

Wireless Position Location

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Abstract

- In 1996, the FCC issued the order for enhanced-911 (E-911) to provide the location of wireless callers using 911 emergency services resulting in significant development in wireless location technologies. Interest in locating wireless callers has continued to grow well beyond providing emergency services to include law enforcement scenarios such as criminal tracking and border enforcement, to commercial applications such as targeted location-based marketing.
- This tutorial describes the wireless position location technologies in use today including both handset-based and network-based approaches and their performance including accuracy, latency, robustness in both outdoor and indoor environments, and applicability across various wireless communication technologies (e.g. GSM, CDMA). Finally, we will discuss location technologies for 3G wireless systems and how hybrid systems that use more than one technology can be leveraged for improved performance.

Agenda

- Background and Introduction
 - E911 and Location Based Services (LBS)
- Wireless Position Location Solution Space
 - Basic Principles
 - Time, Power, or Angle of Arrival
 - Proximity, Fingerprinting
- Wireless Position Location Technologies
- Performance and Error Analysis
 - Estimation Error
 - Geometric Dilution of Precision
 - Non-Line of Sight Performance
- Location Services (LCS)
 - Control Plane vs. User Plane
- Summary

E911 Background and Timeline

- 1996 FCC issues Enhanced-911 (E-911) Report and Order 94-102
 - Phase I: Provide location of cell site (lat, long)
 - Accuracy within 5km (average cell site coverage radius)
 - Phase 2: Initial accuracy within 125m 67% of the time
- 1999 FCC revises Phase 2 accuracy requirements
 - Network Based Techniques within 100m 67% of the time, and within 300m 95% of the time
 - Handset Based Techniques within 50m 67% of the time and 150m 95% of the time
- 2002 FCC requires wireless operators provide E911 location data
- 2007 FCC mandates stricter accuracy standard
 - Must meet Phase 2 accuracy requirements at the community PSAP (Public Safety Answering Point) instead of averaged across entire national network
 - Forces consideration of hybrid approaches

Business Case for Location Based Services (LBS)

- FCC mandates geolocation for E911: *High cost to implement*
- Carriers leverage geolocation techniques to provide Location Based Services (LBS)
 - Recoup costs associated with E911 implementation
 - Additional revenue stream and service differentiation
 - Mobile Resource Management, location based advertising, etc.
 - Reduce subscriber churn
- LBS Market Drivers
 - LBS supports focus on long term value creation
 - Increased consumer awareness of location-based applications (OnStar, Garmin, etc.)
 - Competitive pressures driving operators to seek service differentiation
 - High-speed data networks and enhanced handsets enable more sophisticated LBS capabilities
 - Threat of internet players e.g. Google, Yahoo having great success in wired world
- LBS Market Challenges
 - High cost of geolocation technology can slow down rollout
 - Lack of A-GPS handsets
 - No single location technology can optimally address all calling environments
 - Privacy concerns affecting both supply and demand
 - Limited user awareness of LBS benefits

LBS Market Forecast (Frost & Sullivan):

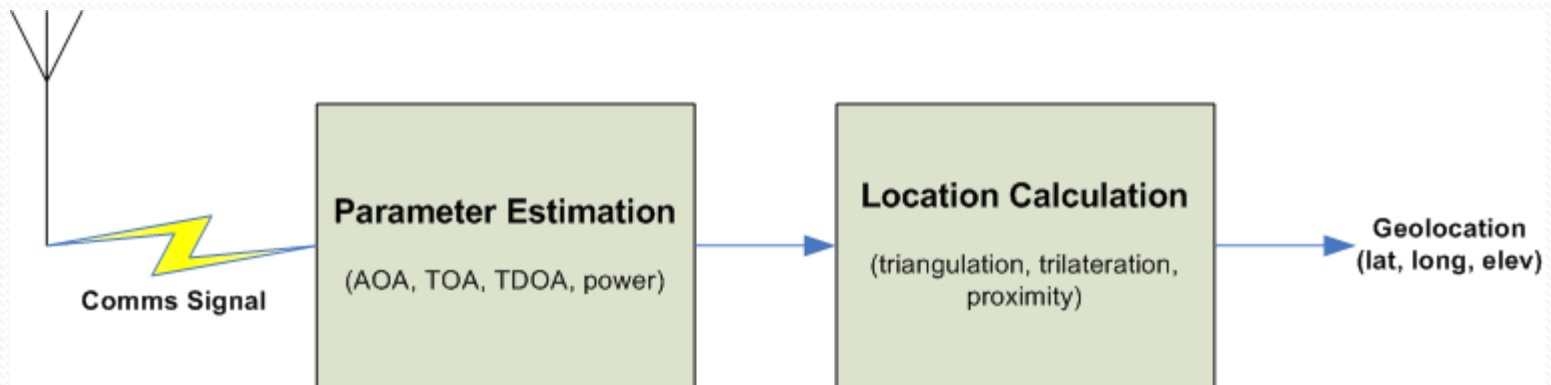
Projected annual US LBS revenues will reach \$3.5B by 2013 with approximately 46 million subscribers

Performance Requirements

- High Accuracy
- High Yield
- Low Latency
 - *TTF* (*time to first fix*)
- Locate all models of mobile phones
- Locate stationary and moving phones
- Locate mobile phones indoors and outdoors
- Locate mobile phones across all environments (urban, suburban, rural)
 - *60% of all calls in urban and indoor environments*
- And low cost of course with minimum modifications to handsets and the network

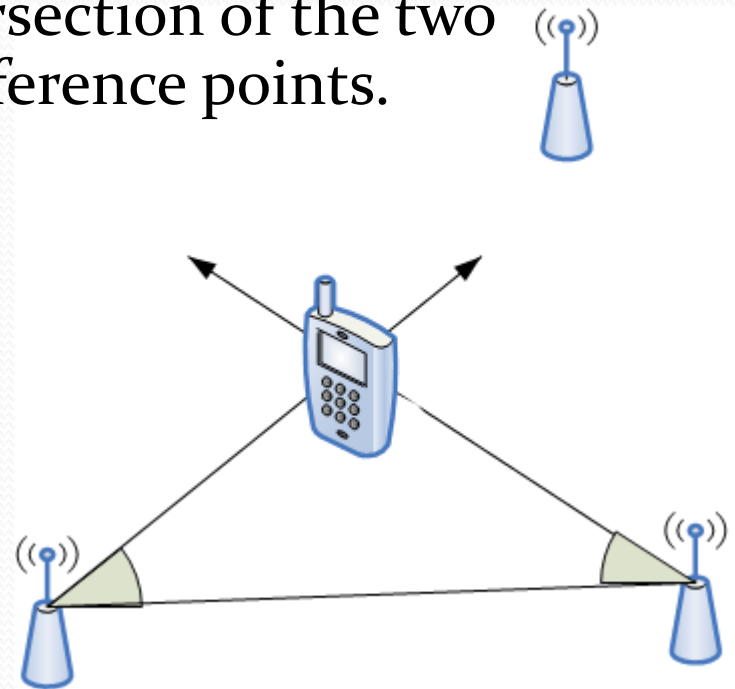
Basic Principles

- Typical solution space involves estimation of signal parameters followed by location calculation.
- Signal Parameter Estimation includes:
 - AOA (angle-of-arrival)
 - TOA (time-of-arrival) and TDOA (time-difference-of arrival)
 - Signal Power
- Location Calculation includes:
 - Triangulation (bearing angles)
 - Trilateration / Multilateration (distance from multiple reference points)
 - Proximity (uses closest reference point)
 - Fingerprinting (RSS, multipath)



