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Enhanced Observed Time Difference Location Technology Through Fading Channels in GSM Networks

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Abstract: This study presents a communications model that investigates the position accuracy of a Global Standard Mobile (GSM) phone employing the Enhanced Observed Time Difference (EOTD) location technology. The EOTD positioning technique requires the Mobile Station (MS) to detect signals from at least three Base Stations (BS). This study assumes the three BSs are synchronized in time. For a given BS geometry with respect to the MS, a Monte Carlo simulation was performed to assess the two-dimensional position accuracy of the MS in Rayleigh and Ricean fading channels. In each channel, a Monte Carlo simulation was performed for a good and a bad BS-to-MS geometry. Location-based services have been standardized for incorporation into 3rd generation wireless communications as a result of the Federal Communications Commission's (FCC) mandate on wireless carriers to provide Automatic Location Information (ALI) during emergency 911 calls. This mandate has driven the wireless carriers to explore terrestrial, satellite and hybrid based location technology solutions. The study concludes with the fact that EOTD as the primary location technology does not fulfill the FCC E911 mandate and Hybrid technologies might overcome the EOTD limitations.

Key words: GSM, fading channels, EOTD, location services

INTRODUCTION

Location services in cellular networks are going to be deployed as a standard feature in 3rd generation wireless communication systems. The FCC required all Personal Communication System (PCS) and mobile communication networks to possess the capability of accurately locating the MS during an emergency 911 call. This requirement is also needed to comply with existing networks and phones. Since the early stages of GSM, it was understood that a location determination feature would be implemented. In the USA, the GSM is implemented in the 1900 MHz band and is referred to as GSM/PCS 1900 or GSM North America[1].

The Enhanced Observed Time Difference (EOTD) location method is based on an existing feature in GSM stations, which is Observed Time Difference (OTD). OTD calculates the time difference between signals coming from two different BSs to the MS. The EOTD calculation extends the OTD technique by incorporating another time difference to determine the synchronization of the BS in the GSM network. Many factors impact the two-dimensional accuracy of an EOTD position solution. For example, BS to MS geometry, multipath, channel classification and network synchronization are few parameters that affect position accuracy. Recent field studies implementing the EOTD have shown two-dimensional position accuracies ranging from 50 meters to 500 meters[2-4].

This study analyzes the accuracy of an EOTD position estimate in a GSM network for three BSs arranged in two geometries (good, poor) under two different channel models. A *Rayleigh flat fading* channel is representative of a city environment, with a lot of objects between the BS and MS that yields significant signal fading and multipath delay. The rural environment is represented by a *Ricean fading* channel because of its benign signal fading and line-of-site between the BS and the MS. In cellular networks, more BSs are typically visible in city environments than in rural environments due to the density of people in each sector. This impacts the availability of an EOTD position estimate in each environment. However, EOTD system availability is not the focus of this study. The position accuracy is computed and the performance of EOTD in each channel is compared.

MATERIALS AND METHODS

System model: This study describes the key components of the simulation used in this effort. The basic concepts

Table 1: Synchronization burst structure

Bit number	Length of field	Contents
0-2	3	Tail bits
3-41	39	Encrypted data bits
42-105	64	Training sequence
106-144	39	Encrypted data bits
145-147	3	Tail bits
148-156.25	8.25	Guard period

of GSM and EOTD are presented first. Next, the whole system structure is discussed with the techniques used to extract the timing and data information for location determination.

GSM: GSM (Global System Mobile) is a digital wireless standard that was developed by the European digital mobile telephone standard. This standard works in the 900MHz frequency band (in the USA GSM works in the 1900MHz band) and utilizes two 25MHz bands, each divided into 200 KHz channels called ARFCN (Absolute Radio Frequency Channel Numbers) that are assigned to users for use. GSM is based on TDMA (Time Division Multiple access), which allows several users to share the same bandwidth giving them access at different time intervals. A GSM frame consists of 8 time slots, each with 156.25 bits wide. Since the 25 MHz band has 125 channels of 200 KHz bandwidth, 1000 traffic channels exist. The frame is the basic data block in GSM, multi-frames and super-frames are just groups of frames that are handled by GSM. Radio transmissions on both channels (forward and reverse) are made at a channel data rate of 270.833 Kbps (1625/6 Kbps) using binary GMSK (Gaussian Minimum Shift Keying) modulation (with BT = 0.3). The signaling bit duration equals to 3.692 μs and the effective channel transmission rate per user is 33.854 Kbps (i.e., 270.833Kbps/8). Due to overhead data, the actual data rate/user becomes 24.7 Kbps.

