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An Implementation of Time of Arrivals Location Positioning Technique for GSM Networks

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***ABSTRACT**:* Positioning algorithms are of great importance in recent years, as the means of providing location based services (LBS) including wireless emergency services. Telecommunication engineers are frequently puzzled by the accuracy of the implemented technique in contrast with the cost. In this paper, we summarize the most known location techniques. Then we introduce a novel Time of Arrivals (TOA) location positioning method in GSM networks using three Base Stations (BSs). In order to determine the subscriber's position, the algorithm makes use of the Turin's [5] TOA positioning algorithm. The algorithm's accuracy is improved by introducing an additional weight coefficient reflecting the LOS/nLOS propagation. Finally, the cost function is simulated in a microcellular city centre environment and compared to Turin's.

Keywords: GSM Networks, Cost Function

I. INTRODUCTION

A radio mobile-position system operates by measuring, processing and storing physical quantities related to radio signals travelling between a mobile terminal and a set of transceivers e.g., satellites or BSs. There are various solutions for implementing a radio mobile positioning system, which can be classified into two major categories: network based (or unmodified handset) and handset based (or modified handset) positioning. The former techniques require that the existing handsets have to be redesigned in order to meet new requirements, while the latter need adjustments only at the BSs or switching centres. Furthermore, with the first approach, the Mobile Terminal (MT) utilizes transmitted signals from the BSs to estimate its own position while with the second approach the BSs measure the transmitted signals from the MT and relay them to a central site for processing.

Handset-based Mobile Positioning Technology

This category is referred to as "handset based" because the handset itself is the primary means of positioning the user, although the network can be used to provide assistance in acquiring the mobile device and/or making position estimate determinations based on measurement data and handset based position determination algorithms [1]. In comparison to network based solutions, modified handset positioning techniques perform better and they have much more accuracy, but their biggest disadvantage is the additional cost for new handsets. Furthermore, weight and sizes of the mobile terminals will be increased so power efficiency will be reduced because of additional hardware.

<u>SIM Toolkit</u>

This technique requires a modified SIM Toolkit (STK) which works as an API between the

Subscriber Identity Module (SIM) of a GSM mobile phone and an application, in order to estimate the position of the terminal. Its accuracy lies from close to Cell of Origin's to a lot more precise through additional means such as use of the mobile network operation called timing advance (TA). STK works quite successfully in case the mobile terminal is in the idle state.

Enhanced Observed Time Difference (E-OTD)

This technique is also encountered as handset based TOA and specially equipped handsets are required. E-OTD technique operates by instating location receivers called location measurement units (LMU) at several places geographically dispersed in the radio coverage area of a cellular network. Each of these LMU has an accurate timing source. Moreover, E-OTD requires software modification at existing handsets. The main advantage of E-OTD technique is its high accuracy but on the other hand its most important handicap is that the mobile device needs to be visible by the base stations.

Global Positioning System (GPS)

Unambiguously, the main technology for the implementation of handset based positioning is the GPS. It is a universal system consisting of three interlocking segments: the space segment, the user segment and the control segment. The space segment consists of 24 satellites each in its own orbit 20.000 km above the Earth which means that it takes 12 hours to orbit the Globe. As for the GPS control, or ground, segment it consists of unmanned monitor stations located around the world (Hawaii and Kwajalein in the Pacific Ocean; Diego Garcia in the Indian Ocean; Ascension Island in the Atlantic Ocean; and Colorado Springs, Colorado); a master ground station at Schriever (Falcon) Air Force Base in Colorado Springs, Colorado; and four large ground antenna stations that broadcast signals to the satellites. The stations also track and monitor the GPS satellites. GPS receivers are used for detection, decoding and processing the signals sent from the GPS satellites. Their size and shape varies according to the application and thus they can be hand carried or installed on aircraft, ships, military vehicles, cars and motorbikes. The typical hand-held receiver is about the size of a cellular telephone, and the newer models are even smaller weighed only 28 ounces.

Assisted Global Positioning System (AGPS)

GPS suffers position errors from satellite clock, satellite orbit, ephemeris prediction, ionospheric and tropospheric delays, ext. AGPS is the combination of GPS technology and network enhancement solutions. In that method a GPS network cooperates with a cellular network infrastructure always detecting the satellites constellation status in order to provide information such as satellite visibility, Doppler, ephemeris and clock correction. As a result, AGPS can increase the precision of the positioning up to ten meters, but the penalty is the additional cost of the modified device for the user. Furthermore, AGPS carries the main disadvantage of the GPS which is the need of at least three satellites in sight, a deficit which makes its implementation difficult in built areas and indoor environments, where people spend a significant portion of their time. Because of its high accuracy, the A-GPS method can be used to provide rich services to the users like self-navigation and emergency services.

