# Map-based Positioning using Mobile Phones

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**Key words**: Low cost technology; Positioning; Mobile Phones; Traffic State Acquisition.

## SUMMARY

The acquisition of road users to influence the traffic flow is known under the name of 'Floating Car Data' and different services are offered on the market. Probably because of the high communication costs – the GPS position has to be sent to a centre via the mobile telephone system – the availability for an area-wide acquisition of traffic data is low and could not win recognition on the market yet. In the project Do-iT (Data Optimisation for Integrated Telematics) with grant of the BMWi (Federal Ministry of Economics and Technology) the possibility is investigated to carry out positioning with the use of the existing infrastructure of the mobile telephone system, so that the acquisition of traffic flow is enabled without additional communication costs even apart from motor-ways ('Floating Phone Data'). High potential is given through the fact that almost everyone has a mobile phone and the high availability in downtown areas. However, the positioning accuracy is reduced in comparison to GPS.
In this paper the authors present first results for positioning within the GSM network and matching to a digital map for assessing the road network. The measures used are timing advance value and signal strengths. The results and difficulties occurred are analysed and potential for further improvement is pointed out.

## ZUSAMMENFASSUNG

Die Erfassung von Verkehrsteilnehmern zur Beeinflussung von Verkehrsströmen ist unter dem Namen „Floating Car Data“ bekannt und wird in unterschiedlichen Diensten am Markt angeboten. Vermutlich infolge der hohen Kommunikationskosten – die GPS-Position muss per Mobilfunktechnik an eine Zentrale gesendet werden – ist die Durchdringungsrate für die flächenhafte Verkehrsdatenerfassung zu gering und hat sich am Markt bisher nicht durchsetzen können. Im Projekt Do-iT (Daten Optimierung für integrierte Telematik) wird mit Förderung durch das BMWi (Bundesministerium für Wirtschaft und Technologie) eine Möglichkeit untersucht, die Ortung mit der vorhandenen Mobilfunkinfrastruktur und somit ohne zusätzliche Kommunikationskosten eine Verkehrsflussbestimmung auch abseits der Autobahnen durchzuführen („Floating Phone Data“). Dem Potenzial, das durch die hohe Durchdringungsrate von Mobiltelefonen in der Bevölkerung und die hohe Verfügbarkeit im innerstädtischen Bereich begründet ist, steht eine im Vergleich zu GPS deutlich herabgesetzte Positionsgenauigkeit gegenüber.

In diesem Artikel stellen die Autoren erste Ergebnisse für die Ortung mit Mobilfunkdaten und das Herstellen eines Kartenbezugs vor. Die verwendeten Mobilfunkdaten sind der Timing

Advance Wert und Signalstärken. Die Ergebnisse und aufgetretene Schwierigkeiten werden analysiert und weitere Lösungsansätze aufgezeigt.

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## 1. MOTIVATION

Anybody is concerned by daily traffic problems: e.g. when the way to work is transferred to a stay in a traffic jam or in the case of accident occurring on the planned driving route. Redirection instructions are given and a decision for or against these instructions is based on your personal assessment. In general nobody knows how many drivers follow redirection instructions and if these instructions lead to a faster attainment of the destination.

To solve these daily problems the traffic state has to be acquired and forecasted. For the acquisition different techniques exist. On the one side local loop data allow to measure the traffic flow including all travelled vehicles at the place, where the measurement unit is installed. On the other hand the technique 'Floating Car Data' (FCD) is in use. Therefore the position of a vehicle is determined by using the GPS navigation solution. Thereafter the position is transferred to a service centre via SMS. Besides the installation costs for the equipment in the cars the costs for sending SMS may be the reasons for the rare use of the method. Summarising the before mentioned two techniques exist: one delivering complete data at space-discrete points and another one delivering trajectories for a few vehicles only.

These problems can be overcome using mobile phones and their possibilities to determine positions, since almost every driver has a mobile phone nowadays. With other words a technique to determine trajectories for an increased number of vehicles is available and has to be further developed. The restriction of this technique is its positioning accuracy that does not reach the one of GPS. The great advantage of this technique that will be described in this paper is the availability of the mobile phone data without any implementation of further sensors and without any modification within the GSM network as well as the mobile phones itself. Driving force of the FPD (Floating Phone Data) approach is nevertheless a possibility of traffic flow observation without any additional communication costs. The improvement of the positioning quality should be realised by sophisticated algorithms and by matching the positioning results on the digital road map. This task is one of the targets of the project Do-iT (Daten Optimierung für integrierte Telematik / Data Optimisation for Integrated Telematics) granted by the Federal Ministry of Economics and Technology (Bundesministerium für Wirtschaft und Technologie - BMWi). Within this project trajectories related to the digital road map the so-called Floating Phone Data are generated. For further information regarding Do-iT we refer to Wiltschko et al. (2006) or to BMWi (2006). This paper will focus on the generation of FPD, describe the first results obtained by the developed and applied methods and outline further possibilities to improve the results.

