APPLICATION OF DIGITAL CELLULAR RADIO FOR MOBILE LOCATION ESTIMATION

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Abstract: The capability to locate the position of mobiles is a prerequisite to implement a wide range of evolving ITS services. Radiolocation has the potential to serve a wide geographical area. This paper reports an investigation regarding the feasibility of utilizing cellular radio for the purpose of mobile location estimation. Basic strategies to be utilized for location estimation are elaborated. Two possible approaches for cellular based location estimation are investigated with the help of computer simulation. Their effectiveness and relative merits and demerits are identified. An algorithm specifically adapted for cellular environment is reported with specific features where mobiles, irrespective of their numbers, can locate their position without adversely loading the cellular system.

Key Words: ITS, GSM, Cellular Radio, DRGS, GPS.

1. INTRODUCTION

Intelligent Transportation Systems (ITS) is an umbrella term representing an evolving research field that addresses different aspects of road transportation related problems by offering new range of solutions with the help of state of the art information technology and advanced telecommunication facilities. In the context of ITS, information concerning mobile location is one of the basic requirements that is crucial to implement evolving services like Dynamic Route Guidance System (DRGS), Fleet Management, Emergency Vehicle dispatching etc. to name a few, although, the requirement for accuracy varies form application to application[1]. In case of Route Guidance and Navigation there is a need for higher accuracy in location data, since guidance or navigation relies on the assumption of availability of reliable location data, otherwise a mobile could easily become lost by following a wrong route or taking a wrong turn. Considering another application where vehicles could act as floating sensors providing information concerning traffic situations it has just experienced, demand for location accuracy could be a bit relaxed. Even less accurate location data could be used for vehicular fleet management system where knowledge about a mobile's present location in terms of a street or road section or even area might be adequate enough depending on the particular demand.

Although satellite based Global Positioning Systems (GPS) can provide accurate positional information for mobile users there is considerable interest in assessing systems, which do not have to rely on GPS. It is clear that Global System for Mobile Communication (GSM) does have some estimate of the distance of a mobile from its serving base station (BS). The objective of this paper is to investigate to what extent the cellular infrastructure of the second generation (e.g. GSM) and future cellular phones could be used to estimate mobile location co-ordinates.

In the following, an overview of different techniques that are used for locating a moving object is given in section-2. The feasibility of cellular radio based location system is addressed in section-3. Section-4 elaborates the location estimation algorithm employed in this simulation-based investigation and the results are reported in section-5. And finally a conclusion is drawn in section-6.

2. MOBILE LOCATION FINDING TECHNIQUES

There are various methods that could be used to locate the position of a mobile. They could be broken down into three basic categories[2]: Proximity systems, Dead-reckoning methods, and Radio location methods (includes Satellite based GPS)

It is possible to realize each of these basic categories through a multitude of different technical approaches and combinations of one or more of these categories are also receiving serious consideration[3].

2.1 Proximity Systems:

In these systems, proximity devices such as microwave or infrared beacons (e.g. Auto guide project in London[4]), provide the location of mobiles by determining the relationship between the mobile and fixed locations strategically placed throughout the city. Since beacons are positioned at known points in the road network, any passing mobile is able to update its position by interrogating the beacons[5]. As shown in Fig. 1, the beacon service area only permits a mobile to retrieve information from that specific beacon. Therefore, location accuracy directly depends on the size of this area and by reducing the area of operation higher location accuracy is achievable.

Due to the functional requirement, a communication channel is needed between a mobile and the proximity device either to receive the broadcast message identifying the location (requiring a simple channel) or to interrogate for similar information (requiring a half or full duplex channel). Since a mobile can only be located whenever it encounters proximity device, the frequency of positioning proximity devices will determine the continuity and accuracy of locating and monitoring mobiles.

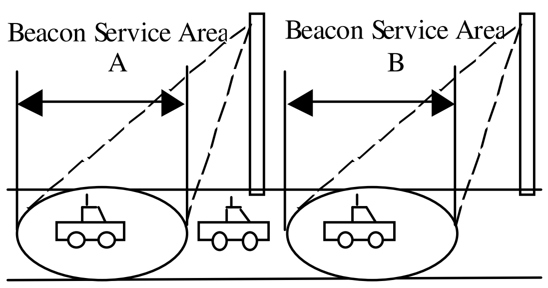

Fig. 1: Vehicular location fixing with proximity devices.