Network based Mobile Positioning Technology

This category is also referred to as "unmodified handset" which means that there are no changes in the mobile device. On the contrary, this technology requires changes in the infrastructure of the BS, the Base Station Controller (BSC) or the Mobile Switching Centre (MSC). In addition, network based positioning is less expensive and more easily implemented than handset based positioning but it is less precise. Because of the poor implementation complexity, the limited cost and the satisfactory performance, network based techniques are usually preferred for mobile positioning.

Cell of Origin (COO)

According to the COO, the network uses the closer (to the handset) BS to identify the cell where the subscriber is. The accuracy depends upon the cell area and it can be up to 150 metres for an urban area. Moreover depending on the radio architecture the accuracy is approximately (150m – 5 Km) in microcellular design, (500m – 150 m) in picocellular indoor or outdoor or (35Km – 150) in macrocellular design. Although the accuracy is not high and cannot be applied for emergency usage it is popular amongst the operators as it does not require any modifications in the handset or the network, hence it is comparatively cheap to deploy. Herein, it has to be mentioned that COO is the initial and fundamental positioning technique before the utilization of a second more accurate method like the next displayed. To be more specific, in cellular networks the use of the following methods requires that the network knows the cell where the MT lies. This is substantial as the network must decide which BS to use for the implementation of the appropriate positioning technique.

Angle Of Arrivals (AOA)

According to AOA method, the angles of arrivals of a signal from the MT at a pair -or more- BSs are measured by using antenna arrays. The position of the MT is defined by the intersection of at least two directional lines of bearing. Location errors occur in AOA technique by reason of nLOS propagation and multipath. Due to nLOS propagation the reflected signal received at BS antenna array has different AOA than the direction of the MT. Moreover, even in LOS propagation, multipath which means scattered signals near and around the BS would still alter the measured AOA. For macrocells, where the BSs are usually above roof level or at least above the terrain, the scatter signals are located close to the BS. On the other hand, for microcells where the BSs are placed below roof level and thus surrounded by local scatterers following a large spread distribution.

Power OF Arrivals (POA)

In POA method, the signal strength received at the BS from the MT is measured and by the use of a known mathematical propagation model the path attenuation loss is determined [2]. Since the measured signal strength is translated to a distance estimate, the MT's position lies on a circle centered at the BS. As in TOA method, the MT's location derives from the intersection of more than one circle.

Errors in POA method are caused by multipath fading and shadowing phenomena. Degradation of the signal strength received at the BS can be as high as 30-40 dB on the order of a half of the wavelength due to multipath. A solution to this apart from low mobility MTs, could be the utilization of the average strength of a set of measurements. In case of shadowing, error can be reduced by using premeasured signal strength contours centered at the BSs [3].

Time Difference Of Arrivals (TDOA)

In TDOA solution, the estimation of the MT's location is based on measuring the differences in the time of arrival of the signal from the MT to more than one pairs of BSs. Considering that, a signal travels with the speed of light ($c = 3 \cdot 10^8$ m/s) and using the equation $d = c \cdot t$ the time difference is converted to a constant distance difference which geometrically means that the MT lies on a hyperbolic curve with foci at the BS's locations. The position of the MT is provided by the intersection of more than two hyperbolae which means that at least two pairs of BSs are needed (Figure 1). Therefore, for the implementation of the TDOA at least three BSs are required.

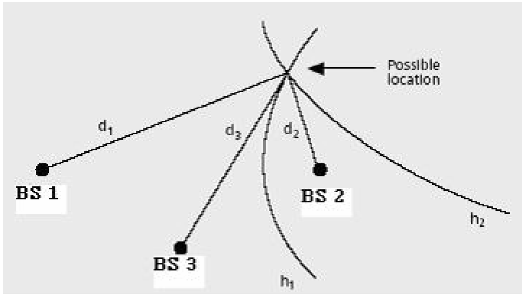

Figure 1 [4]: The TDOA method

II. TOA TECHNIQUE

In the TOA technique, the location of the MT derives from measuring the time needed for a signal to travel from a number of BSs to the MT. Again, the equation $d = c \cdot t$ provides the distance of the MT from the BSs. Geometrically, the MT lies on a circle centred at the BS's location and radius the distance *d*. By using at least three BSs, the position of the MT is given by the intersection point of the three circles.

