wireless report to the FCC from January 31, 2006 it stated that: 1. As of January 13, 2006 Verizon Wireless provides Phase I E911 service to a total of 3,100 PSAPs serving an estimated population of 213 million residents. It provides live Phase I E911 service to PSAPs in parts or all of 48 states. 2. Verizon Wireless also provides Phase II E911 service to a total of 2,229 PSAPs serving an estimated population of 183 million residents. It provides live Phase II E911 service to PSAPs in parts or all of 47 states.

The report also mentions that all of Verizon Wireless’ handsets today are GPS-capable and that the carrier requested a limited waiver to allow it an additional six months to meet the Commission’s 95% GPS handset penetration milestone. To the report’s issue date, Verizon Wireless has converted about 93% of its customer base to GPS capable handsets.

Sprint Nextel (SN) Corporation submitted its last report to the FCC in May 1st, 2006. In the reports it stated that SN brought its total Phase I deployments to 3,530 PSAPs on its combined networks and its total Phase II deployments to 2,777 PSAPs. Phase I and II
services are now available in portions of 48 states, Puerto Rico and the District of Columbia^{16}.

Sprint Nextel also seeks a waiver of the Commission’s 95% handset deployment rule until December 31, 2007. It notes that as of December 31, 2005, it had distributed over 68 million GPS enabled handsets and that its GPS handset penetration rate now exceeds 84%^{16}.

3.3.2. A-GPS providers

Today there are many companies that provide A-GPS deployment. The deployment includes integrated GPS into the cellular devices and A-GPS location server. The growing success of wireless location-based services and the technologies required to support them is evidenced by the more than 45 wireless operators worldwide with A-GPS deployments, a number that continues to grow as wireless location technology expands in response to the exponential increases in user demand^{17}.

Qualcomm, which acquire SnapTrack at the year of 2000, is one of the largest A-GPS providers. Verizon Wireless is one of their customers. Their ‘client’ product (the GPS receiver that integrates to the cell phone) is called gpsOne. It supports IS-95A/B, CDMA2000, GSM, GPRS, and WCDMA (UMTS) networks. It can dynamically select between three modes of operation, MS-based, MS-assisted and Standalone GPS. The server technology Qualcomm provides is called QPoint. QPoint combines GPS satellite
information with ranging information from a cellular network to provide all-terrain location information\textsuperscript{18}.

SiRF Company provides assisted GPS technology to Sprint-Nextel. The company provides chips that can be integrated to the cellular device. One of them is the SiRFstarIII. Its architecture is designed to meet the rigorous demands of wireless and handheld LBS applications, and provides location performance, both indoors and out, for 2G, 2.5G, 3G asynchronous networks\textsuperscript{19}.
References – chapter 3


Chapter 4 – Integrating location-based applications to cellular networks
As a result of the Wireless E911 mandate, the wireless carrier can now provide the location of the caller with good accuracy. This circumstance has opened a new opportunity for the carriers - the caller’s location can be leveraged to offer location-based applications to the users. Having a cell phone as a device that is able to run and/or communicate with an application that is based on its location is a revolution in the field of cellular applications.

4.1. Location based applications for cellular devices

Location based applications are applications that provide some information per a device’s location. One common application is the navigation system in vehicles. The device in the vehicle includes a GPS receiver. Based on the location of the device in the car, navigation instructions are given to the driver.

Cellular devices expand the possibilities of location applications ideas. One reason is that cellular phones are massively used by almost every type of population – kids, teenagers, adults and elderly people – and therefore can be developed for each population need. Another reason is that the cellular device is always with the user and hence can be used in any scenario. Here are some examples for possible scenarios: user looks for his car in the parking lot, mother looks for her children in a mall, manager wants to know where her workers are, etc.
Despite the opportunity the E911 created, the location-based applications market in cellular devices is only in its beginning. The number of applications that are currently offered by the carriers is limited. The location applications have not yet become something that is massively used by users like SMS, ring tones, and cell phone cameras.