GSM has various types of channels that handle both data and control signaling. Every channel type has a distinct signal structure that identifies it from other channel types. The Traffic channel uses what is called the Normal Burst as its signal/time slot burst. The control channel uses various bursts, such as the Synchronization burst and the Frequency correction burst. In the timing calculation for location determination, the Synchronization burst of the control channel is used. The burst consists of 156.25 bits[5,6] Table 1. Once the control data is available, it goes into a source/speech coding stage, then channel coding with interleaving, finally the burst is formed and gets modulated and sent to the RF portion of the MS/BS for transmission. Control data goes through a Cyclic Block encoder with a generator polynomial given by:

$$g(x) = \left(x^{23}+1\right)*\left(x^{17}+x^{3}+1\right) \tag{1}$$

This adds 40 bits to the control data for error correction. The data is then passed through a rate 1/2 convolutional encoder with K = 5 (constraint length). The two polynomials used are:

$$G_0(x) = x^4 + x^3 + 1 \tag{2}$$

$$G_1(x) = x^4 + x^3 + x + 1 \tag{3}$$

Once the data get encoded and encrypted, the burst is formed. The burst is then passed on to the modulator. The modulation scheme for GSM is GMSK. The data is converted into an NRZ (Non-Return to Zero) stream ∈ [-1,1] and then passes through a gaussian filter with a transfer function given by:

$$h(t) = \frac{1}{\sigma T\sqrt{2\pi}}\exp\left(\frac{-t}{2\sigma^2 T^2}\right) \tag{4}$$

where,

$$\sigma = \frac{\sqrt{\ln(2)}}{2\pi BT}$$

and BT = 0.3. BT is the bandwidth-bit-duration product. The obtained GMSK signal after pulse shaping becomes:

$$s(t) = \sqrt{2E_b T}\cos\left(2\pi f_c t + \theta(t) + \theta_0\right) \tag{5}$$

where,

$$\theta(t) = \sum_i m_i \pi h \int_{\infty}^{t-iT} g(u)du$$

$\theta(t)$is the accumulated phase and

$$g(u) = h(t) * \text{rect}\left(\frac{t}{T}\right)$$

The modulation symbol rate is 1/T = 1625K/6 symbols/s (i.e., ≈ 270.833K symbols/s). GMSK has the feature of possessing a smooth phase trajectory as compared to MSK (Minimum Shift Keying). Also, it is most attractive for its power and spectral efficiencies[7].

Location technologies: Location technologies can be classified into three categories; stand-alone, satellite-based and terrestrial-based. In most location determination systems, ranges are formulated between two entities. Multiple remote entities, with known locations, transmit signals for the equipment of a remote user for range determination. The multiple ranges are used to formulate a position[8-10].

Stand alone systems: A stand-alone system does not rely on multiple range measurements in order to formulate a position of the user. Instead, this type of system attempts to provide a user's location based on quantities such as the received power level[11]. An example is U.S. Wireless' RF fingerprint technology. RF signatures are taken arbitrarily in a local area and stored in a database. The RF signatures are stored as a function of two-dimensional position. Two-dimensional position is determined by recording the RF signature of a costumer desiring a location estimate. The RF signature of the caller is compared to the RF signature already in the database. When a match occurs, the position is already known based on the prior data. The availability and accuracy for a stand-alone system are heavily dependant upon the environment of the caller. This system performs well in areas with heavy density of reflectors because it induces unique RF signatures whereas an open environment can lead to multiple positions with the same RF signature.

Satellite-based systems: The Global Positioning System (GPS) is classified as a satellite-based system because it possesses a nominal constellation of 24 satellites that provide ranging signals to an earthbound user for location determination. Satellite-based location systems provide excellent worldwide accuracy and availability. However, both performance criteria degrade significantly when line-of-sight is lost between the user and the satellite. This occurs because L-band frequencies lose significant power when obstructed by buildings and heavy foliage.