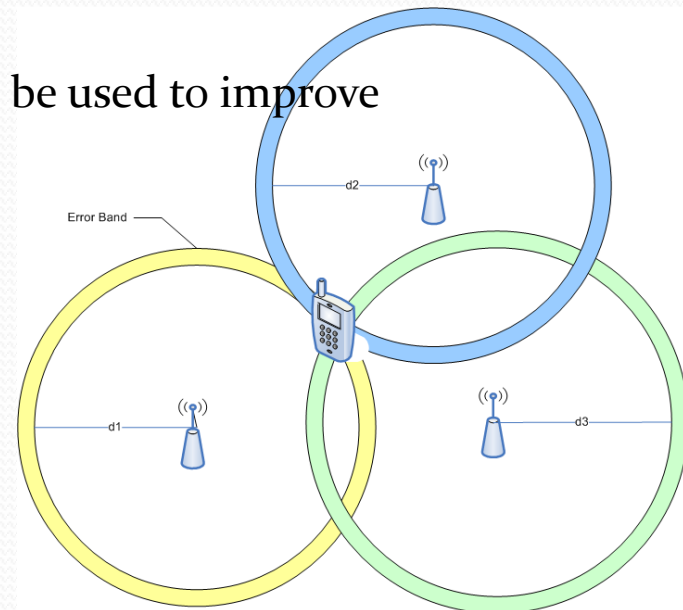
Triangulation: AOA (angle-of-arrival)

- Determine the angle-of-arrival of the mobile signal received at multiple base stations with known location.
- Typically requires an antenna array at the base station.
- Location is determined by the intersection of the two lines of bearing from the known reference points.



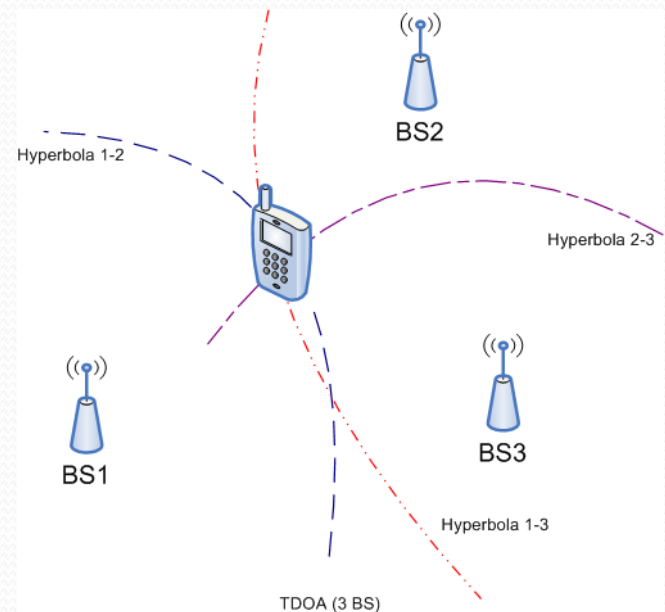
Trilateration

- Measures the distance from the mobile to multiple reference points (base stations) with known locations.
- Location is determined as the intersection of the circles drawn around each reference point.
- Time-of-Arrival (TOA) trilateration
 - Signal propagation time is calculated from the Time-of-Arrival of each signal measured at the mobile and used to determine distance from each reference point based on the propagation speed in the medium (speed of light)
- Received Signal Strength (RSS) trilateration
 - Distance is proportional to RSS, path models can be used to improve accuracy



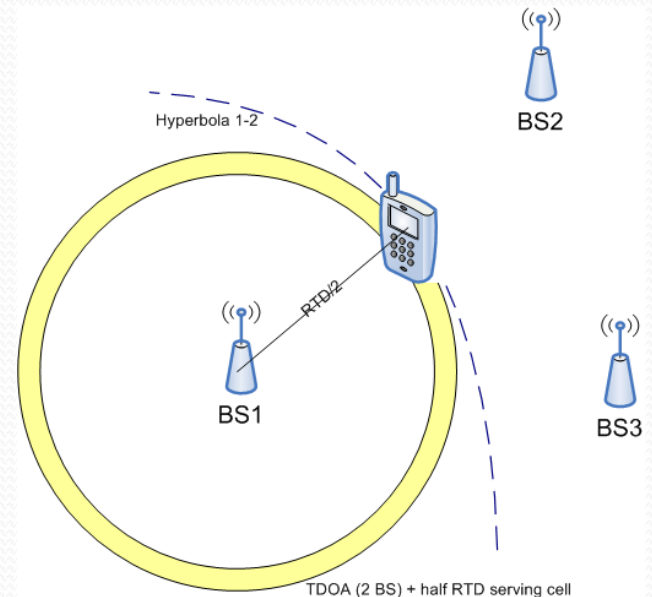
TDOA (≥ 3 Base Stations)

- The time-difference-of-arrival (TDOA) is measured between multiple pairs of reference points with known locations.
- Each TDOA measurement yields a hyperbolic curve on which the mobile may reside.
- The intersection of multiple curves produces the location estimate.



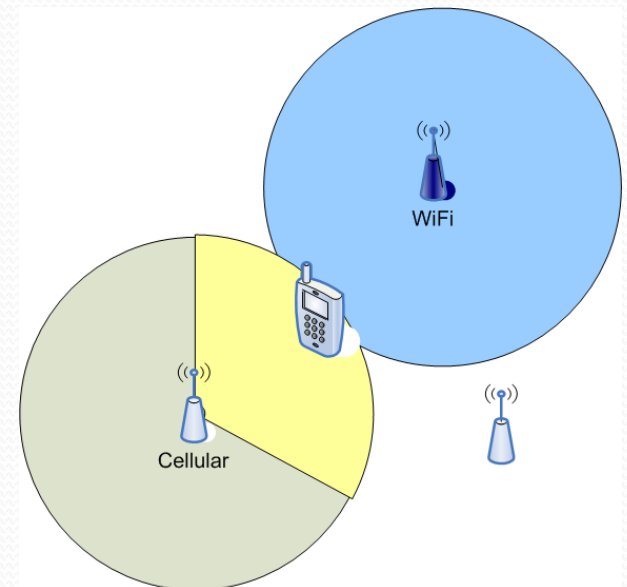
TDOA (2 Base Stations)

- If only 2 base stations are available, then only one hyperbolic curve is produced based on the TDOA.
- The Round Trip Time (RTT) of the signal between the mobile and the serving base station can be used to get a radial distance measurement.
- The intersection of the circle with radius equal to half the RTT and the hyperbolic curve indicates the position of the mobile.