## 2. GSM NETWORK AND AVAILABLE MEASUREMENTS

### 2.1 Base Transceiver Stations

Communication between mobile stations (MS) in a GSM network is basically realised by base transceiver stations (BTS) (Roth 2002). Several of these stations are managed by so-called base station controllers (BSC). Within one service area (a few km expansion) these BSCs are bundled in one mobile switching centre (MSC). If the MS changes from one BTS to another, this is called handover. For network-based positioning within the GSM network, several interfaces to grip measurement data can be used. The focus herein is on the Abis interface between BTS and BSC, compare figure 1. From this interface one can get the measurements described in the chapters 2.2 and 2.3.

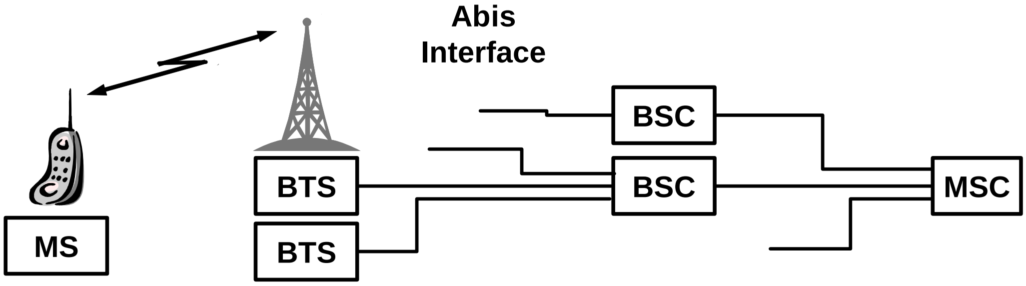


**Figure 1**: Structure of the GSM network and Abis interface (compare Wiltschko et al. 2006)

Each BTS can be identified by a Cell-ID. Other important information for positioning such as position, frequency and transmitter power of the BTS are also available within the network.

### 2.2 Timing Advance Value

For communication between BTS and MS time slots are used, which have to be exactly synchronised. For this reason the signal propagation delay has to be taken into account (Roth 2002). The timing advance (TA) value is an estimation for the distance between MS and the serving cell (BTS in which the MS is logged in). The TA value indicates the time delay for the MS to send one Burst[1]. It is divided into 64 slots (0-63) (Jonsson/Olavesen 2002). The resolution of the TA value results from (Walke 2001)

$$dTA = \frac{TA \cdot c \cdot t_{bit}}{2} = \frac{TA \cdot 3 \cdot 10^8 \frac{m}{s} \cdot 3{,}69 \cdot 10^{-6} s}{2} = 554 \text{ m} .$$

Herein, speed of light with $c = 3 \cdot 10^8 \frac{m}{s}$ is taken for the velocity of propagation for radio waves. $t_{bit}$ is the duration of one Bit in the GSM network. The maximum error for the measurements is expected to be ± 0,5 bit in Walke (2001). With a resolution of 1 bit the range of uncertainty is 2 bit. Therefore, the accuracy of the determination of the distance is limited to

1 Burst = data packet that is sent within one time slot (0,577 ms), (Schucan 2004)

1108 m (± 554 m). The accuracy of the determination of the TA value is dependent from the distance between MS and BTS and increases with approximation to the BTS (Wiesmann 2000). Since the measurement of the TA value is system intrinsic, it enables network-based positioning (Reed et al. 1998).

### 2.3 Signal Strength

A mobile station can measure the signal strength of the serving cell and up to six neighbouring BTS for handover decisions and other purposes of network optimisation and administration. These measurements are available at the mobile stations and are transmitted to the network during communication (Walke 2001).

The accuracy of the signal strength depends on multipath propagation, shadowing effects (moving and fixed objects) and short-term-/fast fading and is thereby related to the conditions regarding LOS (Line of Sight) respectively NLOS (Non-line of Sight) (Wiesmann 2000). The signal attenuation is also effected by changing environmental conditions like rain, snow, humidity and temperature (Kriegl 2000).

The signal strength is measured between - 110 dBm and - 48 dBm and can uniquely be allotted to a 64-ary RXLEV-parameter (RXLEV = 0 matches - 110 dBm, RXLEV = 63 matches - 48 dBm) (Walke 2001). Therefore, the resolution of the signal strength measurements is restricted to 1 dB.

The unit dBm is transmission power related to 1 mW (Detlefsen/Siart 2005). It holds:

$$\text{Transmission power}\,[\text{Watt}] = 10^{\frac{\text{dBm}}{10}} \cdot 0{,}001$$

$$\text{Transmission level}\,[\text{dBm}] = 10 \cdot \log\left(\frac{\text{Watt}}{0{,}001}\right).$$

The difference of two transmission levels related to dBm is again the dimensionless relation of two numbers decibel. The accuracy for the signal strength is theoretically given with 4 dB (up to -70 dBm) respectively 6 dB (Walke 2001). The accuracy decreases with increasing distance, i.e. the standard deviation gets higher. Walke (2001) states that accuracies of 2-3 dB are achieved empirically.

