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Traffic congestion estimation service exploiting mobile assisted positioning schemes in GSM networks

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Abstract

To relief overstressed roadways, intelligent transport systems are required, which are able to evaluate the traffic situation in near real time, and provide traffic information to road users. Conventional solutions use limited and cost intensive installations, embedded in the roadways. Other techniques, without those installations are less accurate. An accurate and reliable low cost solution uses floating cellular data, collected from mobile subscribers. This information can be utilized to estimate the locations and velocities of the subscribers' vehicles, and in turn becomes the basis for traffic congestion estimations. In this paper, the authors first present means to increase the accuracy of known cellular positioning techniques, and introduce a traffic congestion estimation service application, exploiting the increased localization accuracy.

Keywords: floating cellular data (FCD); intelligent transportation system (ITS); location services; traffic congestion

1. Introduction

As a result of increasing motorization, urbanization and population growth, road traffic congestions have increased worldwide. Forecasts imply that road traffic will grow faster than road capacity within the next years, leading to a worsening of the traffic situation [1]. Requirements to ameliorate traffic congestions include efficient traffic management, using intelligent transport systems (ITS). They allow not only traffic management but also traffic reporting to advice road users.

The basis of ITS is the acquisition of traffic related data, which allows to judge how traffic is moving. The quality of the traffic estimation depends on the accuracy, reliability, up-to-dateness, and the statistical value and amount of the acquired data. To provide traffic information, several techniques from both private and government entities have been proposed and implemented [2]. On the one hand they include traffic warning systems such as SigAlert, evaluating traffic jam messages from police or individuals, and on the other hand sensor based approaches, using a limited installation of fixed sensors, such as radar-based traffic counters, loop sensors embedded in roadways, speed cameras or video cameras with image processing capability, infrared traffic counters, or ultrasonic traffic congestion detectors.

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The first approach, evaluating traffic jam messages, is not reliable and yields to high time delays between the occurrence of a traffic congestion and its reporting. It is nevertheless an important information source, but not applicable to provide high quality traffic information to road users in real-time.

Also the second approach, which uses certain traffic sensors, has a limited reliability and can be influenced by extreme whether conditions. Moreover, the used traffic sensors are expensive in installation and maintenance, and therefore not widespread. The level of tolerated congestion can be seen as a rational choice between the costs of improving the transportation system and the benefits of quicker travel. Cost-intensive installations of additional sensors to cover worldwide all streets are therefore neither practical nor economical feasible.

To improve traffic transport management, complementary solutions have been introduces, where traffic data is collected from the vehicles, moving with the traffic [3]. In particular taxis, which are often equipped with both GPS (Global Positioning System) and a permanent wireless radio link, are capable to provide and update ongoing vehicle system data such as position and speed. This information can be collected in a database and evaluated by a service provider in order to estimate the current traffic situation. This Floating Car Data (FCD) method, where the traffic information is collected from the cars, has the advantage that no additional roadway infrastructure is required. On the other hand is the representativeness of a group of taxis, connected with the mentioned traffic data base, limited.

Another FCD method utilizes traffic data, collected from the cellular network. We can assume that nowadays nearly every driving car carries at least one mobile cell phone, which is registered into a cellular network. The locations of the cell phones can be retrieved from the location based service (LBS) server, or estimated by triangulation. After localization and continuous tracking of the cars, also their velocity can be estimated. The cellular based localization is less accurate than GPS based localization. But this disadvantage is more than compensated by the higher statistics and potential coverage of the cellular approach, which can be applied to nearly every subscriber.

The estimation of traffic density and velocity, using the cellular phone network, has been discussed in several publications. However, most of the previous work deals with theoretical models and software simulations [4],[5],[6], whereas the consideration of implementation aspects was mostly neglected. FCD implementations must consider not only the non-line-of-sight (N-LOS) propagation in mobile networks, but also the limited availability of information, which can be retrieved out of the cellular network or out of the mobile equipment.

Information, which can be used for localization in cellular networks include the mobile system's protocol data, which is exchanged between the networks' infrastructure elements, or between base transceiver station (BTS) and mobile station (MS). Another data source may be additional, satellite based positioning equipment, such as GPS, which may be attached to mobile phones. Owing to the fact, that GPS enables mobiles are still quite rate, this manuscript will focus on non-satellite bases localization.