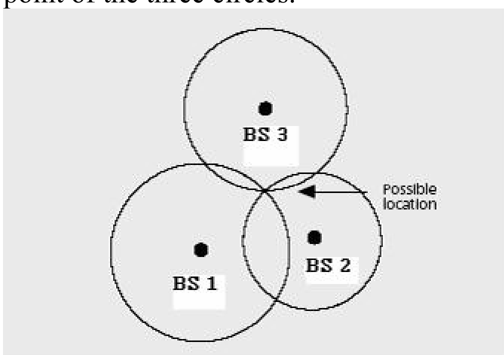

Figure 2 [4]: The TOA method

Quite a few methods have been introduced as solutions to obtain the time estimates including phase estimation, pulse transmission, burst transmission, signalling and spread spectrum techniques. In the first technique, phase detectors are employed in the BSs and synchronization of the BSs used for positioning is required [5]. In pulse transmission and spread spectrum systems, the time estimates are computed by implementing correlation techniques [5].

Due to measurement errors in time estimates the circles. In that case, location algorithms have been introduces in literature to resolve the problem [6]. Moreover TOA method suffers from non Line Of Sight (nLOS) propagation which means that between the BS and the MT exist one or more obstacles. In that case, the signal does not travel directly from the MT to the BS but it reaches the latter through reflections or diffractions on buildings, cars, other obstacles, ext. As a result the signal takes longer path in comparison to the direct path in LOS propagation. The typical location error caused by nLOS propagation in GSM networks has been calculated to 400-700 m approximately [7].

Several methods have been introduced to mitigate the location error caused by nLOS propagation. An effective one, proposed by Turin [5], is to change the location algorithm taking into consideration that in nLOS propagation the measured distance $c\tau_{BS_i}$ is greater than the real one $c(\tau_{BS_i} - \Delta t)$ (Δt is the nLOS propagation error) and therefore the possible location of the MT lies inside the circle centred in BS's position. For the three BSs TOA technique, the intersection of the three circles provides an area (feasible area in figure 3) where the MT can possibly lie. An initial estimation of the MT location can be finding the centre of the feasible area. In case of three BSs (figure 4), supposing that the coordinates of the three points of intersection which set the feasible area E, are (x_1, y_1), (x_2, y_2) and (x_3, y_3) the coordinates of the centre of the area E are:

$$(\hat{x}_{MT}^{(0)}, \hat{y}_{MT}^{(0)}) = \left(\frac{x_1+x_2+x_3}{3}, \frac{y_1+y_2+y_3}{3}\right) \text{ [8]}$$

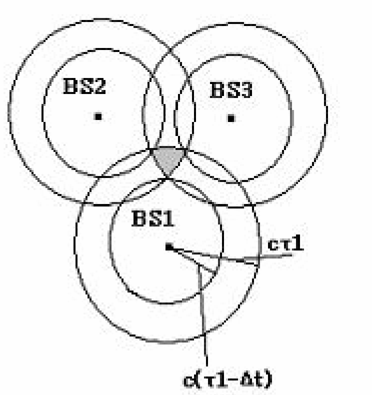

Figure 3: nLOS propagation error in TOA

In several cases where the MT is quite close to one BS and the circles do not intersect the feasible area is estimated as a circle around the adjacent BS. Furthermore, a position nearby that BS is chosen as the initial guess. In order to enhance the initial guess and minimize the location error a non-linear least square solution can be introduced. According to this, for each BS used in location process, the following function is formed [5] [9]:

$$g_i(x,y) = c\tau_{BS} - \sqrt{(x - x_{BS_i})^2 + (y - y_{BS_i})^2}$$

The feasible area E can be appointed by the following inequalities:

$$E = \{(x,y) \mid g_i(x,y) \ge 0 \forall i = 1,......N_{BS}\}$$

$$=> E = \{(x,y) \mid (x - x_{BS_i})^2 - (y - y_{BS_i})^2 \le (c\tau_{BS_i})^2 \forall i = 1,......N_{BS}\}$$

N_{BS} is the number of the BSs.