By use of a mathematical model that describes the attenuation of the signal strength, the signal strength can be interpreted as a distance (Andersen et al. 1995). Therefore the well-known Okumura/Hata-Model can be used (Walke 2001):

$$P_T - P_R = 69{,}55 + 26{,}16 \cdot \log(f) - 13{,}82 \cdot \log(h_T) - a(h_R) + (44{,}9 - 6{,}55 \cdot \log(h_T)) \cdot \log(d)$$

$P_T$ : transmitted signal strength — $h_T$ : (effective) BTS height

$P_R$ : received signal strength — $h_R$ : MS height above topography

$f$ : transmitting frequency — $a(h_R)$ : correction factor for MS height

$d$ : distance from MS to BTS

Provided that the antenna height of the BTS is 30 m and the height of the MS is 1,5 m ($a(h_R) = 0$) the simplification holds (Walke 2001):

$$P_T - P_R = 49{,}14 + 26{,}16 \cdot \log(f) + 35{,}22 \cdot \log(d)$$

For this reason the distance d between MS and BTS is (in meter) determined to:

$$d = 1000 \cdot 10^{[(P_T - P_R - 49{,}14 - 26{,}16 \cdot \log(f))\ /\ 35{,}22]}.$$

## 3. POSITIONING METHODS

In this paper two different procedures for positioning with mobile phones are presented. The first one is positioning with signal strength and TA values, the second one is performed by signal strength matching.

### 3.1 Positioning with signal strength and TA values

Both signal strength and TA values are available from the Abis interface. From the current state of the project, these data have to be acquired using a mobile station Siemens ME 45 instead. This leads to the following limits:

- update rate is 2 s
- the TA value of the serving cell which is available during a call has to be matched manually to the current Cell-ID since handovers are not explicitly transferred
- signal strength of the serving cell can not be used, because it is modified during call for improved connection quality.

Several test runs were carried out in Leonberg near Stuttgart. Different characteristics were considered like motorways and downtown areas. For purpose of analysis and evaluation GPS positions were measured simultaneously.

#### 3.1.1 Least squares adjustment

After transferring RXLEV values in distances as described in chapter 2.3, the distances between one MS and different BTS from one epoch are used to determine the position of the MS by least squares adjustment using the functional model of an arc section (see figure 2), compare Niemeier (2001) and Kahmen (1993). The antenna directions are also taken into account. The TA value is introduced with higher weight, forcing the position estimation to the serving cell.

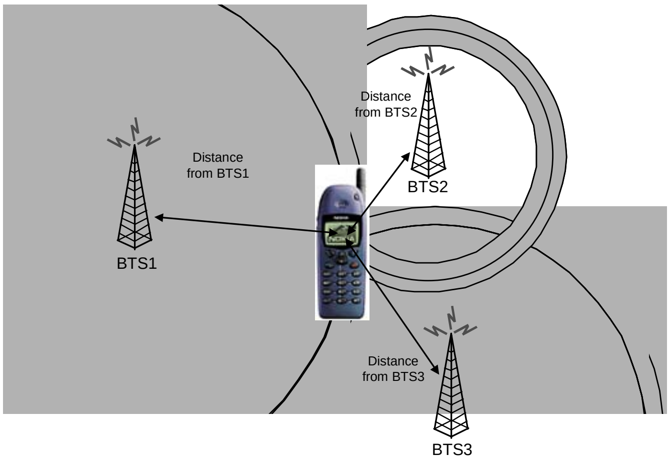


**Figure 2:** Arc sections for positioning within the GSM network

First results of this method for a sequence of positions are shown in figure 3. The black dotted lines show the assignment of the adjusted positions to the GPS positions. As can be seen high deviations occur between single epochs. The mean deviation is 840 m with a standard deviation of 961 m. These results can be improved by using a moving average with filter length 13, see figure 4. Now, mean deviation is reduced to 663 m and the standard deviation is 736 m.