Localization of mobiles is a desirable asset not only for traffic management, but also for emergency and rescue services such as the American E911 or the European E-Call. Cellular based positioning of users in mobile networks has therefore been discussed over the past about ten years, often focusing on GSM (Global System for Mobile Communications) [7],[8]. It is particularly noteworthy that the techniques discussed in [8] influenced the standardization in UMTS (Universal Mobile Telecommunications System) and GERAN (GSM/EDGE Radio Access Network). For instance, the specification TS 25.305 [9] specifies the locating methods to be supported in UMTS.

Generally, we distinguish between mobile assisted GPS-free positioning, i.e. the mobile calculates its position using the signals received from base transceiver stations (BTSs), and mobile network based GPS-free positioning, i.e. the position of a mobile is determined at the network using transmissions from the mobile. Mobile network based GPS-free positioning is quite common, whereas mobile assisted GPS-free positioning has been treated in only few publications. Position estimation methods, evaluating the radio signal measurements inside mobile phone have been discussed in [10]. The study in [11] estimate traffic situations by evaluating the Cell Dwell Time (CDT), i.e. the duration how long a mobile phone remains in a cell, which is associated with the cell-ID of the connected BTS. In this communication, the authors introduce means, to improve the localization accuracy and therefore the reliability of the estimated traffic situation. This is achieved by evaluating collected statistics of additional information beside the cell-ID. The mobile assisted positioning system is then applied to a framework of a traffic congestion estimation service (TES).

2. Localization techniques in cellular networks

2.1. Overview

Non-satellite based positioning in cellular networks is possible by exploiting mobile network information, e.g. for GSM which will be considered here. Determining the position of a mobile, commonly involves two main steps:

- measurement or collection of information, which is related to the mobile's location, and
- position estimate computation based on the measurements.

In case of GSM, the available information, which is related to the mobile's location, is:

- cell-ID,
- *RSSI* (Received Signal Strength Indicator), and
- *TA* (Timing Advance).

The cell-ID is, in combination with the Location Area Code (LAC), the Mobile Network Code (MNC) and the Mobile Country Code (MCC), a unique identifier of a base transceiver station (BTS). The ID of the BTS, having a connection to a certain mobile station (MS), is known by both the mobile network and the mobile station, and can be used to estimate the position of the mobile subscriber.

The *RSSI* is a 6 bit value, indicating the strength of the base transceiver station's (BTS's) radio signal that is received by a mobile station (MS). For an increased accuracy, it can be used to estimate the distance between BTS and MS, before determining the MS's absolute position.

The *TA* is also a 6 bit value. It indicates the signal propagation delay from MS to BTS and can also be used to estimate the distance between MS and BTS. This allows a more accurate localization of the MS.

2.2. Cell-ID based localization

The unique ID of the BTS, which has a connection to a certain mobile station (MS) is known by both the mobile network and the mobile station. If the locations of the network's BTSs are known as well, it can be used to estimate the position of the mobile subscriber.

The simplest localization technique, evaluating the cell-ID, is to estimate the mobile station (MS) in the location of the connected base transceiver station (BTS). This is a very rough and inaccurate localization technique, since it does not take the cell's geometry into account. Due to the directional characteristic of common BTS antennas, they are in fact often located at the border of the cell. If beside the cell-ID no additional information is known, then the estimation error can be minimized, by estimating the mobile station's location in the cell's center of gravity. The determination of the cell's center of gravity requires the knowledge of the cell's geometry. An accurate determination of the cell's geometry can be achieved by measurements of the radio signal power from the reference BTS and the neighboring BTS in an area around the reference BTS. This section describes how to determine the cell's center of gravity in a simplified mathematical model, which does not require radio measurements.