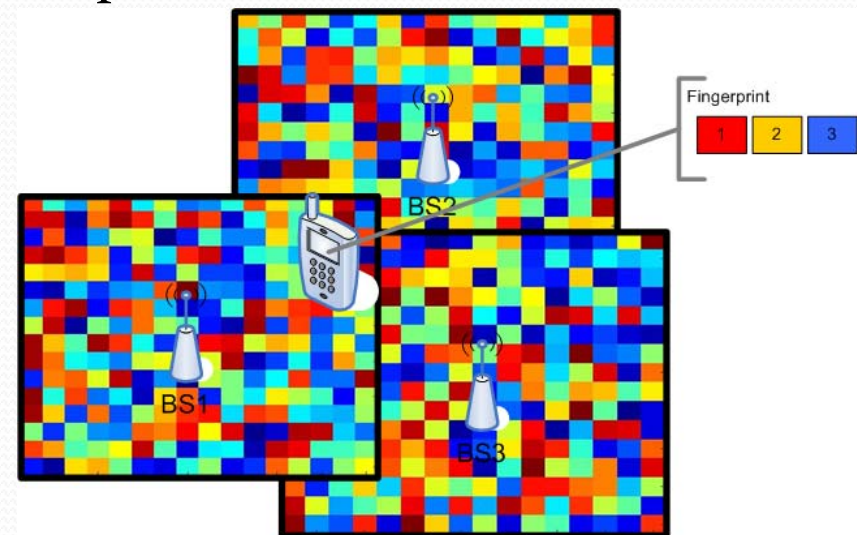
Proximity

- Mobile position location is determined by assigning the coordinates of a known location that is “close” to the mobile.
 - Base station serving cell
 - Closest WiFi access point
- Can also use the intersection of multiple overlapping areas to improve accuracy.



Fingerprinting

- Uses the received signal strength or multipath characteristics of a specific location to “fingerprint” that location.
- Compares measured values at the mobile to those stored in a pre-calculated database to determine the best match.
- Works better in complex urban environments with large variability in the multipath channels per discrete location.



Wireless Position Location Technologies

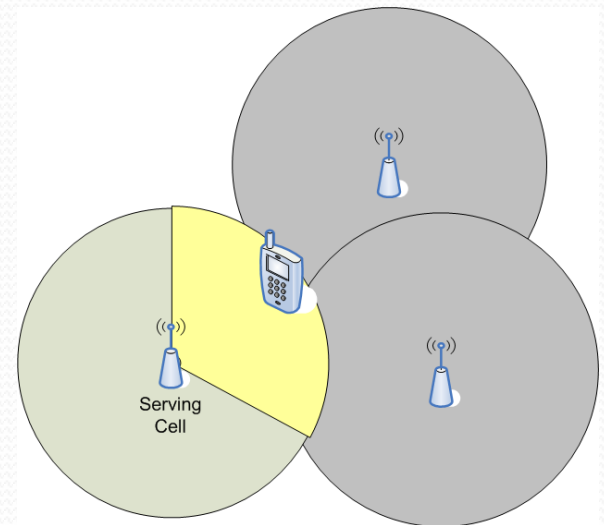
Technology	Category
Cell ID + TA	NETWORK
A-GPS	HANDSET
AFLT	HANDSET
E-OTD	HANDSET
OTDOA	HANDSET
UTDOA	NETWORK
RSS Trilateration	HANDSET
RF Fingerprinting	NETWORK
AOA	NETWORK
MIMO	Both

Handset-based or Network-based

- Handset-Based Techniques US CDMA wireless carriers
 - Primary Techniques
 - A-GPS (Assisted GPS)
 - GPS (Global Positioning System)
 - Hybrid Technique: handset GPS w/ additional information from the network
 - Fallback Technique
 - AFLT Advanced Forward Link Trilateration
- Network-Based Techniques US GSM wireless carriers
 - Primary Technique
 - U-TDOA (Uplink Time Difference of Arrival)
 - Fallback Technique
 - CGI+TA (Cell-Global Identity plus Timing Advance)

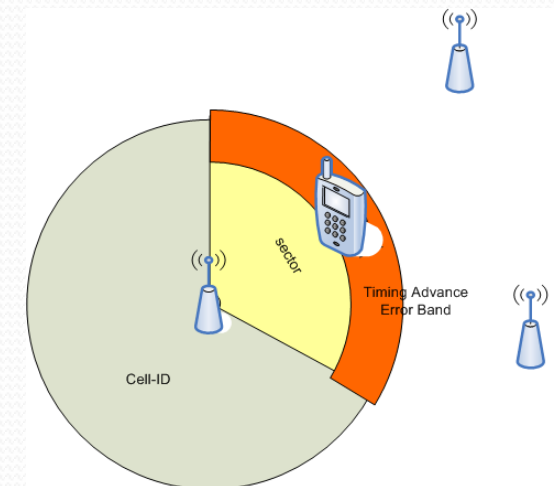
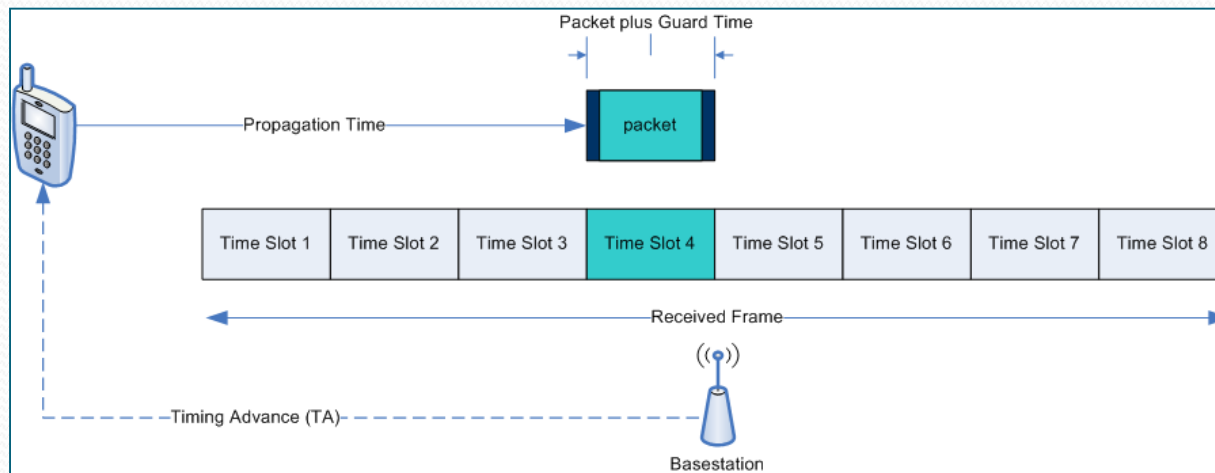
Cell-ID

- Network-Based method of locating mobile by reporting location of serving cell and sector.
- Accuracy is based on coverage radius of serving cell, and therefore is much better in urban environments.
 - 300 m to 20km
- Low cost of implementation. Use existing network infrastructure, same techniques used to determine handoff.