The next step is to form the following cost function:

$$G(x,y) = \sum_{i=1}^{N_{BS}} a_i g_i(x,y) \text{ [5] [9]},$$

α_i are weights reflecting the signal strength as received at the i_{th} BS, *($i=1,.....N_{BS}$)*.

If no information about signal strength is available or not taken into account, it is possible to set $a_i = 1 \forall (i = 1,......N_{BS})$. The location estimate is finally given by the couple *(x, y)* that minimizes the cost function inside the feasible region.

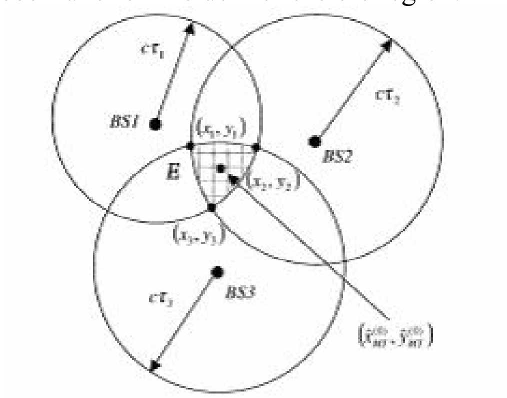

Figure 4 [9]: Initial guess for the three-TOA method

In order to mitigate even more the Turin's cost function from location errors due to nLOS propagation, a weight coefficient 1_i is proposed. To implement the weight 1_i the network has to meet the following requirements:

- BS antenna arrays in order to measure the angle of the received signal
- A Geographical Interface System (GIS) available to the network operator.

Another requirement is the introduction of a First Obstacle Distance Function, FODF(θ), which is defined as the Euclidean distance between the BS and the nearest obstacle found along the azimuth direction identified by angle θ of the received signal. FODF derives from GIS. If FODF(θ)<ct (t is the time estimate) then the MT is in nLOS with the BS. If FODF(θ)>ct the BSi is in LOS and then

$l_i = 1$. If one BS is in nLOS then $l_i = \frac{1}{10}$. If two BSs are in nLOS and $FODF_1(\theta)-ct_1<FODF_2(\theta)-ct_2$ then $l_1 = \frac{1}{10}$ and $l_2 = \frac{1}{100}$. In that case, the proposed cost function follows:

$$G'(x,y) = \sum_{i=1}^{N_{BS}} l_i a_i g_i(x,y)$$

III. TOA TECHNIQUE IMPLEMENTATION IN GSM

To begin with, it is the writers' purpose to intervene in the GSM network's infrastructure as less as possible. In the following a number of interventions are proposed in both busy and idle mode of the subscriber's MT in order to implement TOA technique.

Idle Mode

a. The Master Switching Centre (MSC) starts a periodic location update procedure to page the MT. The response message from the MT contains the Temporary Mobile Subscriber Number-TMSI), and the Location Area (LA) identity.
b. In that point, the Base Station Controller (BSC) becomes also aware of the serving BS (CGI number) which is one of the three BSs.
c. The BSC requests from the MT through a Stand alone Dedicated Common Control Channel (SDCCH) the list of the received signal power from the adjacent and the serving BSs (6+1 BSs).
d. The MT responds through the SDCCH and the measurement report is forwarded to the BSC through the serving BS.
e. From the list of the 6 BSs the BSC chooses the two with the greater signal power BUT which are controlled by it. This is proposed because if the BSs belong to different BSCs, there must be signalling through the MSC and thus making the implementation even challenging.
f. Herein, the writers suggest a new Link Access Protocol D-channel (LAPD) layer 3 Paging Command message (Single Paging Command) which contains one BS's CGI and the TMSI of the MT. The BSC launches sequentially three Single Paging Commands. Then, sequentially each BS sends a Paging Request message to the MT through Paging Channel (PCH) and the MT sequentially transmits three Channel Requests messages through Random Access Channel (RACH).
g. When a BS transmits the Paging Request to the MT a clock (in BS) initiates timing and finishes when the Channel Request through RACH reaches the BS. The obtained time is divided by two and provides the time estimate.
h. The three time estimates are sent back to the BSC where the position estimation of the MT according to Turin's algorithm takes place.