Terrestrial-based systems: Terrestrial-based systems rely on the existing cellular network BSs to act as ground-based transmitters. Ground-based transmitters are used to emit multiple ranging signals for the MS to generate a location. The system availability is impacted significantly because the BSs are added based upon the percentage of people that live within a geographic area. As a result, more BSs exist in areas with high densities of people as opposed to rural areas that contain low densities of people. This layout of BSs was designed for communication systems and is not optimized for location systems. This study focuses on the EOTD positioning technique, which falls under terrestrial-based systems. A description of other terrestrial-based systems is given below.

Angle of Arrival (AOA) positioning: This system determines the MS position based on triangulation. It is also called direction of arrival. The intersection of two directional lines of bearing defines a unique position, each formed by a radial from a BS to the MS in two dimensional space. This is not a feasible method because of the need of directional antennas or antenna arrays which cannot be realized on a MS.

Time of Arrival (TOA) positioning: The system determines the MS position based on the intersection of the distance circles. Since the propagation time of a radio wave is directly proportional to the distance traveled, the MS position can be easily calculated relative to a BS. Three measurements determine a unique position. Same principle used in GPS.

Time Difference of Arrival (TDOA) positioning: The system determines the MS position based on trilateration. This system uses time difference measurements rather than absolute time measurements as TOA does. It is often referred to as the hyperbolic system because the time difference is converted to a constant distance difference to two BSs (as foci) to define a hyperbolic curve. The intersection of two hyperbolas defines the position. Therefore, it utilizes two pairs of BSs (at least three for two dimensional case) for positioning.

The main TDOA location technologies considered for GSM and CDMA are E-OTD and A-FLT (Advanced forward link trilateration)[9].

EOTD algorithm: EOTD is a TDOA positioning method based on the OTD feature already existing in GSM. The MS measures relative time of arrival of the signals from several BSs. The position of the MS is determined using trilateration. Three basic timing quantities are associated with this method:

Observed Time Difference (OTD): Is the time interval observed by an MS between the reception of signals from two different BSs.

$$\mathrm{OTD} = t_2 - t_1 \tag{6}$$

Real Time Difference (RTD): Is the relative synchronization interval in the network between two BSs. If RTD=0, this means we have a synchronized network. (t_3 is the moment BS1 sends a burst and t_4 is the moment BS2 sends a burst)

$$\mathrm{RTD} = t_4 - t_3 \tag{7}$$

Geometric Time Difference (GTD): Is the time interval measured at the MS between two bursts from two BSs due to geometry. If we denote d_1 as the length of the propagation path between BS1 and the MS and d_2 between the MS and BS2, then

$$\mathrm{GTD} = \frac{d_2 - d_1}{c} \tag{8}$$

where c is the speed of light. Also,

$$\mathrm{GTD} = \mathrm{OTD} - \mathrm{RTD} \tag{9}$$

Another method classified under E-OTD is a mixed TOA and TDOA approach. It measures the time of arrival of the signals from a BS to the MS and to the network node LMU (Location Measurement Unit) and uses Eq. 10 to derive the MS position. There are five quantities associated with this method:

- The observed time from a BS to the MS (MOT) is a time measured against the internal clock of the MS.
- The observed time from a BS to the LMU (LOT) is a time measured against the internal clock of the LMU.
- Time offset ϵ is the bias between the two internal clocks of the MS and LMU.
- The distance from MS to BS (DMB).
- The distance from LMU to BS (DLB).

These quantities are related by:

$$\mathrm{DMB} - \mathrm{DLB} = c\left(\mathrm{MOT} - \mathrm{LOT} + \varepsilon\right) \tag{10}$$

There will be one such equation for each BS. Since there are three unknowns (MS position x, y and clock offset ϵ), at least three BSs are required to solve for the MS location x and y and the unknown clock offset ϵ. The position of the MS is determined by the intersection of circles centered on the BSs common to observations made by the MS and LMU.