4.2. Integrating location-based application to the cellular network

There are few ways to integrate location based application to the cellular network. The application can be integrated on the cellular device and run from there. The application on the device can also communicate with an application server that is located outside of the cellular network and runs a different part of the location application. Another option is that the location-based application is fully run on the application server. The application server can get the location from the cellular network or from the cellular device.

Two integration schemes will be presented in this section. One uses the cellular components of the E911 system (section 4.2.1). I favor this approach to implement location based application. The second scheme was implemented by Verizon Wireless in their network (section 4.2.2). In this solution, the location applications are integrated to the cell phones.
4.2.1. Using the MPC for location based application

The Wireless E911 phase II call environment includes three new network components: MPC, PDE, and CRDB (See section 2.2.3). The MPC (Mobile Positioning Center) is a server that interacts with the PDE (Position Determination Entity) in order to get the cellular device location. The MPC, based on a defined protocol called ‘E2’, passes the location information to the ALI. Figure 4.1 presents the phase II network.

Figure 4.1 – Wireless E911 phase II network

The MPC is the network component that collects the caller location. In order to get the location information of a caller, an application server would need to communicate with the MPC. The general term for MPC is location server. On UMTS and GSM networks the component is called GMLC.
The location application type presented in this section is intended to serve building complexes such as campuses, malls, museums, hospitals, etc. The application receives the caller location in the complex and returns the requested information. Examples are: where is the nearest exit from the building, how to get to the information desk, how to get to the administration office, etc.

The following is a suggested call flow for such a location-based application:

1. The user turns on the GPS function on the cell phone.
2. A call is made by the user to a specific phone number, which is the application number.
3. The application server receives the call and presents options to the user to choose from (for example: for the nearest parking lot press ‘1’, for direction to the information desk press ‘2’, etc).
4. The user picks the desired option.
5. The application server sends a location query to the MPC. It sends the caller’s cell phone number in order to identify who is the user that needs to be located.
6. According to the user’s phone number, the MPC get the caller’s location and sends it to the server.
7. The application server receives the user’s location and accordingly sends the appropriate information to the caller.
8. The user receives the requested information.
4.2.1.1. Mobile Location Protocol

The Open Mobile Alliance (OMA) is a standards body that develops open standards for the mobile industry. It is a voluntary forum for industry stakeholders to agree on common specifications for products and services\textsuperscript{2}. One of the standards the OMA developed is the Mobile Location Protocol (MLP).

The MLP is an application-level protocol for querying the position of mobile stations independent of the cellular network technology. The MLP serves as the interface between a Location Server and a location-based application. A Location Server is the MPC or the GMLC\textsuperscript{3}. See figure 4.2.

![Figure 4.2 – MLP concept\textsuperscript{4}](image)

MLP is a protocol that can be used when communicating with the MPC. But the communication channel between the location application server and the MPC must be secure. Due to the fact that the caller’s location is transferred on this channel and this information should not be open to the public. SSL (Secure Socket Layer) is a way to
establish a secure connection between client and server. The MLP supports the https protocol that uses SSL.

4.2.1.2. Pros and Cons

The primary disadvantage of this application type is the traffic load in the cellular network. All calls to a specific application come from one complex and are served by the same MPC since one MPC is usually in charge of multiple cells. Each call to the application server requires a query to the MPC. There are cases when live tracking of the caller is required from the application. In that case, periodical queries to the MPC will be required as per the call. All of the above can result in a load on the MPC.

Requesting the location from the cellular device also loads the network traffic. If control plane is being used, the network signaling channels are used in order to send the assisted parameter to the cell phone. If the UE-assisted solution is used, the cellular device will send its GPS measurements to the network. It means that getting the location of the caller can cause a lot of traffic in the control channels of the cellular network.