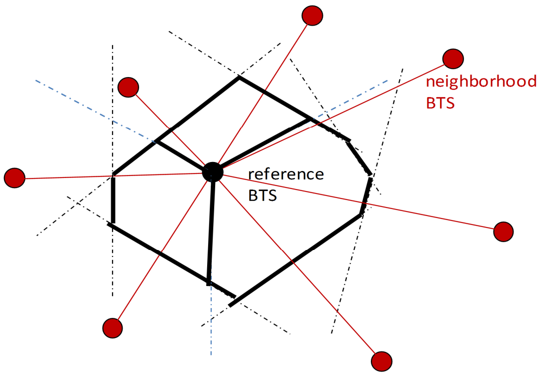

Fig. 1. Construction of a Voronoi diagram

The cell geometry can roughly be determined in a simplified model, which assumes free room propagation and an equivalent radiated power (ERP), which shall be assumed to be the same for all BTSs. In this case, the cell geometry becomes the Voronoi diagram of the BTSs. Fig. 1 illustrates the construction of a Voronoi diagram. The cell borders are build by the middle bisectors of the connections from the reference BTS to the neighborhood BTS. If there are several BTSs in the location of the reference BTS, having different directional characteristic, then the cell, resulting from the Voronoi diagram, must be divided into sectors, which represent the cells of the different BTSs in the same location.

The outcome of the construction of the cell geometry shall be the set of the N cell's corners $\boldsymbol{c}_i = \left(x_i, y_i\right)^{\mathrm{T}}$, $i = 1 \ldots N+1$, with x_i, y_i being the coordinates of the i-th cell corner in two dimensions, and with $\boldsymbol{c}_{N+1} = \boldsymbol{c}_1$. The center $\boldsymbol{s}$ of gravity can then easily be calculated by being the cell's area.

$$\boldsymbol{s} = \frac{1}{6 \cdot A} \cdot \begin{pmatrix} \sum_{i=1}^{N} \left(x_i + x_{i+1}\right)\left(x_i y_{i+1} - x_{i+1} y_i\right) \\ \sum_{i=1}^{N} \left(y_i + y_{i+1}\right)\left(x_i y_{i+1} - x_{i+1} y_i\right) \end{pmatrix}, \tag{1}$$

with

$$A = \frac{1}{2} \cdot \sum_{i=1}^{N} \left(x_i y_{i+1} - x_{i+1} y_i\right) \tag{2}$$

Fig. 2 shows an example of a computer constructed cell geometry of a cellular GSM network in Duisburg, Germany. The black marker in the middle of Fig. 2 represent the location of a reference BTS. The other gray markers in the centers of the three cell sector represent the centers of gravity, and the true locations of test mobiles to be located.

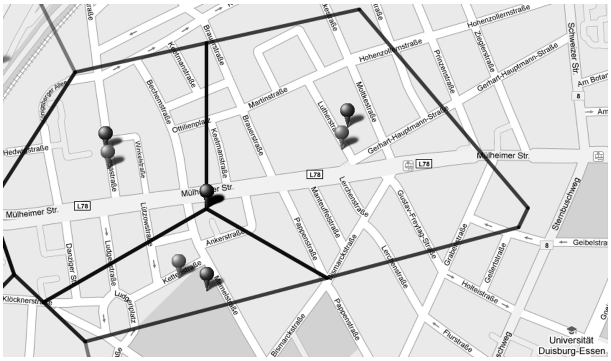

Fig. 2. Cell geometry of a GSM network in Duisburg

The accuracy of the cell-ID based localization technique, using cells' centers of gravity, has been determined in measurement trips in the area of Duisburg. The estimation error d_{err} has been determined by the distance between the position, which was estimated with the cell-ID method, and the position of a GPS measurement, which served as a reference. Fig. 3 shows the probability function of d_{err}. In 50% of all cases, it kept below 356 m, and in 90% of all cases below 881 m.

Since the cell-ID is known by the mobile network, it can not only be used in mobile assisted positioning methods, but also in network centralized positioning methods. The mobile stations (MSs) know the cell-IDs from the broadcast control channels (BCCHs) of the base transceiver stations (BTSs). Every mobile station tracks the BCCHs of up to 7 base transceiver stations in its neighborhood. This is done to allow appropriate preparations for hand-over. Beside the increased number of cell-IDs, the tracking and measurement of the BCCHs provides also the received signal strength indicators (*RSSI*s).