The E-OTD method requires a minimum of three spatially distinct BSs. All these BSs must be detectable by the MS. More than three measurements generally produce better location accuracy. An implementation of the E-OTD method may require an LMU to BS ratio between 1:3 and 1:5.

The MS position is found by creating 3 non-linear range Eq:

$$\sqrt{(x - x_1)^2 + (y - y_1)^2} = d_{L1} + c\left(\Delta\hat{t}_1 - \Delta t_{MS}\right) \tag{11}$$

$$\sqrt{(x - x_2)^2 + (y - y_2)^2} = d_{L2} + c\left(\Delta\hat{t}_2 - \Delta t_{MS}\right) \tag{12}$$

$$\sqrt{(x - x_3)^2 + (y - y_3)^2} = d_{L3} + c\left(\Delta\hat{t}_3 - \Delta t_{MS}\right) \tag{13}$$

In each equation there are three unknowns: x, y and Δt_{MS} which is the time offset of the MS clock from the time offset of LMU. The BS coordinates are known as well as the distances from the BS to the LMS. The solution of this system of equations can be obtained either by numerical methods or by special algorithm that obtains the solution in closed form.

Mobile to base station system model: The simulated system is shown in Fig. 1. It consists of all the portions used in a GSM system. The data gets encoded and then the burst (frame) is generated as defined in Table 1. This burst then gets modulated using a GMSK digital modulation scheme. The channels investigated in this study are the *Rayleigh flat fading* and *Ricean fading channels*. These channels have a direct effect on our burst detection, which impact the location processing of the mobile station.

In the BS (reciever part), the data gets demodulated and the burst is then detected using cross-correlation (i.e., a matched filter). After detecting the burst, the data gets decoded and at the same time the channel/transmission delay is calculated, from which the distance between the MS and BS is determined. Data processing and solving of the EOTD equations follows. This simulation assumes the MS and BS went through the synchronization phase and also that the LMU data are available at the BS at that moment to aid in the location determination process and solving of the EOTD Eq.

The cross-correlation between the incoming signal and the training sequence produces a peak when the portion of the GSM burst containing the training sequence is detected. This peak, indicates the instant of a frame reception, from which in a synchronized system, the delay can be found and then used to identify the MS to BS signal delay and then used in the EOTD location equation. In Fig. 2, an example of the cross-correlation plot is provided when 3 bursts are transmitted consecutively. Notice the three distinct peaks corresponding to the three bursts that were sent.

Channel models: The effect of various channels has been analyzed extensively for communication system applications, but it has not been analyzed for Location service and Telematics applications. The effect of a severe/bad channel on a voice communication system might lead to bad voice quality, or a call drop. While such

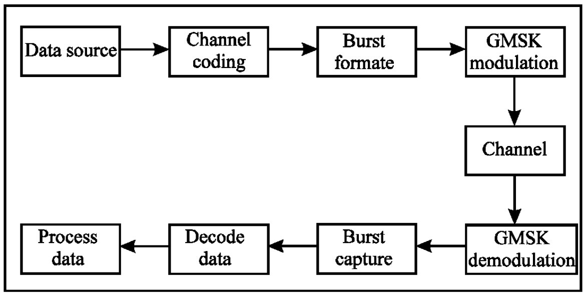

Fig. 1: GSM system block diagram

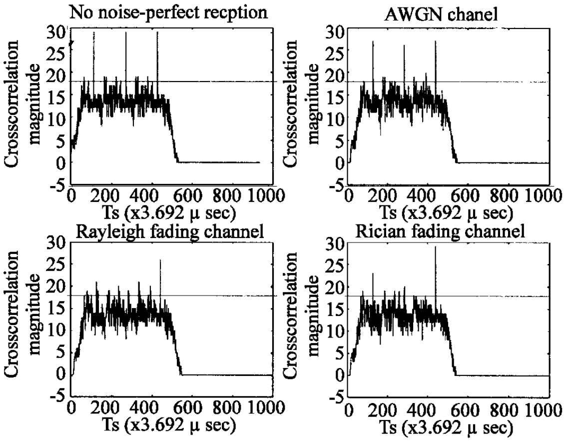

Fig. 2: Burst detection using cross-correlation. (a) Perfect channel with no noise (b) AWGN with Eb=No = 10dB (c) Rayleigh fading channel with 1Hz Doppler shift and 5-paths with -6dB worse Eb=No (d) Ricean Fading channel with 1Hz Doppler shift and Eb=No = 0dB for the line of sight path

channel impairment can cause large deviation in location determination that might not aid in serving an E-911 call, or locating an accident location. The severity of such channel impairments depends on the application at hand and since this study focuses on Location based and Telematics services, such channel effects are simulated and their effect on MS location estimation is studied.