Another disadvantage of this design is the interfacing with the E911 system. The E911 system was designed for 9-1-1 calls and not to support applications. Using components from this system to support a location application might not be reliable.

Location applications that serve a specific area should support all callers. The advantage of this type of application is that it can interface with all carriers’ MPCs and thus give support to all callers; not only to callers from a specific carrier.
Since the application covers a relatively small area, it can provide an excellent cover for every possible location in the area. The small area also makes it easy to apply more complicated features such as live directions and identifying where another caller is.

4.2.2. Location based services that are offered by Verizon Wireless

The Verizon Wireless commercial location based services (LBS) was launched early in 2006. The location based services run on the users’ cell phone and not on an application server. Only certain types of cell phones support location based services. Those cell phones have the Qualcomm chipset and the BREW (Binary Runtime Environment for Wireless) platform. The Qualcomm chipset includes the gpsOne receiver, which is an A-GPS client (see section 3.3.2). The BREW platform allows developers to create applications that operate on any BREW-enabled wireless phone. The BREW platform sits between the chip system software and the application and offers APIs. It makes the phone's functionality available to the application without requiring the developer to have the chip system source code or even a direct relationship with a device manufacturer.

The location applications are implemented on the cell phone itself using the BREW platform. The applications that Verizon Wireless offers today were implemented by third party companies. Verizon Wireless validated all of the applications before approving them according to company procedure. The procedure starts with examination of the future profitability and public interest of the application. When the application is ready for testing, it is sent to a lab in order to test it thoroughly.
Running the location application on the cell phone means that the location of the user has to be provided on the cell phone. The location can either be calculated on the cell phone itself or sent to the cell phone after being calculated on the network. Since Verizon Wireless uses A-GPS and AFLT as their location methods, both scenarios can happen: In AFLT the location is calculated on the network and then sent to the cell phone; in A-GPS it can be UE-based (calculated on the cell phone) or UE-assisted (calculated on the network). The communication between the cell phone and the cellular network is IP-based.

The user runs the location applications from its cell phone. There is no need to make a call or to set up the GPS receiver. Whenever an application is used, the GPS receiver on the cell phone is automatically turned on.

There is a complete separation between the E911 system and the commercial location-based services system. The E911 uses the signaling channels for communication with the cell phone, while the location applications use the TCP/IP protocol. According to Verizon Wireless, this separation is because the E911 system should be used only for 9-1-1 calls due to their importance. Additionally, Verizon Wireless does not support communication with the MPC, which is part of the E911 system, for commercial use.

The application that Verizon Wireless offers today are consumer and enterprise focused. Navigation & traffic, LBS games, mobile marketing, and social networking are the
consumer focused applications. Enterprise applications include field force automation, real estate and custom solutions.

4.2.2.1. Pros and Cons

The concept of having the application on the cell phone has major advantages. The first is the ease of use. All the user needs to do in order to use location application is to browse to it in the cell phone’s menu. Another advantage is the BREW platform. The platform offers a comfortable development environment that is open to third party companies. That increases opportunities and possibilities for adding more location applications to the services Verizon Wireless offers.

The communication between the cell phone and the cellular network is TCP/IP. The network signaling channels are not used for this communication. This prevents load on the network.

The major disadvantage Verizon Wireless LBS has is that the application can be used only on specific cell phone types. Those types include the BREW platform. Another disadvantage is that location applications that should work with all the carriers and support all users cannot be integrated into the Verizon Wireless network. For example, an application that gives direction to users in a national park cannot be used by Verizon Wireless customers. Verizon Wireless only supports applications that are developed for their cell phones.
References – chapter 4


6 B. Chen and R. Mira – Verizon Wireless engineers (conference call, September 12, 2006)

Conclusions

The GPS receiver has been available for civil use since the early nineties. It has been massively used since then in the civil market, but mostly for the purpose of navigation. The Wireless E911 rules had resulted in two major changes in the GPS civil market: 1. GPS receivers were integrated to cell phones, resulting in large scale of users who carry GPS receiver all day; 2. The Assisted GPS technology, which was discussed more than twenty years ago, became relevant, needed, and available.