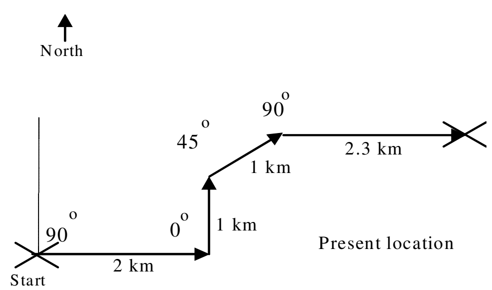

Fig. 2: Vehicular location fixing with dead reckoning.

2.2 Dead-Reckoning Method:

This method relies on distance and heading sensors fitted to the mobile so that progress from a known starting position can be continually monitored and location, in terms of grid reference, can be updated as shown in Fig. 2. Unfortunately, many factors, such as changes in tire pressure, road conditions, surrounding man-made structures, e.g. metallic bridge, can greatly affect the distance and direction measurements. Since, in the basic system, the computed location depends upon all previous location estimates, errors in location data tend to accumulate and can lead to sizeable positional errors. To compensate for this, the system must be updated and reinitialized on a regular basis.

2.3 Radio Location Methods:

This method involves direct measurements of radio signals traveling between a mobile and a number of fixed stations in an attempt to locate the mobile. In general, such methods use time or phase measurements to first determine the length or direction of the radio path and then use this to compute the location based upon known geometrical relationships. Well-established radiolocation systems including GPS (Global Positioning System) satellites, Decca and Loran-C, used in the air and sea, employ trilateration techniques.

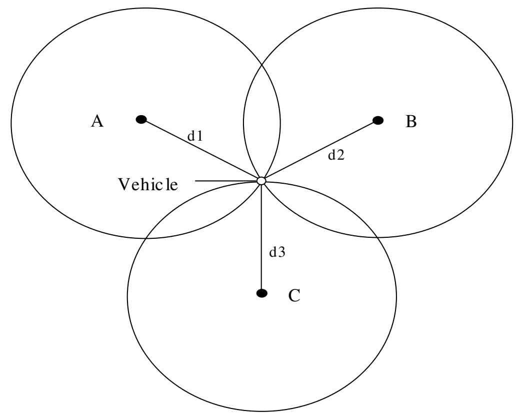

Fig. 3: Vehicular location fixing with trilateration technique.

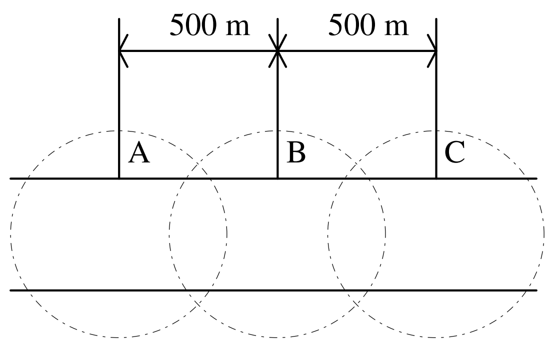

Fig. 4: Cellular radio as a proximity device.

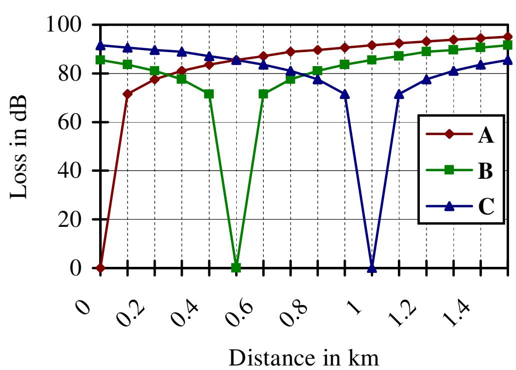

Fig. 5: Signal strength variation received by a mobile moving along a highway from three base stations (A, B, and C).

The trilateration technique generally employs the following two approaches. In the simple form of trilateration, the distance between the mobile and at least three stations is measured by determining the radio frequency travel time from the stations to the mobile and back to the stations. This requires that either two radio frequency channels be provided or the mobile be equipped with a transponder that would rebroadcast the signal at some fixed time increment following receipt of the incoming signal. This information is then relayed to a central location where the location determination is made. Given the three distances d1, d2, and d3, the mobile is then located at the intersection of three circles of radius d1, d2, and d3 centered on station A, B, and C, respectively as shown in Fig. 3.