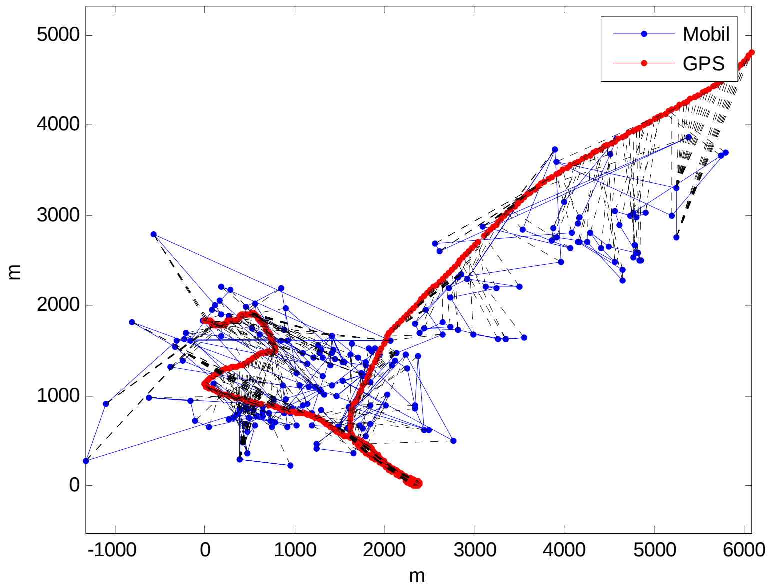


**Figure 3:** Mobile positioning by adjustment with TA value and signal strengths

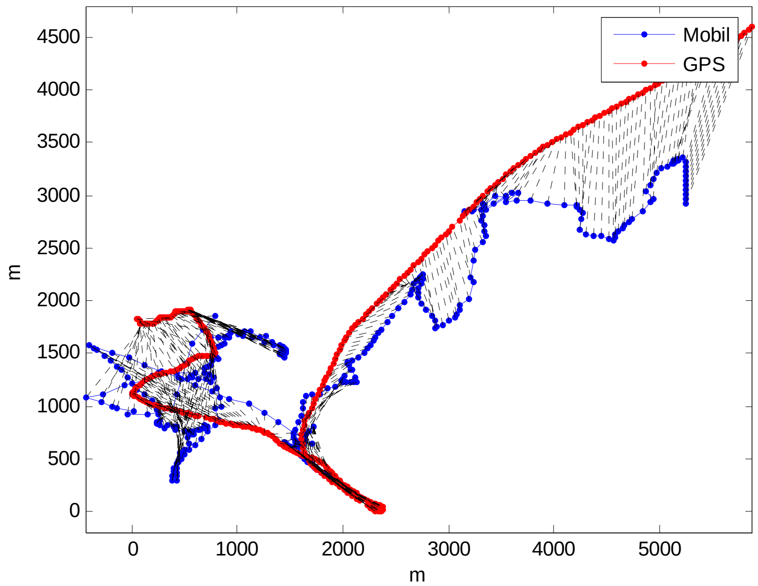


**Figure 4:** Smoothed adjustment results, moving average with filter length 13

### 3.1.2 Kalman filter

Further improvement for positioning within the GSM network is expected to be achieved by using a Kalman filter. One can take advantage of the combination of the underlying functional model to include the assumed vehicle motion and the measurements. Kalman filter theory is omitted here, see Kalman (1960) and Heunecke (1995), our focus is on the approach modelled for positioning with GSM data.

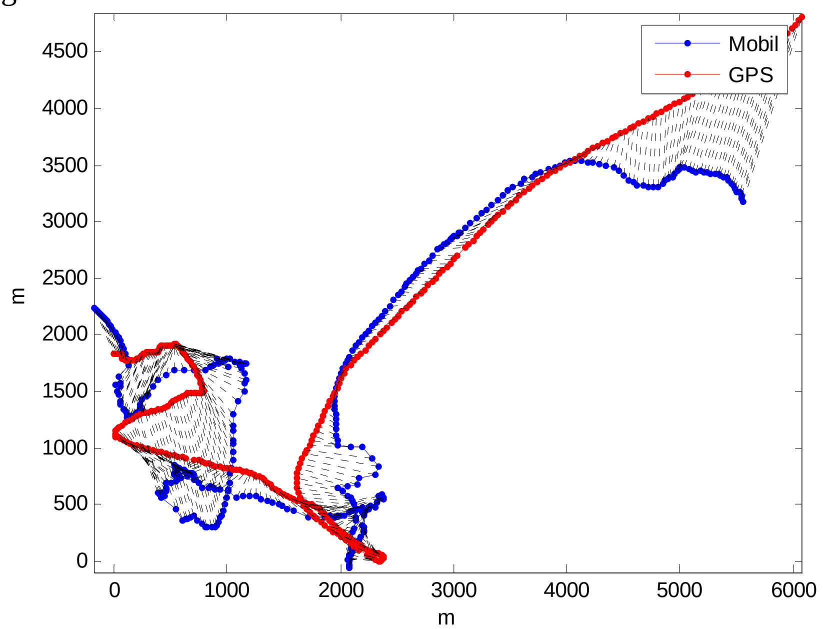


**Figure 5:** Mobile positioning with Kalman filtering

For this purpose the standard approach based on coordinates and uniform motion is found in literature. In (Catrein et al. 2004) the filter input is generated by matching the given signal strengths to a signal strength map via least squares adjustment. Since no such reference is available yet, we use positions iteratively derived like described in 3.1.1 instead. Estimates, i.e. the filter outputs, are position and velocity for each coordinate axis.

Exemplarily results for the same scenario as in chapter 3.1.1 are shown in figure 5. The mean deviation is further reduced to 452 m, the standard deviation is 545 m.