The received signal in a multipath environment can be represented by Proakis[12]:

$$r_l(t) = \sum_n \alpha_n(t) e^{-j\Phi_n(t)} \qquad (14)$$

where $\alpha_n(t)$ is the attenuation factor in the signal received from the nth path and $\Phi_n(y)$ is the phase shift of the nth path (from which the relative delay of the path is determined, where $\Phi_n(t) = 2\pi f_c \tau_n(t)$ and $\tau_n(t)$ is the propagation delay of the nth path). This study considers the effect of the well known AWGN (Additive White Gaussian Noise) channel, the *Rayleigh flat fading* channel and the *Ricean fading* channel. The important parameters of these two channels are discussed next.

Rayleigh flat fading channel: A channel with a large number of paths can be modeled as a Rayleigh channel (here the central limit theorem can be applied and $r_l(t)$ will be modeled as a complex-valued Gaussian random process). The BW (Bandwidth) of this channel is higher than the signal BW and the channel has a constant gain and a linear phase response. The delay spread is lower than the signal bit time. The coherence time is defined as:

$$T_c = \frac{0.423}{f_m} \qquad (15)$$

where fm is the maximum Doppler shift given by $f_m = \upsilon\backslash\lambda$ (v is the speed of the MS and λ is the carrier wavelength)[7]. The coherence time is a measure of the time interval over which a channel response is invariant. The Doppler shift is a measure of the spectral broadening resulting from the time rate of change in the radio channel due to the relative velocity of the MS and BS and the angle of motion direction. This is a channel model that is used for low bit-rate data communications. The pdf of the Rayleigh distribution is given by Proakis[12]:

$$p_R(r) = \frac{r}{\sigma^2} e^{\frac{-r^2}{2\sigma^2}}, \quad r \ge 0 \qquad (16)$$

where σ^2 is the time-average power of the received signal.

Ricean fading channel: A channel that has a dominant component (i.e. Line Of Site), with a fixed number of scatteres/reectors, is represented by a Ricean fading channel. As the dominant component becomes weaker, the channel becomes a Rayleigh one. The pdf of a Ricean channel is given by Proakis[12]:

$$p_R(r) = \frac{r}{\sigma^2} e^{\frac{-(r^2+s^2)}{2\sigma^2}} I_0\left(\frac{r_s}{s^2}\right), \quad r \ge 0 \qquad (17)$$

where $s^2 = m_1^2 + m_2^2$ is the peak amplitude of the dominant signal, m_1, m_2 are the means of the two independent random variables and $I_0(.)$ is the modified Bessel function of the first kind and zero order. Here the pdf has 2-degrees of freedom.

RESULTS AND DISCUSSION

Simulation results for the *Rayleigh flat fading*, *Ricean Fading* and *AWGN* channels are considered for two BS geometries; Good and Poor geometries Fig. 3,4.