In an alternate approach, the differences between the arrival times of the various received signals could be measured and utilized. The time differences define hyperbolas with focal points at the stations. The intersection of the hyperbolas defines the mobile's location. At least three stations are required to resolve any ambiguity in location finding, though increasing the number of stations tends to decrease the error in the position estimate.

Since the radio channel (specifically the mobile radio channel) is quite hostile in comparison to other communication media, a two way transmission requirement of the first approach automatically introduces a greater potential for error in location data than the second approach where only one-way transmission is employed. The first approach also requires an interrogating (polling) signal followed by a response broadcast by a mobile which should be repeated to locate each and every individual mobile that needs to be located. Therefore, the system has a capacity limit. Interestingly the alternative approach seems to have unlimited capacity and could support an infinite number of mobiles.

3. FEASIBILITY OF CELLULAR RADIO BASED MOBILE LOCATION FINDING

From the discussion of the preceding section it can be concluded that, for vehicular location finding an infrastructure of transmitter/receiver stations is a prerequisite for radio-location or proximity systems, or alternatively dead-reckoning could be used provided it is frequently reinitialized to prevent it from accumulating location error.

The widespread deployment and availability of PLMN infrastructure of base stations with limited processing capability automatically invokes huge interest to study their applicability for other services, specifically those that require a similar transceiver infrastructure. Different features of cellular radio could also be investigated to realize new evolving applications. As an example, for efficient operation, TDMA based cellular radio uses some kind of adaptive frame alignment. For example, in GSM the timing advance (TA) signal in the down link provides essential information for frame alignment which is used to set the up-link transmission time properly so that they could reach the base station in the proper time slot and avoid any overlapping in the adjacent slots[6]. This TA signal could be used as a measure of the distance between the mobile and the serving base-station.

3.1 Cellular radio as a proximity system

As previously discussed, a mobile could be located by acquiring information concerning its presence in the vicinity of electronic signposts. To get this information a communication link needs to be established, usually for a short time. Normally in cellular radio operations, mobiles monitor the reception quality of the broadcast channel of all the neighboring base stations and the one with the strongest signal is selected as the serving Base Station. A mobile could be anywhere within a cell, and due to the very nature of the radio channel, the cell size and shape cannot be predicted accurately. Therefore, with this approach it can only be possible to identify the presence of a mobile within the vicinity of a serving BS and the corresponding cell. System areas covered with macro or medium cells are generally large and might not be very useful but the prospect is much brighter where micro cells are employed, for example in an urban city center.

Considering a possible scenario as depicted in the Fig. 4 where a road section is shown with three micro cells and each of the base stations are separated by 0.5 km. Supposing a mobile is moving from cell A towards cell C. Events are considered from the moment the mobile started its journey from the location of the base station A and the path-loss profile of the received signals from A, B, and C are monitored. Assuming all three of the base stations are using same transmission power, existence of a line of sight propagation and employing inverse fourth power path loss formula[7] ($L = 20.\log f + 20.\log d + 32.44$ dB) the received median path loss could be depicted graphically as in Fig. 5.

As can be seen, while the mobile is very close to A, it will select A as the serving BS due to strong signal received from A compared to other neighboring BSs. Therefore, the mobile under consideration could be located to be in cell A. When the mobile is midway between A and B the received signal strength from A and B is very close while signal from C is only around 10 dB less. It should be mentioned that in the mobile environment signal fading of up to 20dB is not uncommon[8]. The situation seems to improve as the mobile approaches base station B. The signal from B is quite distinct and more than 20 dB higher than A and C as the distance between the mobile and the base station B becomes less than 100 meters. At this point, B could be easily selected as the serving BS by locating the mobile to be in cell B. The situation is quite similar when the mobile reaches the mid-point between B and C and it will be possible to select cell C when the mobile is less than 100 meters away from the base station C.

From the preceding discussion it might be concluded that a mobile may be located while traveling through a micro cell and is less than 100 meters away from the specific base station. However, the presence of fading will make it more difficult and in general it can only provide a rough idea about the location of a mobile.