#### 3.1.3 Reference to digital map

Since the results from chapter 3.1.1 and 3.1.2 are not yet applicable for standard map matching algorithms as described in Czommer (2000), the following approach is chosen to determine trajectories with reference to maps:

- In case of handover TA values from previous and next serving cell are used to determine a search area within the digital map via arc section.
- From this search area nodes of the digital map are extracted.
- If there is more than one handover, possible shortest paths are calculated between the extracted nodes.
- Decision for one trajectory is made by comparison of all possible trajectories with the before generated position sequences from Kalman filter respectively least square adjustment.

The determination of the search area is in principle shown in figure 6. The position of handover is approximated by a rectangular search area taking the accuracy of the TA values (compare chapter 2.2) into account.

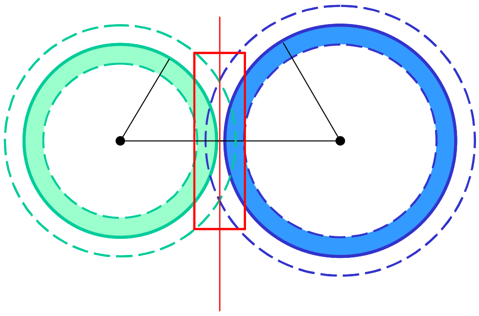

**Figure 6:** Search area in case of handover

In graph theory a path between a source node and a target node is defined as a sequence of edges in which the end-point of an edge must be identical with the initial point of the next edge. For the calculation of shortest paths the algorithm of Dijkstra (1959) is used which works fast and reliable. Here, the extracted nodes of the first handover are defined as source nodes and the nodes of the second handover as target nodes. This procedure is repeated analogously for the second and the third handover and so on.

In figure 7 an example of a test run is shown that contains 4 handovers with 11, 16, 8 and 16 extracted nodes. The results from Kalman filter positioning are used to determine the most probable trajectory from all possible alternative routes. Therefore the perpendicular distance from the MS positions to the alternative routes on the digital map are calculated and a standard deviation is derived.

Obviously the alternative route 3 can be excluded reliably, compare figure 7. The alternative route 1 seems to fit in some parts, but route 2 can clearly be identified to be the most probable. For this test run a correct identification of a road is possible. This is not yet given for all test runs carried out, but further improvement for the map-related trajectories are expected since

- acquisition of TA values will be network based (without manual after-work) and correctness of the arc sections therefore will be increased,
- information about the net geometry will be available to further limit the search area,
- the determined position sequences will be improved qualitatively and
- beside shortest paths also other ways adapted to the behaviour of the road users will be taken into account.