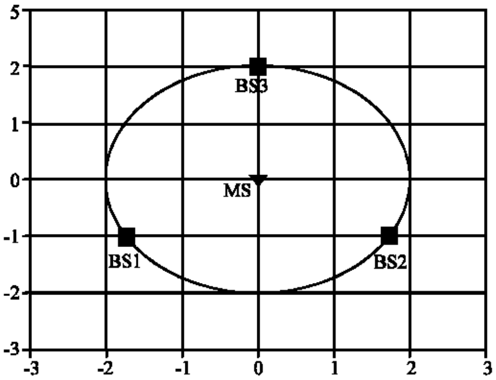

Fig. 3: Good BS to MS geometry, GDOP = 1.291

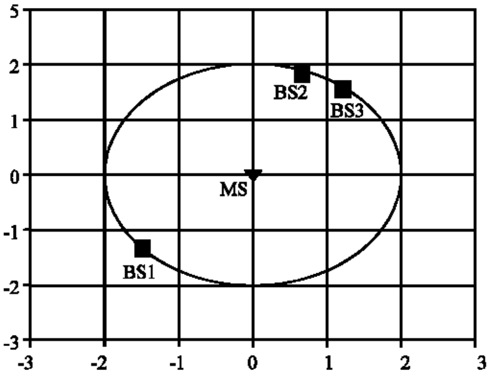

Fig. 4: Poor BS to MS Geometry, GDOP = 4.302

The RMS delay spread for a 900MHz GSM signal in suburban areas is $\sigma_\tau \approx 300$ns[7] which is less than the actual symbol time of 3.692 µs. Also, for the 800M Hz/1900 MHz bands, the coherence time is less than the symbol time (i.e., for the simulated MS speed of 3K m h, Tc = 0.133sec for the 1900MHz carrier frequency), so the channel is closely represented by a Rayleigh at fading channel.

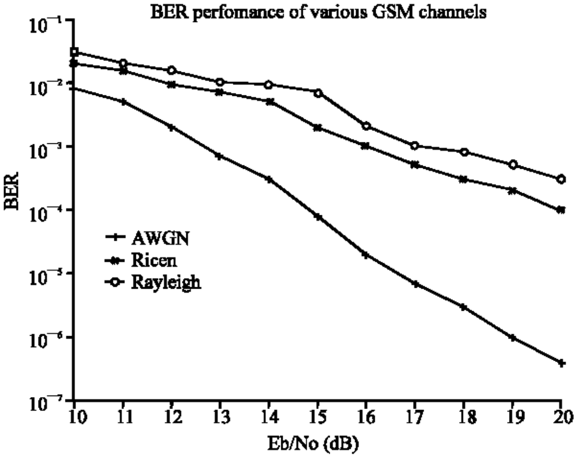

Fig. 5: BER performance in various channels

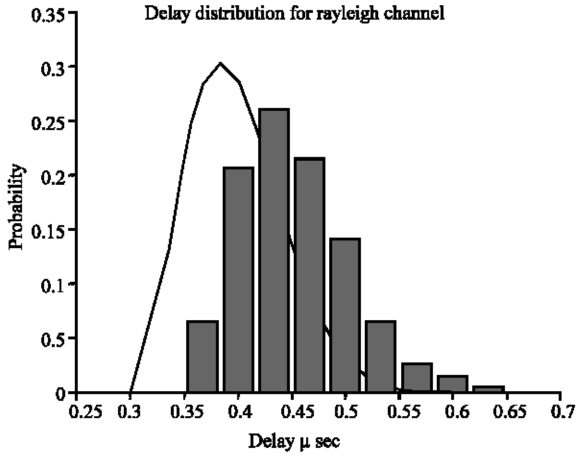

Fig. 6: Delay distribution in Rayleigh channel. This represents the error deviation from the true range of 2Km, i.e. a 6.66 µsec should be added to the delay values indicated to get the true location

In the simulation model, the GMSK receiver has a MLSE (Maximum Likelihood Sequence Estimation) detector that is based on a Viterbi Algorithm with 16-state trellis. The synchronization burst of the GSM frame is generated. A repetition of these bursts are sent, received and analyzed for various channels. After being detected, the BER (Bit Error Rate) performance is plotted for each simulated channel. The frame is then correlated with a replica of itself at the receiver end (reference sequence might be extracted from the incoming data). In addition, the frame is correlated with a reference timer at the receiver end based on the transmitted synchronization burst. The simulation produces three BS-to-MS ranges for each channel. The three ranges are then processed with the EOTD positioning algorithms to arrive at the 2-dimensional position of the MS. The GDOP (Geometric Dilution Of Precision) is 4.302 and 1.291 for Poor and Good BS geometries, respectively.

In Fig. 5, the BER performance of the three channels simulated is shown. Since the Rayleigh channel is the most hostile one, with a large number of multipaths, it has the worst BER. The Ricean channel has better performance due to the lower number of scatterers and the availability of a line of sight from BS to MS. This BER is taken for a single BS to MS link.