3.2 Cellular Radio and Dead-Reckoning System

A dead-reckoning system, as discussed previously, requires distance and direction of travel data to locate the current position of a mobile from the known starting position. The problem of error accumulation with distance, which is inherent to dead reckoning, could lead a mobile to become lost. This situation can be avoided or minimized by regularly correcting the position with some reliable and accurate location data. Thus, the applicability of cellular radio to aid dead-reckoning system will depend on the accuracy of the location estimation capability of cellular radio and it will be addressed in section 6 along with the discussion on simulation and results.

3.3 Cellular Radio and Radio Location System

As discussed previously, the location of a vehicle or mobile could easily be calculated with the help of trilateration technique, for which the required parameters are:

a) distance measures of the mobile from at least three reference points,
b) location (co-ordinates) of each of these reference points

In radiolocation systems, the distance parameters are obtained indirectly by measuring the travel time of radio signals from the mobile to each of the reference points (sensor stations). Only TDMA cellular radio of second generation and future third generation systems will be considered in this paper because of their inherent features which could possibly be exploited for estimating vehicular location relevant to ITS.

Two possible methods can be utilized with a cellular radio to find the distance parameters between a mobile and a base station.

Method 1

Any signal transmitted from a mobile reaches the serving BS with some delay depending on the distance of separation between the mobile and the BS. In the case of a TDMA system, the first signal received by the base station from a mobile will reach the intended time slot with a delay of twice the signal travel time between them. Therefore, this delay could be used as the distance parameter for locating the mobile. Cellular radio, like GSM, actually designates this time difference as timing advance (TA) and feeds this information back to the mobile. Mobiles subsequently use this information to set the next (burst) transmission time earlier by TA, enabling further bursts from the mobile to reach the BS at the proper time slot, thus preventing any overlapping in the adjacent time slots.

If a mobile is forced to access three or more of the base-stations closely located around it and extract the individual TA values along with the co-ordinates of the corresponding base-stations, the position of the mobile could be calculated from these values using trilateration method. This scheme is depicted in Fig.6. Here a mobile with the intention to locate its position sends an access burst (AB1) to the serving base station BS1 that, in return, evaluates the timing advance parameter (TA1) and sends it to the mobile. Repeating the same procedure, multiple timing advance parameters can be gathered from the neighboring BSs.

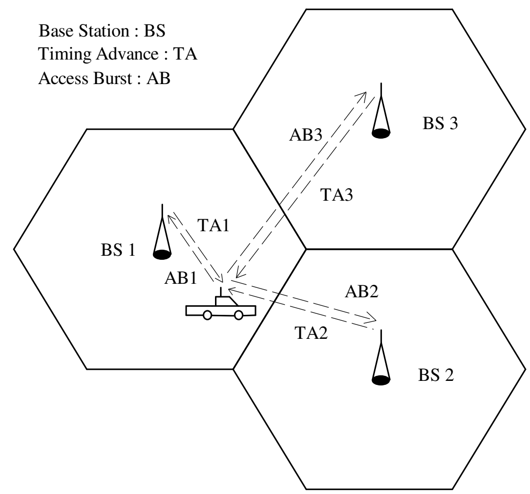

Fig. 6: Using TA (timing advance) parameter for mobile to base station distance measurement.

Since the TA parameter is normally provided in number of bit periods, as in GSM, the accuracy in distance measurement will depend on the bit rate used. Since signal arrival time is also subject to mobile environment induced error, effects such as delay spread could also degrade distance estimation accuracy.

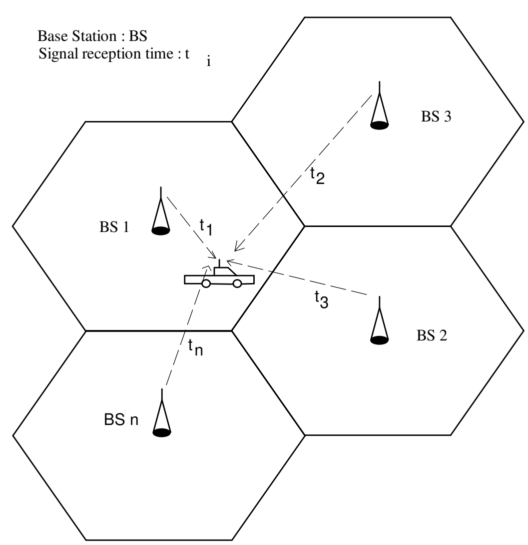

Fig. 7: Location estimation with relative signal arrival time.