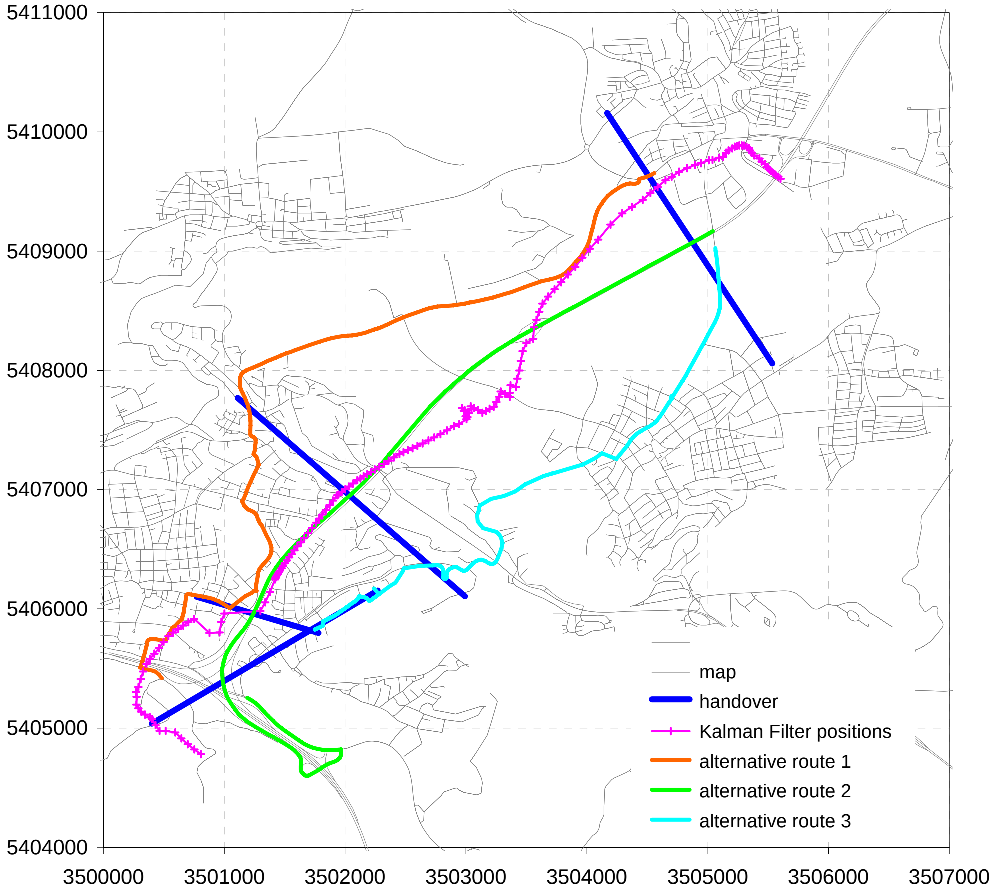


**Figure 7:** Most probable paths and position sequences of Kalman filtering

### 3.2 Signal Strength Matching

Since the procedure presented in 3.1 does not always provide correct identified roads, another method to determine map referenced trajectories is introduced. During investigations it was found out that significant structures in signal strength pattern appear in repeated driving scenarios. So signal strengths measured to received neighbouring cells could be matched to a map of signal strengths. A reference map with signal strengths is not yet available from the GSM network provider attending this project. An own reference is created by use of the test runs. The assignment of the signal strengths to the map can successfully be done with the help of accurate GPS positions of about 1.5 m and is carried out with the respective longest test run.

In figure 8 a promising example for this method is shown, the signal strengths of four test runs are plotted against the distance generated from the map. This can be done due to the knowledge of the GPS positions. The example in figure 9 foreshadows difficulties one has to face with this procedure.

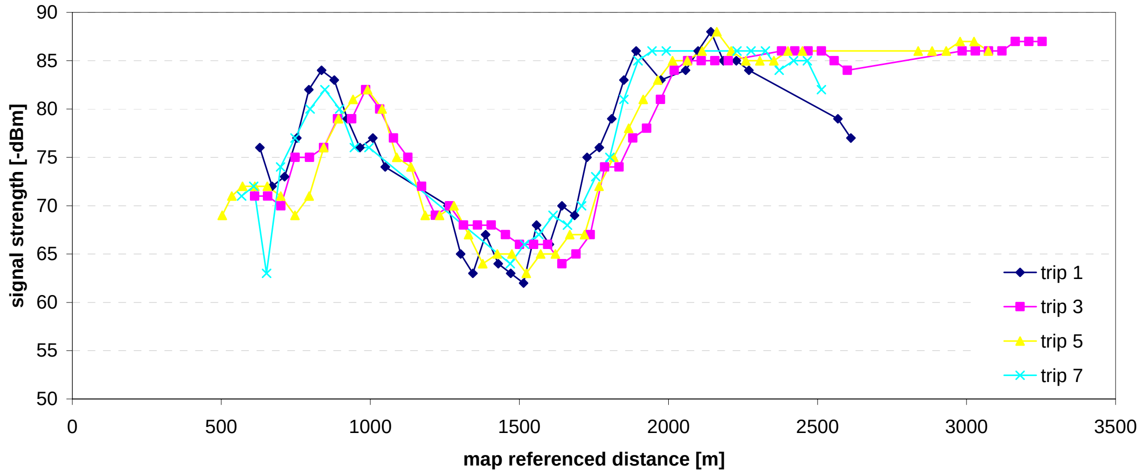


**Figure 8:** Signal strengths, positive example

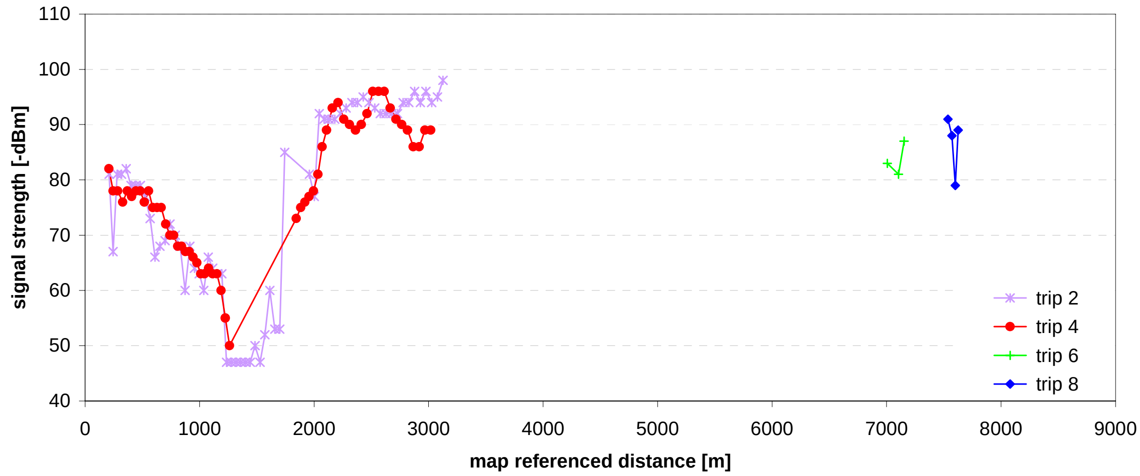


**Figure 9:** Signal strengths, negative example

After the reference signal strengths are fixed, the measured signal strengths can be matched to them. Since measured signal strengths are only time referenced and the respective reference signal strength is position referenced, matching algorithms can not be used in simple form. The matching is made under the assumption of constant velocity along the track by simulation of different velocities. The matching to the map is then carried out by methods of pattern recognition, which work using cross-correlation and least square techniques (compare Czommer et al. 2006). In figure 10 the matching result for one test run is exemplarily shown. One recognises that matching is successful for different velocities. The decision for one velocity is taken by the mean deviation.