The Assisted GPS technology improves the GPS receiver performances by overcoming the GPS receiver’s well known weaknesses. With the technology, the GPS receiver on the cell phone provides the caller locations following the Wireless E911 accuracy demands.

The A-GPS would probably have never been deployed without the E911 requirements. The reason is that the weaknesses of the GPS were never considered a major problem for navigation purposes. They were always taken as a fact.

It will take a few more years in order to get a good perspective of how well did the Assisted GPS technology fulfilled its role in the E911 system. When phase II deployment is over, the PSAPs can start gather statistics of carriers’ performances. The performances can be measured by the following: in what percentage of the 9-1-1 calls did the carrier sent location, how fast did the PSAP get the location information, was the location
information accurate, and are there specific areas/scenarios where there were more issues with the provided location.

The GPS and the other location solutions are now used as a platform for location-based applications that are offered to users by the carriers. At the moment every carrier developed its own location-based application for its customers. The concept of having one location application that can be used by customers from all carriers is still not a common approach. I believe we’ll see some growth in this area due to the high potential of such applications – more air time for the carriers, more convenience for users.
Appendixes
## Appendix A – Current Block II/IIA/IIR/IIR-M satellites

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* Satellite is no longer in service.
** US SPACE COMMAND, previously known as the NORAD object number; also referred to as the NASA Catalog number. Assigned at successful launch.
*** Unsuccessful launch.
### Appendix B – Block II/IIA/IIR/IIR-M individual satellite status

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<td>30</td>
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<td>Launched 26 OCT 1993; usable 22 NOV 1993; operating on Rb std</td>
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Appendix C – C/A code generation

The linear Gi(t) pattern (C/A-code) is the Modulo-2 sum of two 1023-bit linear patterns, G1 and G2i. The latter sequence is selectively delayed by an integer number of chips to produce 36 unique G(t) patterns. This allows the generation of 36 unique C/A(t) code phases using the same basic code generator.

Each Gi(t) sequence is a 1023-bit Gold-code which is itself the Modulo-2 sum of two 1023-bit linear patterns, G1 and G2i. The G2i sequence is formed by effectively delaying the G2 sequence by an integer number of chips ranging from 5 to 950. The G1 and G2 sequences are generated by 10-stage shift registers having the following polynomials as referred to in the shift register input.

\[ G1: \quad X^{10} + X^3 + 1, \text{ and} \]
\[ G2: \quad X^{10} + X^9 + X^8 + X^6 + X^3 + X^2 + 1. \]

The initialization vector for the G1 and G2 sequences is (1111111111). The G1 and G2 registers are clocked at a 1.023 MHz rate. The effective delay of the G2 sequence to form the G2i sequence is accomplished by combining the output of two stages of the G2 shift register by Modulo-2 addition. All thirty-six possible combinations of picking the two bits at G2 are selected.

Figure C.1 shows details about the generated PRCs. Figure C.2 shows the C/A generation process.

---

**Figure C.1 – Code phase assignments**

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<td>1774</td>
</tr>
<tr>
<td>29</td>
<td>29</td>
<td>1 ⊕ 6</td>
<td>859</td>
<td>1127</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>2 ⊕ 7</td>
<td>890</td>
<td>1453</td>
</tr>
<tr>
<td>31</td>
<td>31</td>
<td>3 ⊕ 8</td>
<td>861</td>
<td>1625</td>
</tr>
<tr>
<td>32</td>
<td>32</td>
<td>4 ⊕ 9</td>
<td>882</td>
<td>1712</td>
</tr>
<tr>
<td>***</td>
<td>33</td>
<td>5 ⊕ 10</td>
<td>893</td>
<td>1745</td>
</tr>
<tr>
<td>***</td>
<td>34**</td>
<td>4 ⊕ 10</td>
<td>950</td>
<td>1713</td>
</tr>
<tr>
<td>***</td>
<td>35</td>
<td>1 ⊕ 7</td>
<td>947</td>
<td>1134</td>
</tr>
<tr>
<td>***</td>
<td>36</td>
<td>2 ⊕ 8</td>
<td>948</td>
<td>1456</td>
</tr>
<tr>
<td>***</td>
<td>37**</td>
<td>4 ⊕ 10</td>
<td>950</td>
<td>1713</td>
</tr>
</tbody>
</table>