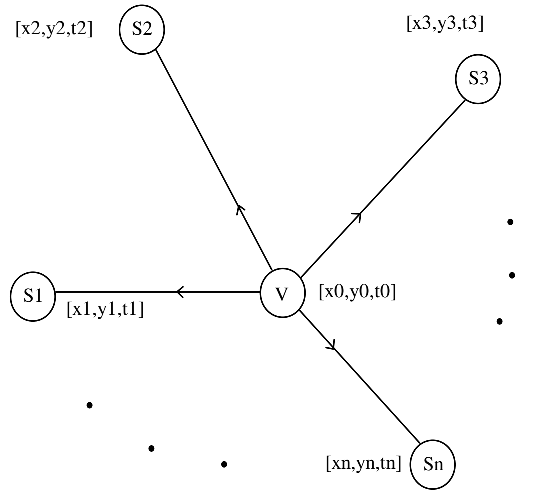

Fig. 8: Location estimation employing signal arrival time to known locations.

Method 2

This method requires all BSs to be time synchronized. Mobiles first use the control channel of the serving base station to synchronize their clock. Then, the time of arrival of the control signals from the neighboring base-stations are sequentially monitored and compared to the serving base-station. These signal arrival times will provide the necessary information regarding their relative distance from the mobile. Now, knowing the location information of these base-stations (co-ordinates) the position of the mobile could easily be calculated from these values using trilateration method. The idea is demonstrated in Fig.7. Here, a mobile in a cell served by BS1 first synchronizes its internal clock with the base station. Considering frame start time as the time reference, (for example), the mobile will sequentially scan all the neighboring base stations and their relative frame start times which will vary depending on the distance between the mobile and each surrounding base station. Since all the base stations are considered as time synchronized with some reference clock, measurement of the frame start time performed by the mobile will be a relative measure of their distance. Knowledge of the geographical location (co-ordinate) of all the neighboring base stations then leads to a set of equations of the form:

$$c(t_i - t) = \sqrt{(x_i - x)^2 + (y_i - y)^2}$$

where c is the speed of light

t_i is the relative signal arrival time

x_i, y_i is the co-ordinate of the i^{th} base station.

All that is now needed is to find the best or most likely value for x, y, and t which gives the location of the mobile.

The geographical location parameter (GLP) of the relevant base stations, in terms of some relevant co-ordinates, could be obtained in multiple ways, although broadcasting these information periodically by the base stations appears to be the best option because this approach avoids any dependency on the cellular system operation and the mobiles being served and offers, ideally, infinite service capacity.

4. IMPLEMENTATION OF LOCATION ESTIMATION ALGORITHM

The operational algorithm to find the estimated location of a mobile is elaborated in this section. In the ideal case, if it is possible to find the actual distance between the mobile and, at least, three neighboring base-stations. Then the point of intersection of the three circles drawn from the base-stations taking these distance measures as the radius would give the actual location of the mobile. But, in the practical situations, there will be error in these distance measures and as a result it will be impossible to obtain a common point of intersection. There will be two points of intersection for each of the base-station pairs and, in the case of three base stations, there are six point altogether. It is now necessary to solve the problem of finding the location of the mobile and, probably, the best way is to find the most likely location of the mobile. Least square algorithm seems to be a good choice.

An algorithm similar to[9] which has been specifically modified and adapted to be usable for cellular radio environment is investigated. Here, the basic idea is to use the time of arrival of a signal at fixed stations (sensors), sent from the mobile, as the location data. The computational algorithm involves reducing the time-of-arrival data to an estimate of location. The particular class of algorithm uses the least-squares technique of fitting the location estimate to the raw time-of-arrival data.