Figure 6 presents the delay deviation from the true range for a Rayleigh at fading channel. This is based on a single BS ranging, that is 2Km away. To get the actual range calculated for a certain point, add/subtract the delay on the graph from the actual 6.66_sec, which is the time of flight of the EM signal through the line of sight to the MS.

Table 2: Error in range calculation for different channels based on a single BS measurement

Channel	Range ERROR
AWGN (Eb/No = 10dB)	10 ~ 20 m
Ricean fading channel (6Hz shift, 2paths+LOS)	44 ~ 107 m
Rayleigh flat fading channel (6Hz shift, 5-paths)	105 ~ 195 m

A monte carlo simulation based on 2000 runs was generated. The obtained delays were categorized into 10 delay regions, from which the histogram shown is drawn. A theoretical Rayleigh probability density function with a σ≈ 0.37 μsec was overlayed over the histogram. The histogram has a σ≈ 0.42 μsec. The delay obtained corresponds to a ranging error deviation between 105-195 m, for this single BS. The velocity of the MS was taken for a walking user, with a speed of 3Km/hour, i.e., Doppler shift of the order of 6 Hz.

Table 2 summarizes the range error deviation from the actual true range for a single BS. The AWGN channel is the closest to the true range because it just represents thermal noise in the receiver and transmitter modules, this is not an actual channel, but is usually incorporated to better understand the behavior of other channels. The Ricean fading channel can represent the rural environment, but usually the BS geometry is not as good as the ones in urban or city environments, in addition the Doppler shift is much higher in rural environments which further degrades the signal quality and location estimation. The third channel is the Rayleigh channel that usually represents the city environment. It has the worst multipath effects, but not that much of Doppler shift.

In Fig. 7 and 8, the scatter plots of the horizontal position error for the EOTD calculated location are shown for both geometries in a *Rayleigh flat fading* channel. This simulation assumed poor and good BS-to MS geometries (GDOP=4.302, 1.291 respectively) and that all BSs are perfectly synchronized. Both assumptions renders results that are optimistic to what would be encountered in the field. The poor geometry produced horizontal position errors within a 50 meter radius 58%.

In Fig. 9 and 10, the scatter plots of the horizontal position error for the EOTD calculated location are shown for both geometries in a *Ricean fading* channel. This simulation assumed poor and good BS-to MS geometries (GDOP=4.302, 1.291 respectively) and that all BSs are perfectly synchronized. The poor geometry produced 62.6% of the 2-dimensional position estimates within a 50 m radius.

In Table 3, the percentage of the estimated location with respect to the FCC requirement is illustrated for both geometries in both channels. For both geometries, the 300 m requirement is satisfied, but the poor geometry of

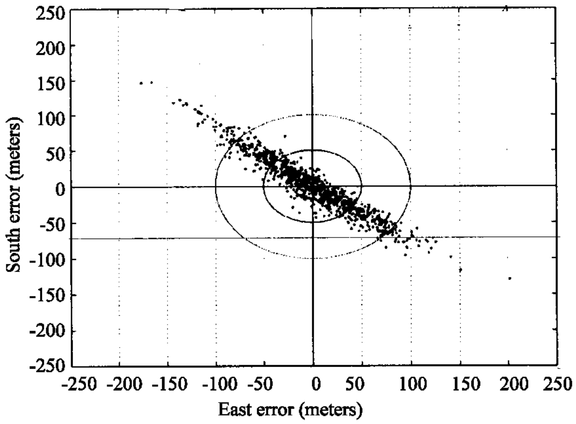

Fig. 7: Horizontal error for the MS location using the EOTD algorithm in a *Rayleigh flat fading* channel, poor geometry (1000 points)