* In the octal notation for the first 10 chips of the C/A code as shown in this column, the first digit (1) represents a "1" for the first chip and the last three digits are the conventional octal representation of the remaining 9 chips. (For example, the first 10 chips of the C/A code for PRN Signal Assembly No. 1 are: 1100100000).

** C/A codes 34 and 37 are common.

*** PRN sequences 33 through 37 are reserved for other uses (e.g., ground transmitters). GPS satellites shall not transmit using PRN sequences 33 through 37.

⊕ = "exclusive or"
Figure C.2 - C/A code Generation
Appendix D – How time synchronization works¹

By using an extra satellite time measurement and a small calculation, the GPS receiver can reset its clock to be synchronized with all satellites. It is easier to show an example of the principle of synchronization in a 2-dimensional drawing². In the following case, there is a need for an additional third measurement. The GPS system works in three dimensions, so an extra forth measurement will be required.

The receiver position is four seconds from satellite A and six seconds from satellite B. Those two ranges cross, and the intersection is the receiver’s position. See figure D.1.

Figure D.1 - True location

![Figure D.1 - True location](image)

But what if the receiver's clock was a second slower compared to universal time? It would call the distance to satellite A 5 seconds instead of 4. And the distance to satellite B would look like 7 seconds. That causes the circles to intersect at a different point XX.

² The example is taken from the Trimble company website.
So the difference between X and XX is the error that the receiver’s imperfect clocks would cause (See figure D.2).

**Figure D.2** - False location

![Expanded Topic: Eliminating clock errors](image)

XX is a wrong position caused by wrong time measurements

If there is another measurement to a third satellite, the situation in a perfect world would be as follows: all the measurements would go through point X which is the receiver’s true position. See figure D.3.

**Figure D.3** - Extra measurement

![Expanded Topic: Eliminating clock errors](image)

But with the one second clock delay the situation look like this (See figure D.4):

The thick circles in the drawing show the "pseudo-ranges" caused by the clock's error. It can be observed that while Satellites A and B's pseudo ranges intersect at point XX,
Satellite C's pseudo range cannot go through that point. This discrepancy alerts the receiver's computer that there is a clock error.

Since any clock error or offset would affect all measurements, the computer looks for a single correction factor that would allow all the measurements to intersect at one point. In this example, it would discover that by subtracting a second from each measurement the ranges would all intersect at one point. With that correction factor determined, the receiver can then apply the correction to all measurements from then on.

The receiver’s clock is then synchronized with universal time. Of course this correction process would need to be repeated constantly to make sure the receiver's clocks stay synced. But with it, the GPS receiver turns into an atomic-accuracy clock.

Figure D.4 - Time correction
Appendix E – Almanac data

Definitions of the almanac parameters:\(^1\):

**ID:** PRN of the SVN

**Health:** 000=usable

**Eccentricity:** This shows the amount of the orbit deviation from circular (orbit). It is the distance between the foci divided by the length of the semi-major axis (our orbits are very circular).

**Time of Applicability:** The number of seconds in the orbit when the almanac was generated. Kind of a time tag.

**Orbital Inclination:** The angle to which the SV orbit meets the equator (GPS is at approx. 55 degrees). Roughly, the SV's orbit will not rise above approx. 55 degrees latitude. The number is part of an equation: \( \# = \pi/180 = \) the true inclination.