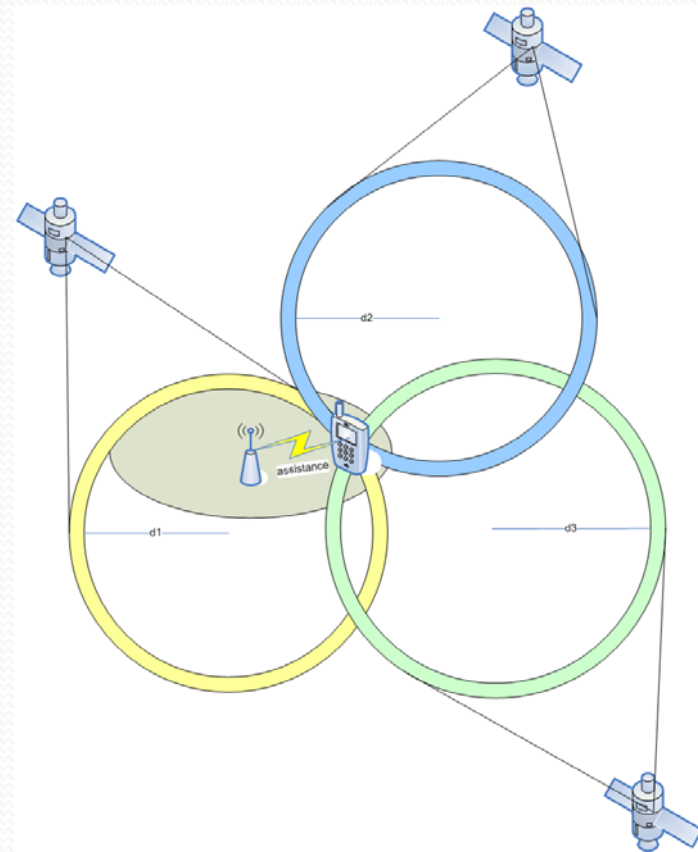
Cell-ID + TA (timing advance)

- Uses the Timing Advance messages utilized within GSM networks to adjust the timing of mobile burst transmission to align the reception of mobile communications at base station within proper TDMA time slot.
- Timing Advance accounts for propagation delay between the mobile and the base station, and therefore can be used to estimate distance from the base station.



GPS (Global Positioning System)

- 24 low earth orbiting (LEO) satellites in six orbits – at least 5 are visible from every point on the earth
- Satellites transmit their location and a timing signal to terminals on the earth
- GPS terminal calculates distance to each satellite based on time delay of received signal (TOA technique).
- With range to multiple (4 or more) known satellites, GPS terminal can calculate its latitude, longitude, altitude and timing offset (trilateration).
 - 3 satellites needed for lat and long only
 - Accuracy improves with more satellites (many GPS chipsets can use up to 12 satellites)
- Satellites must have very precise clocks, but terminals do not have same requirement.



GPS Performance

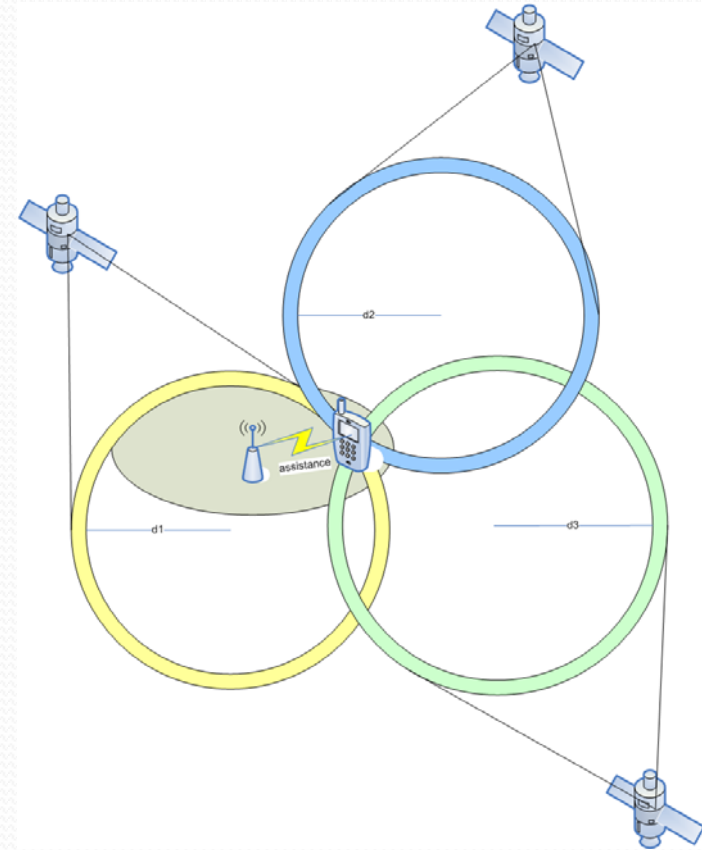
- Accuracy under ideal conditions, with clear open sky is on the order of tens of meters (30m-80m)
- Challenges
 - Latency or Time To First Fix (TTFF)
 - Acquisition times can exceed several minutes
 - Clear view of sky and limited indoor coverage
 - Must have a clear view of the sky to adequately receive multiple satellite signals
 - Low receive power implies reception indoors is limited due to additional path loss through building structures
 - L Band transmission (1575 MHz)
 - Nominal received power of -129 dBm

Differential GPS (DGPS)

- Network of stationary GPS receivers calculates error corrections for all visible satellites and broadcast results to mobile GPS receivers.
- Mobile GPS receivers experience essentially the same errors as the stationary GPS receiver due to close proximity (signal propagation path is essentially the same to both receivers)
- Mobile GPS receivers apply corrections to their received signals resulting in a order of magnitude improvement (accuracy to several meters)

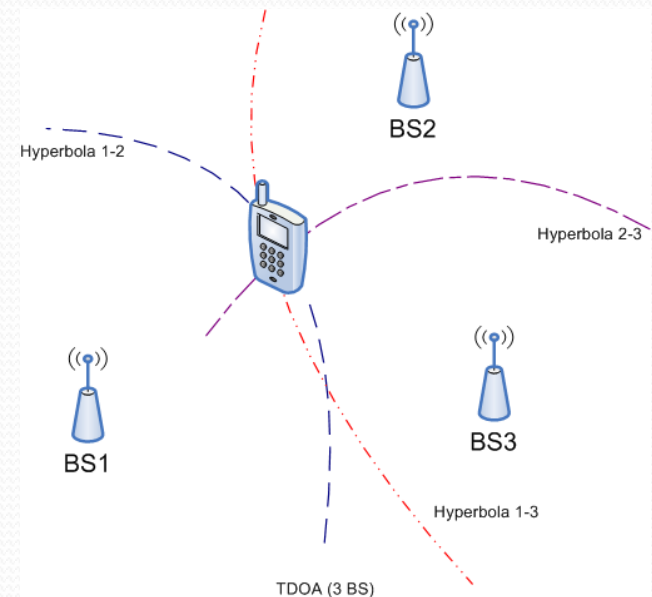
Assisted GPS (A-GPS)

- In order to improve indoor coverage, as well as reduce latency the network can provide additional information to assist the mobile in calculating location - Network Assisted GPS
- Network based reference receivers with clear view of open sky provide location and signal timing information (including PN code phase per satellite) to a location server which forwards to the mobile station.
- Acquisition time is reduced by reducing the Doppler vs. Code Phase search space from several minutes down to 10 seconds or less.
- Accuracy is typically up to 50m, with 15m accuracy in ideal conditions.
- Indoor coverage is still not ideal, and best accuracy is still in open sky. Also suffers in rural environments, where stationary GPS receivers are more widely spread.