The original procedural setup could be easily explained by referring to Fig.8. Here, a vehicle V located at co-ordinates (x_0, y_0) starts transmitting a signal at time t0. A set of sensors $\{S_1, S_2, ..., S_N\}$ placed at co-ordinates (x_i, y_i) respectively receives this signal, delayed and distorted by multipath phenomena and noise. Each station processes the received signal and forms an estimate ti of the time at which it started receiving the vehicle's signal. These estimates referred to a common time reference are relayed to the central processor. At the processor, the quantities

$$f_i(x, y, t) = c(t_i - t) - \sqrt{(x_i - x)^2 + (y_i - y)^2} \qquad (1)$$

where c is the speed of light, could all be made zero by proper choice of x, y, and t (i.e., $x = x_0$, $y = y_0$, $t = t_0$), provided that the sensors estimates $\{t_i\}$ at the stations were correct. Multipath and other time delay errors, however, cause the times t_i to be in error by random amounts, perhaps by as much as several microseconds (each microsecond ≈ 300 meters). Thus, using the observed t_i in Eq. (1), it will, in general, be impossible to pick (x,y,t) to make all $f_i = 0$ simultaneously.

The estimates $(\hat{x}, \hat{y}, \hat{t})$ of (x_0, y_0, t_0) are therefore calculated in the least-squares sense and a computer based search is performed for x,y,t which minimizes,

$$F(x, y, t) = \sum_{i=1}^{N} f_i^2(x, y, t) \qquad (2)$$

Once $(\hat{x}, \hat{y}, \hat{t})$ have been found, t can be ignored and (x,y) used as an estimate of the vehicle's location. This least-squares approach is statistically more justifiable than the procedure of finding intersections of multiple circles or ellipses and then using least-squares methods on the reduced intersection data.

For cellular applications, some modifications are made. First of all base stations are assumed to be time synchronized. The procedure starts with the mobile under consideration synchronizing with the serving base station. The control signal arrival time from this station is considered to be zero (as a reference) at first. Then the mobile starts sequentially monitoring all the surrounding base stations one at a time and records their relative signal arrival time along with their location co-ordinates which could either be broadcast from the serving base station or from each of the individual base stations. These recorded parameters are then applied to the algorithm.

5. SIMULATION AND RESULTS

According to Engel's study[10] the majority of errors in received signal arrival time are between zero and the total multipath spread. However with small but non-zero probability, the magnitude of the error can be many times the multipath spread. It has been suggested [8] that the delay spread is ≤ 0.5 μ sec. in a rural environment, < 1 μ sec. for hilly terrain and ≤ 5 μ sec. for an urban environment. In this investigation all the aforementioned delay spreads are considered in a worst-case scenario.

5.1 Location estimation employing TA parameters

The impact of transmission bit rate on location error could be demonstrated by considering an ideal scenario where transmission environment induced errors (multipath delay) are not taken into consideration. Here, the primarily error source is the way in timing advance (TA) is represented. In the simulation, TAs are represented by integer number of bit periods and other parameters are,

cell size (radius) = 10 km, cell cluster = 7

The relationship between the transmission bit rate and the average of the estimated location error of a mobile is shown in Fig. 9. At 200 kbit/s the average location error is more than 300 m. Increasing the bit rate gradually decreases the location error and at about 1.5 Mb/s the average error is approximately 45 m. Since, in the practical situation, the effect of transmission environment induced errors are unavoidable, the effect of multipath delay on signal reception time has also been considered. Delay spreads of 0.5, 1, and 5 μsec representing rural, hilly terrain, and urban environments are considered and the results are also shown in Fig. 9.

In the case of rural environments, radial location error is around 300 m for 200 kbit/s transmission. Location error gradually falls as the transmission rate is increased and at 1.5 Mbit/s it is just over 50 m.

For hilly regions, the location error profile is more or less the same at low bit rate. At 1.5 Mbit/s it is around 80 m.

In the case of urban environments, the average error in location estimation is quite high. At 900 kbits/sec this error is around 350 m and increasing the bit rate does not improve the situation.

There are several disadvantages of using TA for vehicular location finding. Errors are introduced in mobile to base station distance measurement due to the way TAs are represented. Since TA is given in integer number of transmission bit periods, it can only assume discrete values but this reduces the accuracy of distance measures and increases the error in location estimation.

The operation of locating a mobile requires three or more random accesses to be made to different base stations and corresponding responses be received. Therefore, number of mobiles in a cell and the frequency of location estimation procedure will impose a load on the serving cellular network, which may not be desirable.

In normal operation, depending on the requirement, mobiles are allowed to access the serving base station. Accessing base stations other than the serving one might require higher transmission power, which could introduce considerable co-channel interference.