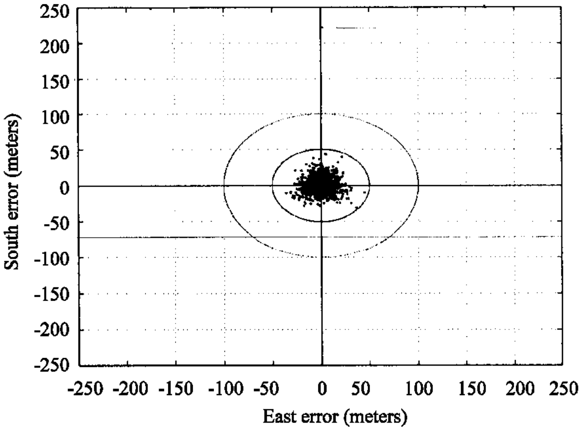

Fig. 8: Horizontal error for the MS location using the EOTD algorithm in a *Rayleigh Flat fading* channel, good geometry (1000 points)

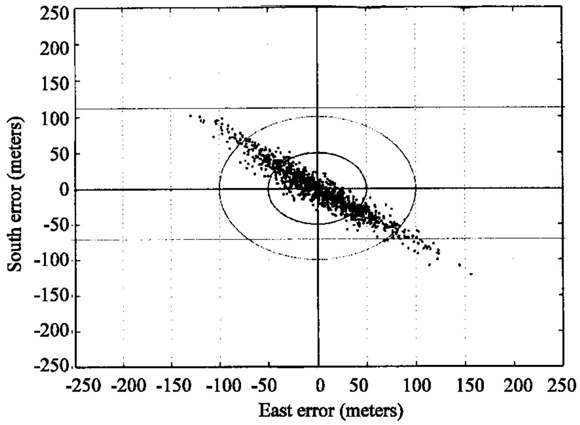

Fig. 9: Horizontal error for the MS location using the EOTD algorithm in a Ricean fading channel, poor geometry (1000 points)

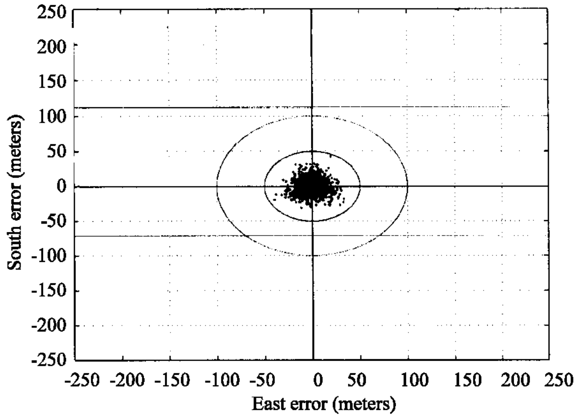

Fig. 10: Horizontal error for the MS location using the EOTD algorithm in a Ricean fading channel, good geometry (1000 points)

Table 3: EOTD location estimation results and percentages of compliance with the FCC requirements

Channel	Geometry	GDOP	MIN (M)	MAX (M)	% 50 M	% 100 M
Rayleigh	Good	1.291	0.31	48.8	100	100
	Poor	4.302	0.92	239.7	58.1	88.8
Recian	Good	1.291	0.42	46.9	100	100
	Poor	4.302	1.36	197.8	62.6	91.6

the *Rayleigh flat fading* channel was 88% for the 100 m requirement and 58% for the 50 m requirement, while the poor geometry of the *Ricean fading* channel was 91.6% for the 100m requirement and 62.6% for the 50m requirement.

CONCLUSION

EOTD location service is a feature already deployed in 2.5G GSM networks. This study analyzed the BER and location error estimation for two wireless communication channels; *Rayleigh flat fading* and *Ricean fading* channels, utilizing two BS geometries, a Good geometry with GDOP of 1.291 and a Poor geometry with GDOP of 4.302. For poor geometry, the *Rayleigh flat fading* channel and the *Ricean fading* channel produced 50 meter accuracy of 58% and 62.6% of all position estimates, respectively. Perfect synchronization between base stations was assumed. The results in this study indicate the EOTD technique is on the fence of meeting the FCC accuracy requirements pertaining to the E-911 mandate. This is a result of the cellular networks being optimized for communication systems as opposed to location systems. Consequently, the availability of EOTD is severely limited in rural areas. This tremendously impacts its effectiveness in serving as the prime location technology enabler for aTelematics service provider. However, EOTD coupled with AGPS (Assisted Global Positioning System) is an area that should be explored further.

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