Advanced Forward Link Trilateration (AFLT)

- Fallback handset-based geolocation technology for US CDMA carriers
 - Forward link: Base Station to Mobile Station
 - Trilateration: Distance from multiple reference points via TDOA measurements
- Base Stations are synchronized via GPS to 2ms. Mobile station receives pilot signal from 3 or more base stations and calculates the TDOA
- Uses IS-801 messages to transmit location information from mobile to network

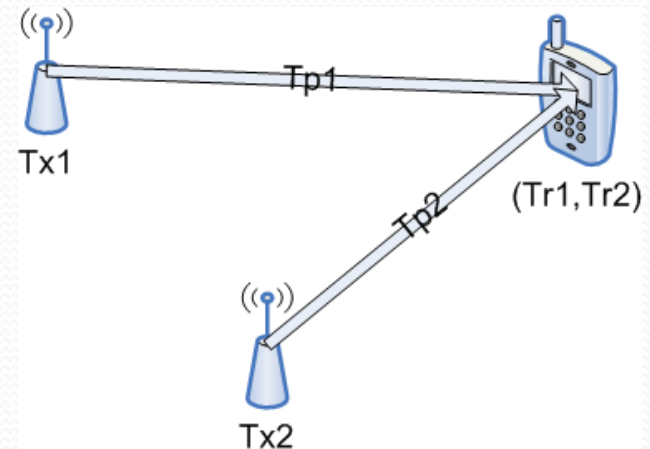


E-OTD

- Operates on GSM/GPRS networks
- Measures the TDOA of the synchronization signals from multiple base stations at the mobile station.
- GSM networks are not synchronized, therefore additional network equipment (Location Measurement Unit – LMU) is required to measure clock differences between base stations and report to mobile stations.
 - $GTD = OTD - RTD$
 - GTD: Geometric Time Difference (TDOA: difference in propagation time)
 - OTD: Observed Time Difference (difference in received times)
 - RTD: Real Time Difference (difference in transmit times)
- Expensive solutions for operators
- Accuracy from 50m to 500m, Latency around 5s

Geometric Time Difference

- $GTD = OTD - RTD$
 - OTD: Observed Time Difference
 - Difference in Received Times: $(Tr_1 - Tr_2)$
 - RTD: Real Time Difference
 - Difference in transmit times $(Tx_1 - Tx_2)$
 - GTD: Geometric Time Difference
 - Difference in Propagation Time $(Tp_1 - Tp_2)$
 - $GTD = Tp_1 - Tp_2$
 - $GTD = (Tr_1 - Tx_1) - (Tr_2 - Tx_2)$
 - $GTD = (Tr_1 - Tr_2) - (Tx_1 - Tx_2)$
 - **$GTD = OTD - RTD$**

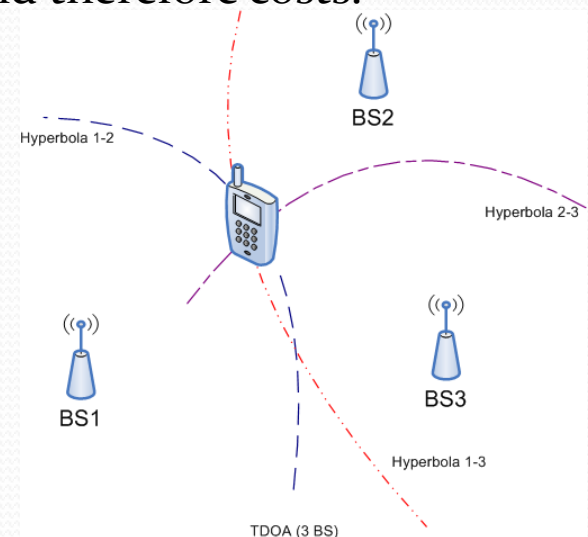


OTDOA

- Similar to E-OTD but used in Wideband CDMA (WCDMA) networks
- Measures the TDOA of the received signal from multiple base stations at the mobile station.
- For unsynchronized networks, LMU is needed to provide additional time difference / synchronization information to mobile station
- Hearability is a problem due to “near-far” effect in CDMA networks
 - Base stations transmit on the same frequency, therefore considerable co-channel interference. Closest base station dominates, and can impair measurements from weaker base stations.
 - Idle Period Downlink (IPDL) – technique to improve hearability by scheduling idle periods so mobiles can measure signals from base stations farther away

UTDOA

- Network-based geolocation technique used by US GSM carriers involving the reception of the mobile signal (uplink) at multiple Location Measurement Units (LMUs) typically co-located with the base stations.
- Three step process:
 1. Acquire mobile signal at multiple time-synchronized locations (LMUs) and report serving cell site, time and freq of mobile.
 2. Measure the difference in signal propagation time between pairs of LMUs (TDOA)
 3. Calculate location based on TDOA and known location of LMUs
- Requires additional network equipment (LMU), and therefore costs.

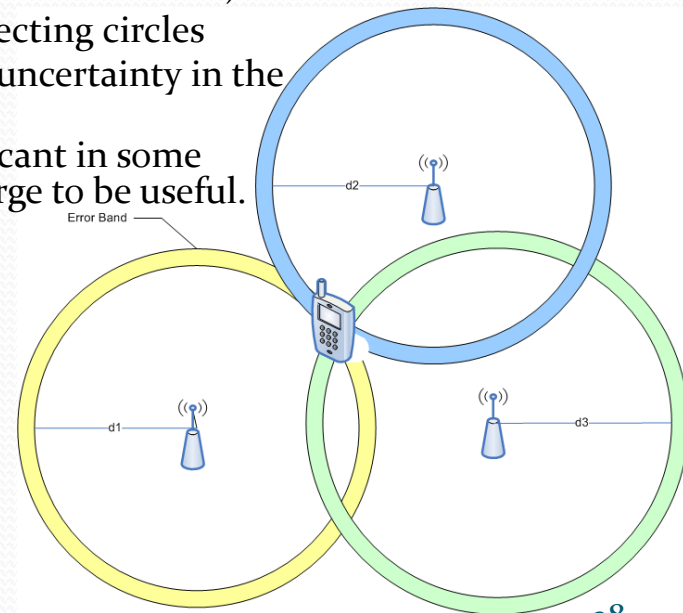


UTDOA

- Accuracy from 50m to 100m with good yield across outdoor and indoor environments.
- Integration times are much longer than needed for demodulation / symbol decoding, which yields considerable processing gain
 - 25 ms integration time over control channel yields 30 dB processing gain over single symbol integration time
- Accuracy improves as the number of LMUs used to calculate TDOA increases
 - typically 8 LMUs involved in location calculation
 - As many as 50 LMUs can be used