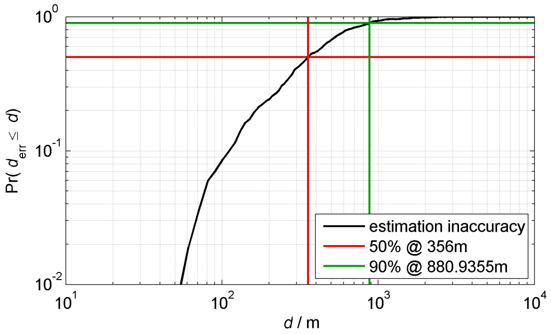

Fig. 3. Cell-ID based localization accuracy in the area of Duisburg

2.3. RSSI based localization

The received signal strength indicator (*RSSI*) is a 6 bit value, indicating the strength of the broadcast control channels (BCCHs), received by the mobile station (MS). Since the MS tracks BCCHs from up to 7 base transceiver station (BTSs) in its neighborhood, it determines up to 7 *RSSI*s.

The *RSSI* has a resolution of 1 dB. A *RSSI* value of $RSSI = 63$, for instance, means that the BTS's radio signal is received with a power of -48 dBm or more. A value of $RSSI = 62$ indicates a signal strength between -48 dBm and -49 dBm. Table 1 shows the mapping between *RSSI* and received signal power [12].

Table 1. Range of *RSSI* parameter

RSSI	Received signal power *p*
0	$p < -110\,\text{dBm}$
1	$-110\,\text{dBm} \le p < -109\,\text{dBm}$
⋮	⋮
62	$-49\,\text{dBm} \le p < -48\,\text{dBm}$
63	$p \ge -48\,\text{dBm}$

If the equivalent radiated power (ERP) of a certain BTS antennas is known, and the mobile station (MS) measures the *RSSI* of the radio signal, transmitted from the same BTS, then the MS can calculate the attenuation of the mobile channel from BTS to MS. The channel attenuation is a function of the distance and can therefore be used to calculate an estimation of the distance between BTS and MS.

There are several radio propagation models, describing the relation between channel attenuation and distance between radio transmitter and receiver. Well known are e.g. the Okumura Hata, COST Hata, and COST Walfish Ikegami models. Since the channel attenuation in cities is essentially effected by obstacles like buildings, the *RSSI* becomes a random variable, with only view information about the true distance between MS and BTS. Fig. 4 shows the attenuation

$$a(d) = ERP - RSSI - 110\,\text{dB} \tag{3}$$

which was calculated after *RSSI* measurements in the area of Duisburg.

The red line in Fig. 4 shows the logarithmic approximation of the relation between distance and attenuation, which minimizes the absolute error. The mean error of this approximation is about 238 m. Nevertheless, this estimation can be used to further improve the localization, when several *RSSI*s from different BTSs are known.

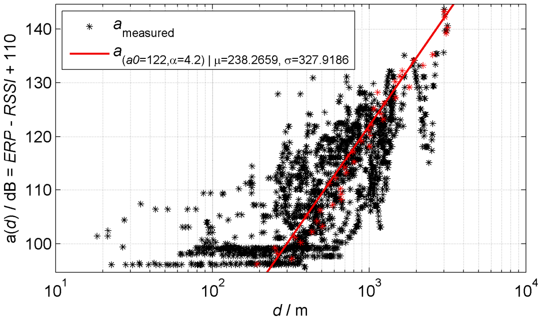

Fig. 4. Channel attenuation from *RSSI* measurements in the area of Duisburg.