**Rate of Right Ascension:** Rate of change in the measurement of the angle of right ascension as defined in the Right Ascension mnemonic.

**SQRT(A) Square Root of Semi-Major Axis:** This is defined as the measurement from the center of the orbit to either the point of apogee or the point of perigee.

**Right Ascension at Time of Almanac (TOA):** Geographic Longitude of the Ascending Node of the Orbit Plane at the Weekly Epoch.

**Argument of Perigee:** An angular measurement along the orbital path measured from the ascending node to the point of perigee, measured in the direction of the SV's motion.

**Mean Anomaly:** Angle (arc) traveled past the longitude of ascending node (value = 0-180 degrees or 0-negative 180 degrees). If the value exceeds 180 degrees, subtract 360 degrees to find the mean anomaly. When the SV has passed perigee and heading towards apogee, the mean anomaly is positive. After the point of apogee, the mean anomaly value will be negative to the point of perigee.

**Af(0):** SV clock bias in seconds

**Af(1):** SV clock Drift in seconds per seconds

**week:** GPS week (0000-1024), every 7 days since 22 Aug 1999

Here is an example for the almanac data that comes in one frame. The data is from January 02, 2006 and includes information on satellites one, two, and three.

******** Week 332 almanac for PRN-01 ********
ID: 01
Health: 000
Eccentricity: 0.6317138672E-002
Time of Applicability(s): 319488.0000
Orbital Inclination(rad): 0.9861962485
Rate of Right Ascen(r/s): -0.7863184676E-008
SQRT(A) (m 1/2): 5153.632324
Right Ascen at Week(rad): -0.1215368185E+001
Argument of Perigee(rad): -1.719493219
Mean Anom(rad): 0.1771027633E+001
Af0(s): 0.2861022949E-004
Af1(s/s): 0.3637978807E-011
week: 332

******** Week 332 almanac for PRN-02 ********
ID: 02
Health: 000
Eccentricity: 0.9079933167E-002
Time of Applicability(s): 319488.0000
Orbital Inclination(rad): 0.9521910104
Rate of Right Ascen(r/s): -0.8126052768E-008
SQRT(A) (m 1/2): 5153.575684
Right Ascen at Week(rad): 0.2936171804E+001
Argument of Perigee(rad): 1.957614150

Mean Anom(rad): -0.3057350668E+001
Af0(s): -0.2288818359E-004
Af1(s/s): 0.0000000000E+000
week: 332

******** Week 332 almanac for PRN-03 *******
ID: 03
Health: 000
Eccentricity: 0.7781505585E-002
Time of Applicability(s): 319488.0000
Orbital Inclination(rad): 0.9260294474
Rate of Right Ascen(r/s): -0.8240343243E-008
SQRT(A) (m 1/2): 5153.599121
Right Ascen at Week(rad): 0.1801558569E+001
Argument of Perigee(rad): 0.656957233
Mean Anom(rad): 0.2344600876E+001
Af0(s): 0.6389617920E-004
Af1(s/s): 0.3637978807E-011
week: 332
Appendix F – U-TDOA operation

The arrival time measurements are made by location measurement units (LMUs) installed at selected BTS sites (one LMU per selected site). The LMUs forward the signal arrival time measurements to the SMLC/SAS serving mobile location center (SMLC). The SMLC then calculates the mobile's position. U-TDOA requires that the target mobile's signal can be measured by at least three LMUs.

Figure F.1 - U-TDOA operation

1. Location request originated by MSC or LBS application
2. SMLC initiates request to appropriate LMUs to measure signal TOAs from target mobile

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3. LMUs measure TOA from target mobile, forward measurements to SMLC
4. SMLC calculates mobile's position
5. Location Center forwards position data to GMLC (through BSC and MSC)
6. GMLC forwards position data to LBS application
Appendix G – Position Determination Data Message in CDMA and CDMA2000 networks

The Position Determination Data Message sent by the base station is comprised of request elements and response elements, as specified below.