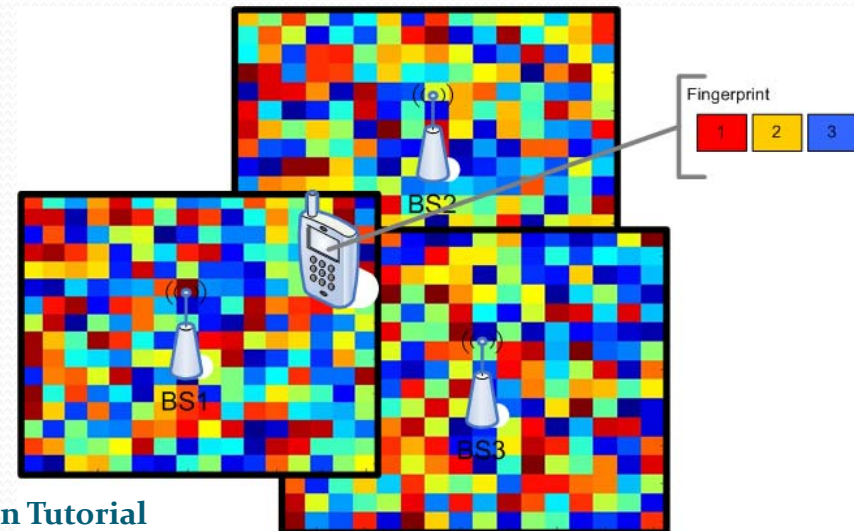
RSS Trilateration

- Received Signal Strength (RSS) is used to calculate the distance between transmitter and receiver based on known transmit power and transmitter location, and an appropriate path loss model.
 - Inverse Square Law (Friis Equation)
 - Power decreases as the inverse of the square of the distance between transmitter and receiver
 - Ideal free space path loss case
 - Does not account for fast fading (multipath), slow fading (shadowing), polarization mismatches, and system losses
 - More realistic mobile communications channel model can be used such as Okumura-Hata Model
 - Reduces affect of fast fading (multipath) through averaging
 - Accounts for distance and slow fading (shadowing) within model
 - Includes 4dB to 12dB correction factor for environment type (rural to dense urban)
- Radial distance from reference points is used to construct intersecting circles
- Error Bands can be constructed for each path to account for the uncertainty in the measurements.
- Number of parameters that affect power estimates can be significant in some environments and variability could make estimation errors to large to be useful.



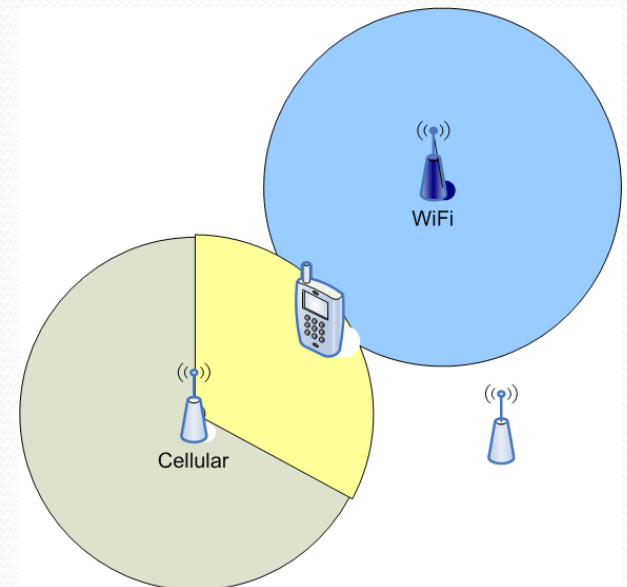
Multipath Fingerprinting

- In dense urban and indoor environments, multipath can have a considerable effect on the received signal.
- If the environment has enough variation, a unique multipath signature can be determined at each location.
- In the pre-deployment phase, RF measurements are made at each location in the area of interest recording multipath delay profile for each base station within reach and saved to database.
 - Can be used with one or more base stations depending on uniqueness of RF multipath environment.
- In the operational phase, the mobile makes a similar measurement and reports the results to the network where a pattern matching algorithm is used to determine the most likely location.



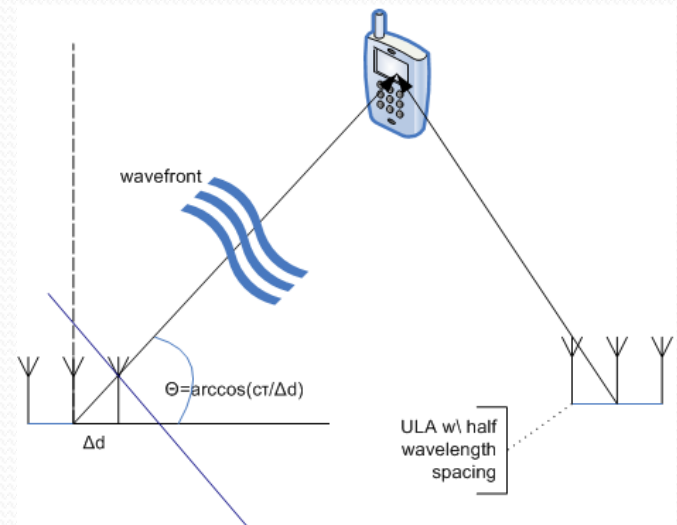
WiFi Proximity

- Smart Phones now have the ability to access the internet via a WiFi connection.
- Proximity to WiFi access points with known locations could enable various location techniques
 - Mobile location = location of closest WiFi Access Point (accuracy equal to WiFi coverage area)
 - Weighted Average of RSS of multiple WiFi Access Points
 - Combination of Cell-ID and WiFi Proximity



AOA

- Angle-of-arrival (AOA) typically uses an antenna array at the receiver to calculate a line of bearing to the transmitter.
 - e.g. a uniform linear array with half wavelength spacing (spatial sampling)
- General Cross-Correlation techniques are used to measure the time-delay or phase-shift between elements which is used to calculate AOA
 - Calculate bearing angle $\theta = \arccos(c\tau/\Delta d)$ using the estimated time delay between elements of array with known spacing
 - Time delay estimated as argument that maximizes the cross-correlation which can be calculated as the inverse Fourier Transform of weighted cross-spectrum
 - Weighting is used to maximize peak detection (whitening)
- Super-resolution techniques (e.g. MUSIC) can be used to improve resolution with added complexity



MIMO

- Multiple Input Multiple Output (MIMO) OFDM (Orthogonal Frequency Division Multiplexing) is being incorporated in many 4G wireless networks (e.g. LTE, WiMax)
- MIMO typically includes multiple antennas at both the receiver and transmitting stations. Therefore, AOA techniques can be incorporated without significant cost.
- OFDM techniques are inherently multipath resistant due to the transmission of multiple narrowband channels, which provides frequency diversity and minimizes the impact of narrowband or frequency selective fading.
- Narrowband geolocation techniques can be used per OFDM channel and averaged to produce a more robust system.