2.4. TA based localization

Since GSM uses TDMA (Time Division Multiple Access), the radio signals of the mobile stations (MSs) must reach the base transceiver station (BTS) in certain time slots. To allow accurate synchronization of the radio signals, which reach the BTS, the MSs must know the signal propagation delay of the mobile channel from MS to BTS. The Timing Advance (*TA*) is a 6 bit value, which indicates the signal propagation delay from MS to BTS and back. It is quantized in bit periods. In GSM, the bit period is $T_b \approx 3.69 \mu s$ [13]. When assuming free room propagation or line of sight (LOS) between MS and BTS, the distance *d* between MS and BTS can be estimated by

$$d(TA) = TA \cdot \frac{T_b \cdot c}{2} \approx 554 \cdot TA \tag{4}$$

where *c* is the speed of light. However, in most cases we must consider N-LOS (none line of sight) channels, in particular in cities, where the radio signal often reaches the receiver after reflections or scattering. This leads to an increased signal propagation delay and *TA*, or an overestimated distance *d*. Along with cell-IDs, the authors also measured the Timing Advance (*TA*) with a mobile phone in the area of Duisburg. The coordinates of the measurement points have been measured in addition by using a GPS device. The distance between the measurement points and the base transceiver stations (BTSs) have been calculated and served as reference distances to calculate the *TA* based distance estimation error. Fig. 5 illustrates the relation between measured *TA* and distance.

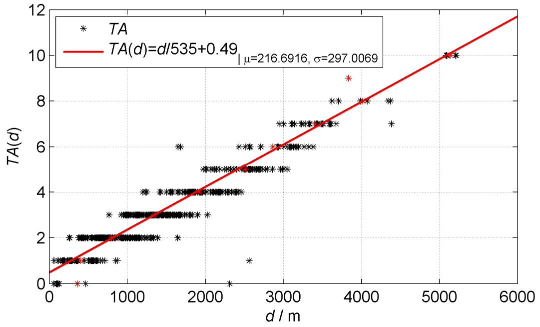

Fig. 5. Timing Advance (TA) and measured distance

The red line in Fig. 5 shows the linear approximation, which minimizes the absolute estimation error. The mean error is about 217 m.

The *TA* can generally be used to increase the accuracy of localizations. But since the *TA* is measured only when a dedicated channel is allocated, the TA method is only conditionally applicable for the traffic estimation application. The cell-IDs and the *RSSI*s on the other hand can always be queried from the mobile, and allow localization with increased accuracy compared with network based methods without mobile assistance. The accuracy can be further improved by averaging consecutive measurement results. Fig. 6 shows the probability function of the localization error d_{err} for mobile assisted localization for the same measurements like in Fig. 3. In 50 % of all cases, it kept below 117 m, and in 90 % of all cases below 245 m.

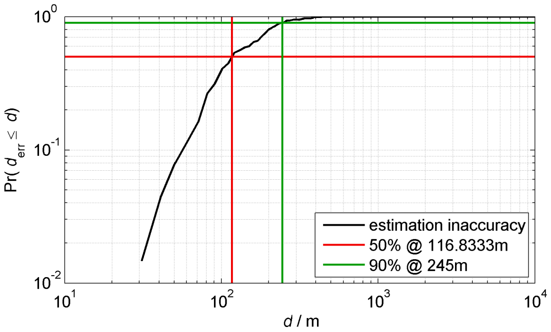

Fig. 6. Mobile assisted localization accuracy in the area of Duisburg

3. Traffic congestion estimation service

The increased accuracy of the mobile assisted positioning can be used for a traffic congestion estimation service (TES) with higher reliability compared to conventional techniques. TES consists of two key components, namely the server side and client side. The server side component is the one responsible for detecting and estimating congestions, whereas the client side is responsible for inquiring about, and then displaying congestion status to the end user.

Fig. 7 shows a traffic scenario. The triangular marker illustrates the mobile subscriber. Different colors, green, orange and red indicate different traffic situations.

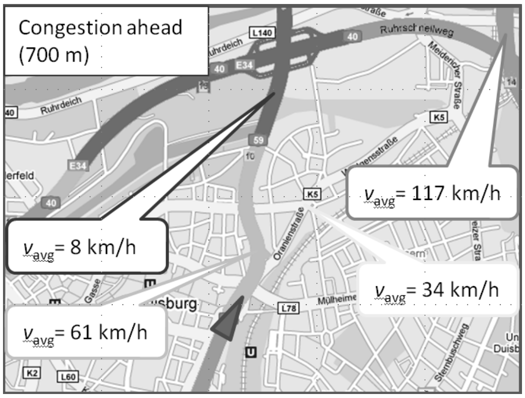

Fig. 7. Traffic scenario on a mobile client’s screen

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