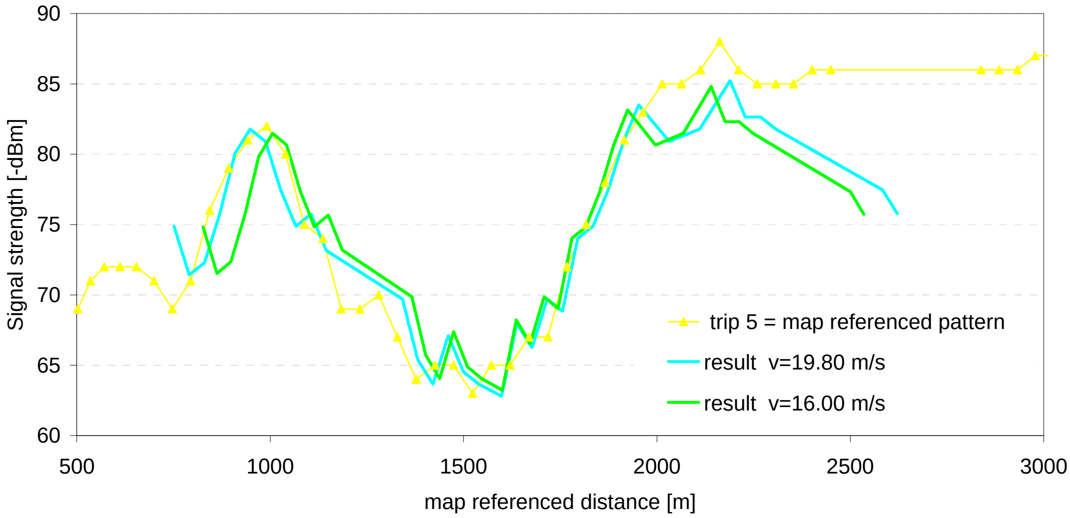


**Figure 10:** Map matching with signal strength

The average deviation between the measured signal strength pattern and the map referenced signal strength pattern amounts to 190 m for all test runs in this scenario. For only 28 % of all antennas regarding this test run a successful solution can be determined. Since signal strengths are always measured to several antennas (at most 6) at the same time, it is not necessary to achieve a matching result for all antennas. In principle it is sufficient if the assignment to one antenna is successful at each point of time. Therefore a complete availability is defined as percentage of the time of the correct assignment to the total time of the test run. For these test runs the availability of successful solutions to one of all antennas increases to 66 %. Figure 11 shows a typical example where a test run is matched to the map with signal strength pattern of several antennas. The solutions are in parts overlapping and therefore redundant.
A typical problem of matching measured signal strengths to map referenced signal strength pattern is the ambiguity: similar patterns may also exist in neighbouring roads. Since a complete map of signal strength is not available for all roads, by now the correctness of the solution can only be evaluated by analysing the two following aspects:

- evaluation of the possibility to match measured signal strengths of one antenna on signal strength pattern of other antennas,
- evaluation of the possibility to match measured signal strengths of one antenna from one test run to a different test run that is located in the vicinity or is driven on a parallel route.