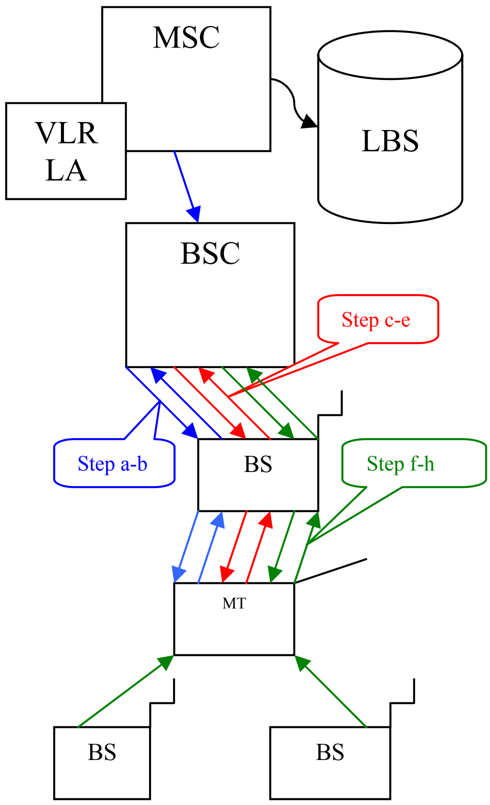

Figure 5: GSM method for the calculation of TOA time estimates (Idle mode)

In the Busy mode scenario, the BSC in where the serving BS comes under is aware of the timing advance between the BS and the MT. Therefore, the time estimate from the serving BS is already known. In addition, the MT constantly transmits to the BS (through SDCCH) a list of the received signal power from the adjacent and the serving BSs. In that case the algorithm steps are modified as follows:

a. The MSC requests from the BSC the timing advance
b. The MSC requests from the BSC the list of the received signal power

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c. According to the list, the MSC chooses the two BSs with the greater signal power.

d. The MSC initiates the single paging procedure (for two BSs this time) and the steps are repeated as above.

It has to be mentioned that according to the busy mode scenario, the BSC may not be able to choose two BSs that come under to the former and the serving BSC can not change. As a result, the position estimation takes place in the MSC. This results to a heavier signaling.

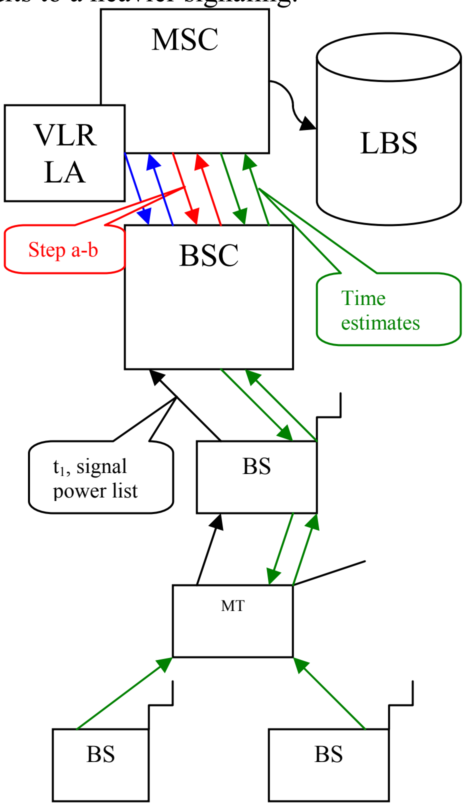


Figure 6: GSM method for the calculation of TOA time estimates (Busy mode)

IV. TOA TECHNIQUE SIMULATION ENVIRONMENT

In order to evaluate the enhanced Turin's positioning algorithm, a 2-D city centre environment simulation, developed in C programming, is used. The introduced environment (figure 7) has a coverage area of 440x440 m^2. Buildings are made of reinforced concrete and streets are made of asphalt. The white squares represent possible subscriber's positions while, the grey ones represent buildings (where it is forbidden for the subscriber to be). There are three BSs, which are above roof level and thus not surrounded by local scatterers, located at the points of coordinates BS1(110m, 418m), BS2(242m, 242m) and BS3(418m, 154m). The electromagnetic field is simplified to a first-order ray trace contribution and the signal reaches the BS/MT through reflections or diffractions on the buildings' walls. There are no reflections on cars, trees, ext. What is more, we propose BS antennas with space diversity techniques so that the time estimate suffers the least possible number of reflections. Finally, the time estimate is translated to distance through $d = c \cdot t$ equation.