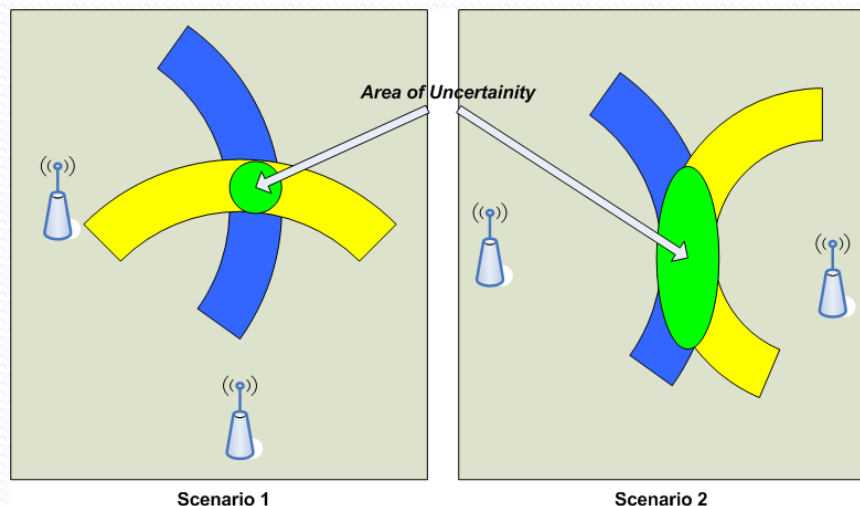
Estimation Error

- Parameter Estimation Error
 - Cramer-Rao Lower Bound (CRLB) sets the lower limit for the variance (covariance matrix) of any unbiased estimate of an unknown parameter.
 - CRLB is defined as the inverse of the Fisher Information Matrix where x is the measurement and θ is the unknown parameter.

$$E\{(\hat{\theta} - \theta)(\hat{\theta} - \theta)'\} \geq J_{\theta}^{-1}$$
$$J_{\theta} \xrightarrow{\text{def}} E\left\{\left[\frac{d}{d\theta} \ln f(\hat{x} | \theta)\right]\left[\frac{d}{d\theta} \ln f(\hat{x} | \theta)\right]'\right\}$$

Geometric Dilution of Precision (GDOP)

- Geometry of transmitters and receivers has an effect on Location Estimate
- Consider a trilateration example range estimate from two base stations results in intersecting circles, and the estimation error in the range is represented as the width of the circle.
 - Scenario 1: base stations are far apart with bearing angle to mobile station nearly orthogonal
 - Scenario 2: base stations are almost collinear
- Scenario 2 results in a larger uncertainty due to the geometry, which is called Geometric Dilution of Precision



Non-Line-of-Site (NLOS) Multipath

- NLOS multipath occurs when
 - The direct path or line-of-site path is obstructed so that only the reflected paths are received
 - or the LOS path is attenuated such that it has a lower received power than the strongest NLOS path.
- Many geolocation algorithms use the parameters of the strongest path.
- NLOS errors are typically modeled as additive bias to LOS estimates.
 - AOA – points to the reflection not transmitter
 - TOA/TDOA – longer reflected path results in longer estimated distance
 - RSS – received signal power includes additional losses due to multipath (fast fading) and shadowing (slow fading)

NLOS Errors

- There are typically two techniques used to address NLOS multipath propagation:
 - Mitigation: NLOS errors modeled as additive bias to LOS data with either known or unknown distribution.
 - NLOS correction is applied to estimate LOS parameters
 - NLOS paths are estimated and filtered out
 - Exploitation: RF Fingerprinting techniques use the NLOS data to uniquely identify a location by its multipath delay profile.

Wireless Position Location in Cellular Networks

- 2G
 - U-TDOA (uplink time difference of arrival)
 - AGNSS (assisted global navigation satellite systems)
 - E-OTD (enhanced observed time difference)
- 3GPP
 - UTRAN (Universal Terrestrial Radio Access Network)
 - Cell-ID based
 - OTDOA (Observed Time Difference of Arrival)
 - A-GPS (Assisted GPS)
- 3GPP2 (cdmaOne, cdma2000) – time-synchronized
 - AFLT (advanced forward link trilateration)
 - A-GPS (Assisted GPS)
- 4G (hybrid techniques)
 - U-TDOA (uplink time difference of arrival)
 - RF Fingerprinting / A-GPS

Summary

Location Technology	Category	Accuracy	Cost	TTFB	Coverage	Wireless Standard	Handset Req.	Network Req.
Cell ID	Network Based	300m-20km	Low	Fast	Moderate	GSM	None	None
Cell ID+SS	Network Based	250m-12km	Moderate	Fast	High	GSM	None	Hardware Mod
Cell ID+TA/RTT	Network Based Handset Assisted	200m-11km	Moderate	Fast	High	GSM	None	Software Mod
AOA	Network Based	100m-200m	Moderate	Moderate	Good(Multipath issues)	GSM	None	HW and SW Mod
TOA	Network Based Handset Assisted	50m-200m	Low	Moderate	Good(Multipath issues)	GSM	None	HW and SW Mod
E-OTD	Handset Based Network Assisted	50m-125m	High	Moderate	Good(Multipath issues)	GSM	Software Mod	Additional HW and SW (LMU)
OTDOA	Handset Based Network Assisted	20m-200m	High	Moderate	Good(Multipath issues)	WCDMA	Software Mod	Additional HW and SW (LMU)
UTDOA	Network Based	<50m	High	Moderate	Good	Multiple	None	Additional HW and SW (LMU)
EFLT/AFLT	Handset Based Network Assisted	30m-350m	Moderate	Moderate	Good(Multipath issues)	CDMA	Software Mod	HW and SW Mod
GPS	Handset Based	30m-80m	Low	Slow	Moderate (urban) High (rural/suburban)	All	Additional HW and SW	Minor Modifications
AGPS	Network Based Handset Assisted	5m-50m	Moderate	Moderate	Variable	CDMA	Additional HW and SW	Additional HW and SW
RF Fingerprinting	Network Based	10m (indoor and outdoor)	Moderate	Moderate	Good	Multiple	None	Additional HW and SW