Request elements sent by base station:

- Request MS Information
- Request Autonomous Measurement Weighting Factors
- Request Pseudorange Measurement
- Request Pilot Phase Measurement
- Request Location Response
- Request Time Offset Measurement
- Request Cancellation

Response elements sent by base station:

- Reject
- Provide BS Capabilities
- Provide GPS Acquisition Assistance
- Provide GPS Location Assistance – Spherical Coordinates
- Provide GPS Location Assistance – Cartesian Coordinates

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• Provide GPS Sensitivity Assistance
• Provide Base Station Almanac
• Provide GPS Almanac
• Provide GPS Ephemeris
• Provide GPS Navigation Message Bits
• Provide Location Response
• Provide GPS Almanac Correction
• Provide GPS Satellite Health Information

The *Position Determination Data Message* received by the base station is also comprised of request elements and response elements, as specified below.

• Request elements received by base station:
• Request BS Capabilities
• Request GPS Acquisition Assistance
• Request GPS Location Assistance
• Request GPS Sensitivity Assistance
• Request Base Station Almanac
• Request GPS Almanac
• Request GPS Ephemeris
• Request GPS Navigation Message Bits
• Request Location Response
• Request GPS Almanac Correction
- Request GPS Satellite Health Information

Response elements received by base station:

- Reject
- Provide MS Information
- Provide Autonomous Measurement Weighting Factors
- Provide Pseudorange Measurement
- Provide Pilot Phase Measurement
- Provide Location Response
- Provide Time Offset Measurement
- Provide Cancellation Acknowledgement
Appendix H – Qualcomm A-GPS solutions in CDMA networks

The A-GPS system Qualcomm implemented for CDMA network is UE-assisted. Both user plane and control plane architecture are supported. The Qualcomm A-GPS server is called ‘PDE’.

The Mobile System (MS) and Base Transceiver System (BTS) together with Mobile Switching Center/Base Station Controller (MSC/BSC) are common to both user plane and control plane architecture. The MS receives GPS signals and CDMA network measurements and communicates with the PDE via BTS and MSC.

In the user plane systems the PDE is interfaced with the Interworking Function/Packet Data Serving Node (IWF/PDSN) to communicate to the Application Server (AS) and MSC/BSC. The user plane architecture is presented in figure H.1.

Figure H.1 - User plane architecture in CDMA network

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In control plane deployments the PDE communicates with the Mobile Positioning Center (MPC) and MSC/BTS directly. The MPC is responsible to interface with Location Services (LCS). The LCS provides location applications that can be used by the user like maps, alerts, etc. The control plane architecture is presented in figure H.2.

Figure H.2 - Control plane architecture in CDMA network


1. A user initiates an emergency service call (ESC, for example, dialing 911 in the United States).

2. The MSC detects the ESC and then sends an Origination Request (ORREQ) message to the MPC. The ORREQ message has two purposes: to obtain call routing information to the nearest PSAP; and to tell the MPC to start the process of obtaining a precise position estimate for the MS. The MPC determines what
PSAP to route the call to based on some coarse location estimate, perhaps simply using the serving cell information.

3. The MPC returns call routing information to the MSC.

4. The MSC signals to the PSAP an incoming voice call.

5. The MSC connects the voice call between the MS and PSAP.

6. The MPC invokes the PDE to obtain a precise position estimate for the MS.

7. The MS and PDE exchange A-GPS and AFLT signaling enabling precision position. No details are shown here but multiple messages are exchanged. At some point during this exchange the PSAP requests from the MPC a precise position estimate for the MS. This is accomplished by sending an Emergency Services Position Request (ESPOSREQ) message from the ESME to the MPC.

8. The PDE returns the precise position estimate to the MPC.

9. The MPC provides the precise position estimate, via the esposreq message, to the PSAP.