Table 1: Radial location error for a range of delay spread.

Delay Spread (in micro seconds)		0.5	1.0	2.0	3.0	4.0	5.0
Radial Location Error	Mean	33.48	71.17	138.03	205.94	268.91	332.67
	Standard Deviation	16.26	31.92	65.1	102.28	123.8	173.8

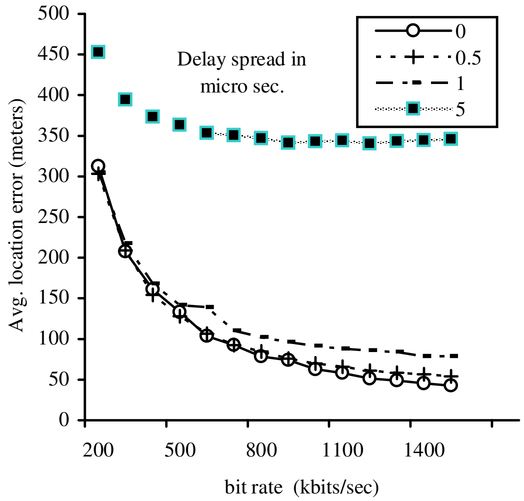

Fig. 9: Location error due to a range of delay spread.

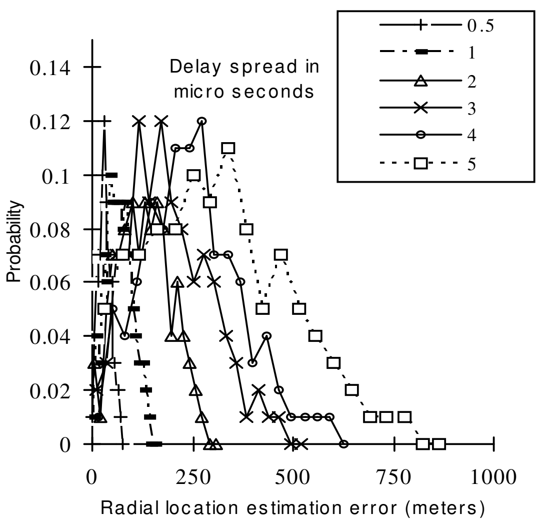

Fig. 10: Probabilities of radial location error for a range of delay spread.

5.2 Location estimation employing relative signal arrival (RSA) time

The average radial location errors for different transmission environment are estimated with the aid of computer simulation and shown in Fig.10 and Table. 1. For a rural environment (with delay spread = 0.5) the estimated location error is 33.48 m which is quite encouraging. In this case the standard deviation is 16.26 m, which is quite narrow.

In the case of a delay spread of 1 μsec representing hilly terrain, average location error is around 71 m with a bit higher standard deviation of approximately 32 m.

As expected, in the urban area with severe multipath problems the simulated experiment indicates average location error in the range of 332.67 m with quite a high standard deviation implying quite high error with wide fluctuation in estimation.

The cumulative probability of location estimation error, as shown in Fig. 11, provides much clearer understanding of the overall situation.

It is evident that mobiles could almost always be located within 76 m radial distances in a rural environment. In the case of a hilly area, this has increased to 150 m. In an urban area the radial location error might be up to 900 m.

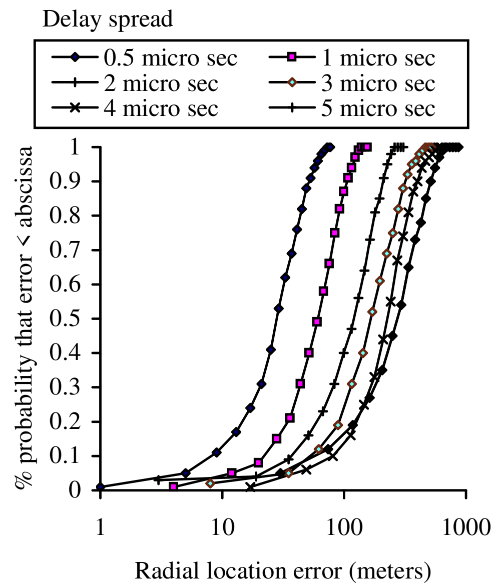

Fig. 11: Location error probability comparison.