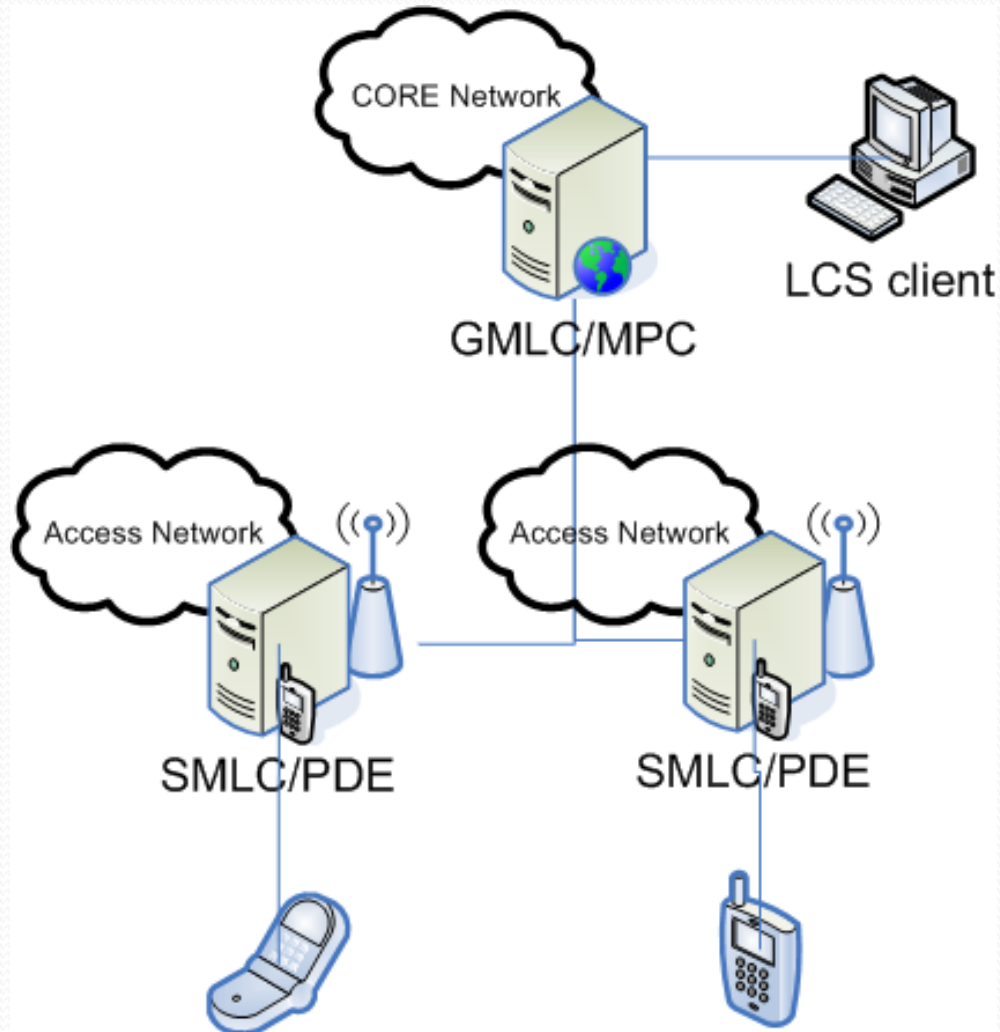
Location Services (LCS) Architecture

- Control Plane: 3GPP
 - Positioning data sent over control channel
 - Primarily network based (can be handset assisted)
 - Advantages:
 - No modifications to handset
 - Network-Based Measurements
 - Supports Law Enforcement applications where location can be determined without knowledge of the handset
 - Location can be determined for visiting devices (no home location server needed)
- Secure User Plane(SUPL):OMA
 - Position determination related messaging is transmitted as user data over IP
 - Constrained to handset based location techniques
 - Advantages:
 - No dependence on core or access network location functions
 - User device (SUPL enabled terminal-SET) uses common location services and protocols across multiple access types
 - Allows roaming SET to query home SUPL location server (SPL) for location with dependence on physical access network.

Control Plane Entities

- Gateway Mobile Location Center (GMLC)
 - Gateway functionality to support circuit service emergency and location based queries
 - Also called Mobile Positioning Center (MPC) in 3GPP2
- Serving Mobile Location Center (SMLC)
 - Hosts position calculation functions and coordination of location requests.
 - Also called Position Determining Entity (PDE) in 3GPP2
- Location Measurement Unit (LMU)
 - Performs / assists in location measurements (not required, dependent on location technology)

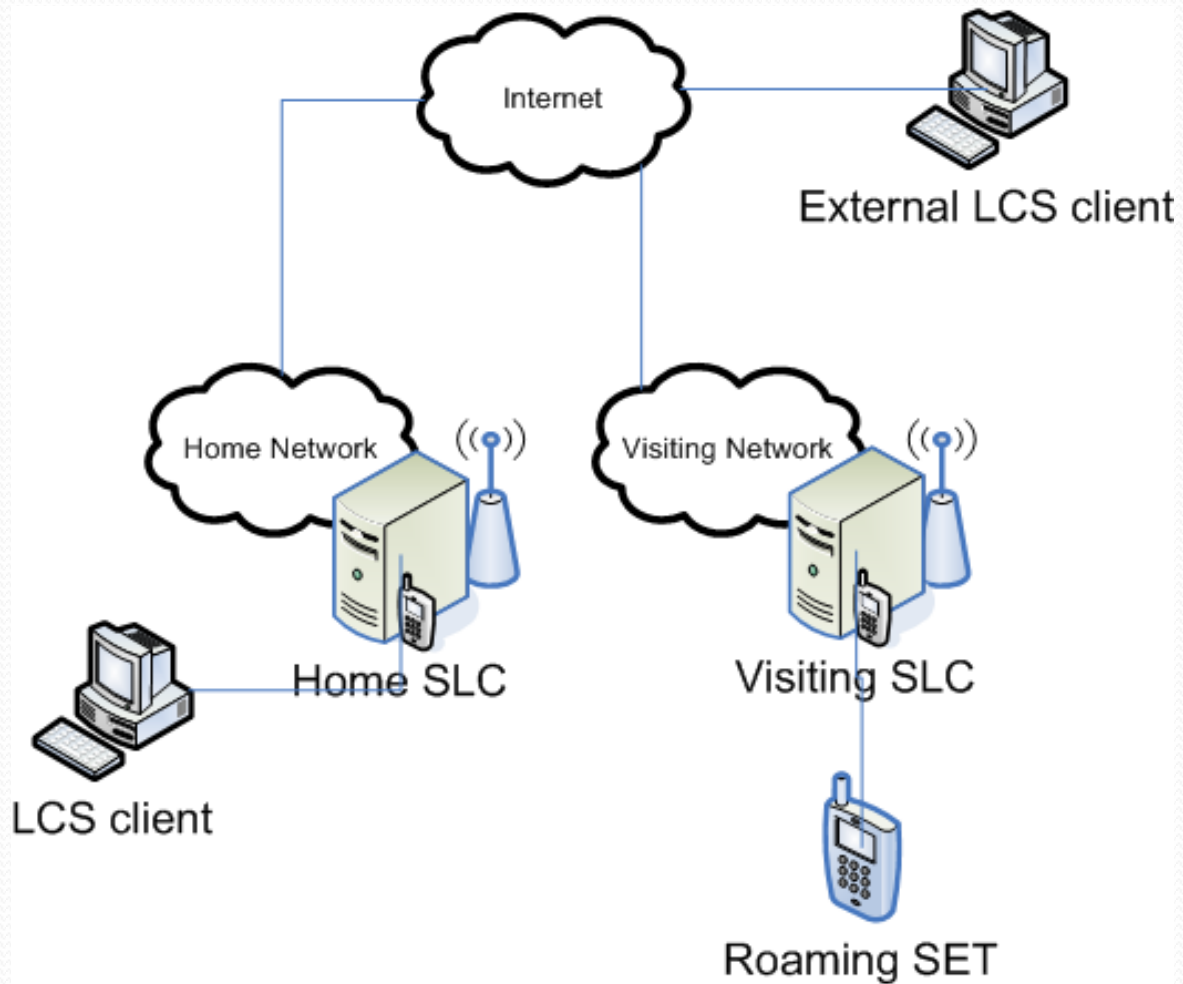
Control Plane Architecture



SUPL Entities

- SUPL Enabled Terminal (SET)
 - Supports Handset based or assisted positioning calculation
- SUPL Location Platform (SLP)
 - SUPL Positioning Center (SPC)
 - Provides positioning assistance to SET and calculates SET position
 - Home and Visiting SPCs
 - SUPL Location Center (SLC)
 - Coordinates network operation of SUPL and manages SPCs
- Mobile Location Service (MLS) protocols
 - MLP: Mobile Location Protocol
 - Query position of mobile station between location server and client
 - RLP: Roaming Location Protocol
 - Protocol between location servers while mobile is roaming
 - PCP: Privacy Checking Protocol
 - Protocol between location server and privacy checking entity

SUPL Architecture



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Biography

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