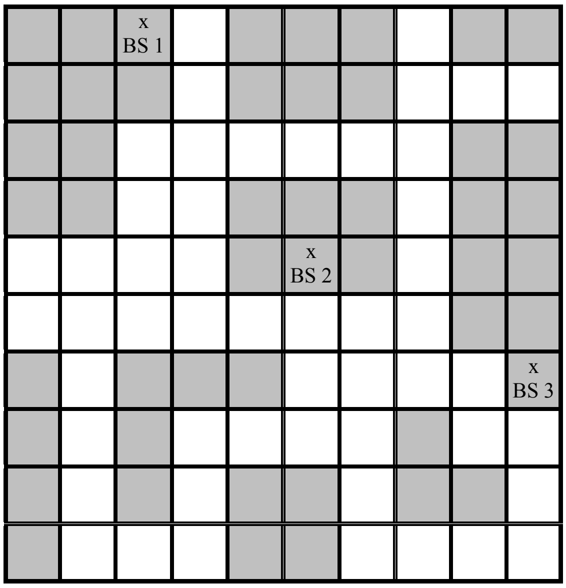


Figure 7: City centre simulation environment

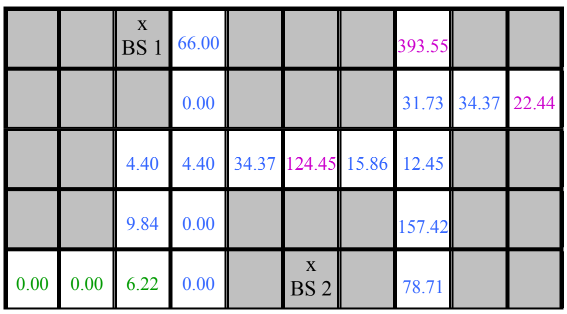
V. TOA TECHNIQUE SIMULATION RESULTS

In every possible MT's position the location error (in meters):

$$\varepsilon_r = \sqrt{(x_{MT} - \hat{x}_{MT})^2 + (y_{MT} - \hat{y}_{MT})^2}$$

is obtained by using the estimated location position given by the minimization of TOA cost function and the true location. In proportion to the number of BSs in LOS, the location error has a different color: Green for three BSs in LOS, blue for two, violet for one and red for none BS in LOS.

The results from Turin's cost function are given in figure 8.



0.00	0.00	0.00	0.00	15.86	18.14	0.00	0.00		
	65.41				26.76	15.86	4.40	4.40	x BS 3
	72.83		298.23	182.16	31.11	70.54		0.00	0.00
	68.31		293.52			88.00			0.00
	67.31	77.97	77.97			88.00	238.62	374.65	22.44

Figure 8: City centre simulation results (Turin's cost function)

Over all the possible locations, a mean value of 62.72 m and a standard deviation of 95.96 m are obtained for the location error. As predicted, the less BSs in LOS the more the location error increases. What is more, in shadowed positions the location error is comparatively high due to many reflections that the signal suffers before reaching the MT/BS.

The results from enhanced Turin's [5] cost function are given in figure 9.

It can be observed that after the introduction of l_i weights the location error in case of three or two BSs in LOS remain as before while in case of a single or non BS in LOS decreases. On the whole, the mean location error diminishes to 42.73 m with a standard deviation of 76.7 m.

		x BS 1	66.00				393.55		
			0.00				4.40	6.22	22.44
		4.40	4.40	34.97	124.45	0.00	4.40		
		6.22	0.00				157.42		
0.00	0.00	6.22	0.00		x BS 2		78.71		
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
	36.28				6.22	6.22	4.40	4.40	x BS 3
	64.06		120.18	123.98	0.00	0.00		0.00	0.00
	68.31		81.84			0.00			0.00
	67.31	77.97	256.15			18.14	238.62	69.57	22.44

Figure 9: City centre simulation results (l_i weights cost function)

Both simulation results abide by the US FCC regulation, which require E-911 location accuracy of 125m in 67% of the cases. In the first approach that percentage reaches the value of 86.3% while in the second is increased to 92.2% of all possible positions.

VI. CONCLUSION

In this paper a novel implementation of TOA location position technique in GSM networks has been introduced. The proposed approach requires modifications in GSM protocols LAPD, RR and MM as well as the insertion of a new LAPD layer 3 Paging Command message (Single Paging Command). Furthermore, an addition weight coefficient in TOA cost function has been proposed. The coefficient demands BS antenna arrays and a GIS map available, but has showed good reduction of the location error due to nLOS propagation.

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