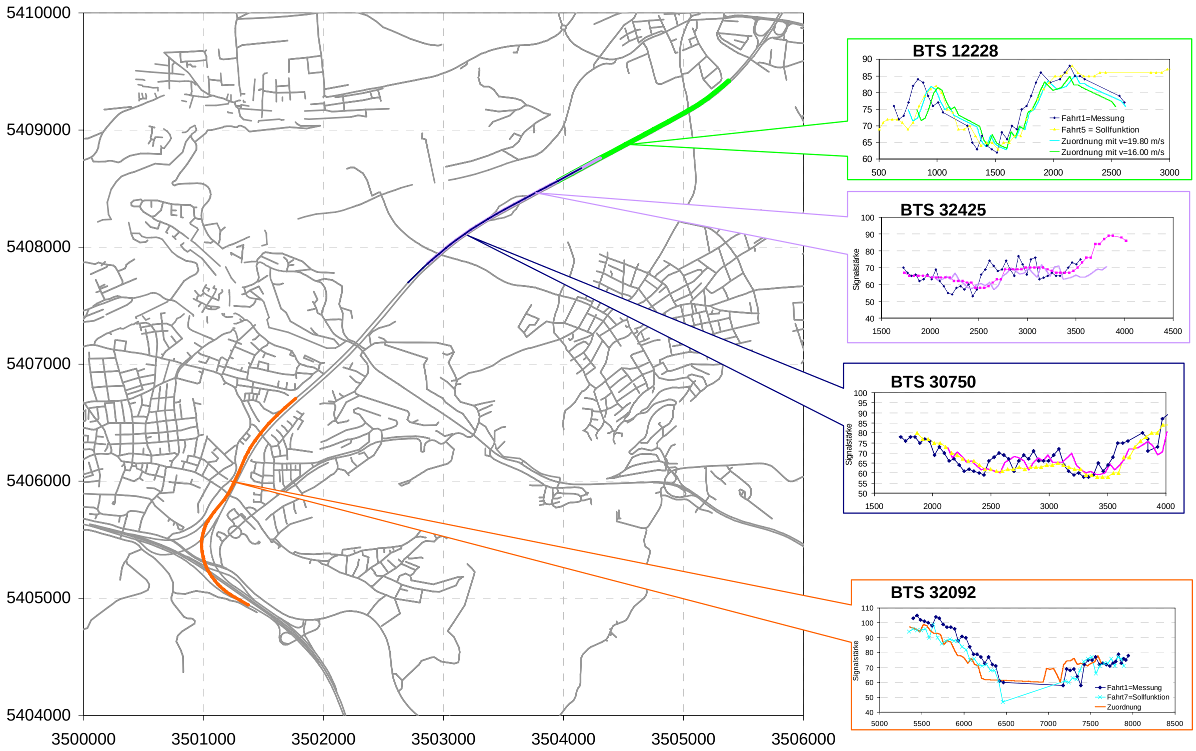


**Figure 11:** Matching with signal strength via several antennas

For these test runs the matching to other antennas was only “successful” for one of altogether more than 90 possible assignments. This leads to a correctness of 99 %. Up to the current state of the investigations it has to be noticed that about 50 % of the test runs can be incorrectly assigned to parallel routes. It is important to mention that a variety of incorrect assignments can only be achieved with unrealistic constant velocity values regarding the matched route. This main problem of matching with signal strengths could be overcome by introducing a limitation for the matching areas by integration of further GSM network information or the use of velocity information from the Kalman filter (see 3.1.2). The required accuracy for this information depends on the environmental structure (density of roads etc.).

One important point that has also to be considered is the repeatability of the matching procedure with data from different times. The test runs are carried out on the same day and therefore only a little temporal variation of the measured signal strength pattern can be expected (compare chapter 2.3). For examination of these difficulties, test runs of one scenario were matched on the map referenced signal strength patterns of other scenarios which follow partly the same routes. The measurements are carried out with a time difference of 14 days. Five identically repeated antennas could be identified for the test runs. The availability of the solutions is reduced considerably from 66 % to 36 % which indicates a clear variation of the signal strength patterns with time. The correctness, however, remains unchanged in the same range (95 %).

Nevertheless, the example in figure 11 shows the possibilities of the matching with signal strengths. Further research activities in the project will deal with the problems shown. We expect that the quality of the matching with signal strengths will improve since

- the signal strength will be available for the serving cell, too
- the model of driving dynamics can be improved (up to now: constant velocity) and
- a coupled use of the information delivered by the adjustment/Kalman filtering of position sequences (3.1) and the matching with signal strengths (3.2) will be introduced.

## 4. SUMMARY AND FUTURE OUTLOOK

The described examples show the first results basing on data acquired at the mobile phones. On the one hand, the results presented in chapter 3 show some difficulties when geodetic standard methods for positioning and matching are applied. On the other hand, no geodetic accuracy has to be achieved. The determined deviations range from few 10 meters up to several 100 meters. The objective is to get an assignment of the mobile phone to the road network. This could partially be achieved. Promising results and further developments could be pointed out. Since these strongly depend on the environment in which a solution is strived for, work especially regarding matching has to be done in downtown areas with a dense road network and lots of base transceiver stations.

Within the ongoing Do-iT project the data will be available through the GSM network and the algorithms will be further improved. Besides expected improvement for the measurements themselves and further network information like cell geometries and reference maps for signal strengths, variations of the algorithms used will be investigated. For example, in Kohlen (2004) it is indicated to use only data from up to three neighbouring cells for positioning and to use signal strength differences to overcome problems with repeatability in signal strength matching. Especially the combination of the different methods like kinematic positioning and signal strength (compare chapters 3.1 and 3.2) should lead to a more reliable and accurate reference to the digital road map and therefore to trajectories (FPD) of higher quality.

The result of the positioning process, the FPD, will deliver a higher penetration rate regarding the active road users. For the first time the real behaviour of the drivers may be measured. The diminished accuracy will be redeemed through the high amount of data leading to a good approximation for the acquisition of the real traffic state and delivering a valuable base for the forecasting task. The traffic-related results will be an improved control of alternating signs and of traffic lights, both based on the measurement of the diver behaviour by FPD.

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