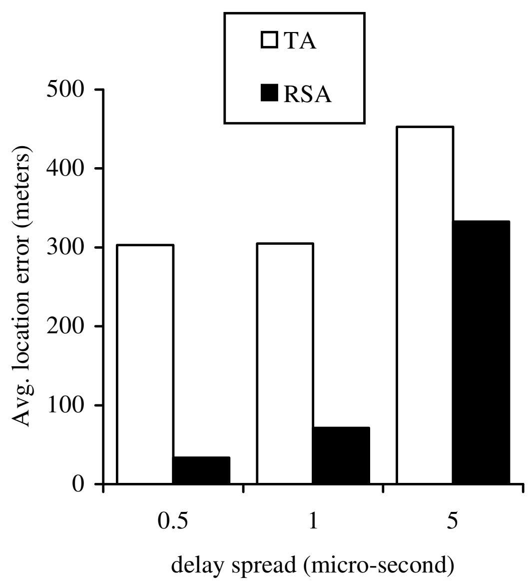

Fig. 12: Location error probability comparison.

Estimating the location of a mobile with relative signal reception time from the neighboring base station has many advantages. Errors in the distance measurement between a mobile and surrounding base stations are minimized by avoiding discrete measurements as used in TA, therefore achieving more accurate location estimation. This is clearly shown in Fig. 12, where, for different signal delay spread, location error comparison between mobile location technique employing TA and mobile location technique employing RSA time is shown for reference cellular system with bit rate of 200 kbis/sec. There is no need for any dedicated bi-directional communication (i.e. random access) between a mobile and the neighboring base stations therefore avoiding any adverse loading effect on the serving cellular network. Applying this location approach, it is possible to cater for infinite number of mobiles and any unwanted co-channel interference generation is avoided. Location estimation accuracy is much higher than the alternative approach.

The accuracy of positional information by cellular radio is not adequate for correcting the accumulation error of a dead-reckoning system, although this information can be used as a clue. If a digital road map is available in the vehicle, then location estimated via cellular radio could be used to isolate the probable area for searching and, by matching the movement profile of the mobile, it might be possible to recover it from a lost condition.

6. CONCLUSION

An investigation regarding the feasibility of employing cellular radio network for mobile location estimation has been reported in this paper. Basic strategies to be utilized for location estimation are elaborated. Two possible approaches for cellular based location estimation are investigated with the help of computer simulation. The results seem to contradict some recent publications where suggestions were made to use timing advance feature of GSM for locating mobiles. There are many disadvantages of using TA for vehicular location estimation as this requires multiple access attempts to be made by a mobile to number of base stations apart from the serving one. Thus, higher transmission power will be needed which will eventually degrade the interference problem in the neighbouring base stations. A different strategy is suggested where the relative signal arrival times from different base stations may be utilized as a measure of their relative distance from a mobile. The prerequisite is time synchronisation of base stations, and mobile with the capability of detecting control signal arrival time from different base stations. The main feature of the strategy is that no additional overhead is imposed on the cellular systems and signal interference generation is avoided by eliminating the need for employing TA from the neighbouring cells. The accuracy of the mobile receiver to detect relative signal arrival time from the neighbouring base stations relative to the serving one will influence the estimation process. Two-dimensional GLP has been considered in the current study for simplicity. The effect of more realistic three-dimensional GLP and corresponding location estimation accuracy needs further investigation.

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NOMENCLATURE

ITS	Intelligent Transportation Systems
GSM	Global System for Mobile Communication
DRGS	Dynamic Route Guidance System
GPS	Global Positioning Systems
BS	Base Station
PLMN	Public Land Mobile Network
TA	Timing Advance
AB	Access Burst
GLP	Geographical Location Parameter
RSA	Relative Signal Arrival

BIOGRAPHY

Farhat Anwar was born in Dhaka, Bangladesh in 1963. He received his B.Sc. and M.Sc. degrees in Applied Physics and Electronics from the University of Dhaka in 1982 and 1983 respectively, and Ph.D. from the University of Strathclyde, Glasgow, UK in 1996. He is currently an Assistant Professor at the department of Electrical and Computer Engineering, International Islamic University Malaysia. He has 14 years of teaching and research experience. Dr. Anwar’s primary research interest is in the area of performance analysis of computer communication and mobile cellular networks.