

Estimating Driving Trajectories for Cellular Network Subscribers

CHRISTOPH KIESLICH

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Declaration

I hereby declare and confirm that this thesis is entirely the result of my own original work. Where other sources of information have been used, they have been indicated as such and properly acknowledged. I further declare that this or similar work has not been submitted for credit elsewhere.

Hagenberg, June 16, 2014

Christoph Kieslich

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Kurzfassung

Mobilitätssimulationen sind ein wichtiges Instrument um den Betrieb von mobilen Kommunikationssystemen zu garantieren. Der Zweck von Mobilitätssimulationen ist herauszufinden wie mobile Benutzer das Netzwerk beeinflussen. Üblicherweise werden diese Mobilitätsmodelle von stochastischen Prozessen oder Umfragen abgeleitet. Ein weiterer Ansatz ist es, diese Modelle aus echten Informationen der Mobilfunkbenutzer abzuleiten. Dies erlaubt dem Netzbetreiber sein Netzwerk mit Bewegungsmodellen seiner Mobilfunknutzer zu simulieren.

In dieser Arbeit wird ein System vorgestellt zur Erzeugung von Trajektorien für Mobilfunkbenutzer. Die hierdurch erzeugten Trajektorien können anschließend in Mobilsimulationen verwendet werden. Das vorgestellte System untersucht Handover Events. Da GSM Handover nur durchgeführt wenn das Mobiltelefon im „connected“ Modus ist, können Trajektorien nur für Mobilfunkbenutzer erzeugt werden welche gerade Telefonieren. Es wird ein Ansatz präsentiert welcher mit Hilfe von Prädiktionsrechnungen die Position des Handover ermittelt. Das System verwendet Bevölkerungsdichtekarten um die Start- und Endposition des Mobilfunkbenutzers zu schätzen. Die erzeugten Trajektorien bestehen aus der gefahrenen Route und Zeitstempeln welche Rückschlüsse auf die Geschwindigkeit geben.

Abstract

Mobility simulations are important for the operations of mobile communication networks. They aim to investigate how moving subscribers affect the underlying core network. Usually the mobility models behind this simulations are derived from stochastic processes or surveys. A different approach is to derive this mobility model from real world subscriber information. Therefore, network operators can make mobility simulations with their own subscriber behavior.

Within the scope of this thesis, a system to estimate driving trajectories for subscribers in cellular networks will be presented. The estimated driving trajectories can then be used in mobility simulation frameworks .The developed system investigates handover updates in the network operator's core network. Since handover events only expose a coarse location information, an approach to estimate the handover position based on coverage prediction maps will be delineated. The developed system utilizes population density maps to estimate the start and end position of the subscriber's journey. The estimated trajectories covers the traveled route as well as timestamp to derive the subscriber's velocity.

Chapter 1

Introduction

In times of increasing traffic volume in mobile communication networks the research area of mobility simulations gain more and more interest. An important figure in mobility simulations is to understand the mobility behavior of subscribers. Since the beginning of mobile communication networks stochastic mobility models and surveys have been used to describe the mobility behavior of individuals. Stochastic mobility models e.g. random walk, however, have a great disadvantage as they do not cover the real behavior. On the other hand mobility models derived from surveys cover the real behavior but their sample size is limited. A third approach is to use call detail records to derive the mobility behavior of subscribers. This approach investigates handover events. Handover events are issued whenever a subscriber, who is in an active call, leaves the extent of the cell site. A handover is than carried out in the network that hands the connection over to a closer cell site. This information can then be used to estimate a coarse subscriber location.

Another important aspect of mobility simulations is the timing. The timing reveals when subscribers are go to work or leaving work. This is an interesting fact as it means that an increase in traffic load is happening in cell sites covering work places. Since handover events contain a time-stamp, they can enable mobility simulations with timing information. On the other hand stochastic mobility models are driven by a function and can therefore only provide timing information based on input parameters. Surveys can contain timing information but each survey only covers a particular date.

1.1 Challenges and Goals

The main goal of mobility models is to describe the mobility behavior of a set of individuals. Instead of using expensive surveys or defining a stochastic mobility model, call detail records shall be used to investigate the behavior of subscribers. Call detail records can be gathered by a network operator

in an inexpensive ways. Therefore network operators can test and simulate their networks with mobility models derived from their subscribers.

The goal of this thesis is the conception and implementation of a trajectory generation pipeline which allows generating trajectories for mobile subscriber. Since GSM only issue handover event when the subscriber is an active call; trajectories can only be generated for connected subscriber. Although, location area updates are issued in GSM in idle mode, this events are not used to generate trajectories because of their limited location accuracy. The handover events between the call establishment and termination are used for the trajectory generation. One of the main challenges is to estimate the subscribers start and end position. This process utilizes population density maps to assign a random start and end position.

Besides the traveled route, trajectories consists of timing information. The timing information defines for each position the time when it shall be traversed. The generation pipeline uses an estimated handover position and the time-stamp to annotate the trajectory with timing information. To estimate the handover position the coverage area of the involved cell sites is used. Therefore, a valid representation of the coverage area for each cell site is needed.

1.2 Structure

The thesis is divided into seven chapters. This chapter gives a short introduction of the challenges and goals as well as the motivation and importance of this research.

The second chapter introduces related work in the field of trajectory estimation for mobile subscribers. It points out different approaches researches have proposed for targeting this problem.

In the third chapter the GSM communication network and the data used by the generation pipeline is explained successively.

The concept of the trajectory generation pipeline is described in the fourth chapter. First the required input data is explained in full detail. Second important concepts in respect to the generation process are described.

In the fifth chapter insights on the implementation of the system are given. The most important aspects in respect of input data retrieval and processing are delineated in more detail.

The sixth chapter shows various results that have been gathered using the developed system. Two examples of generated trajectories for subscribers in semi-rural and urban areas are depicted.

The seventh and last chapter gives a brief résumé and describes potential enhancements and limitations of the developed system.

Chapter 2

Related Work

The following chapter presents state-of-the-art approaches and projects related to user mobility modeling and traffic analysis. These projects are used to derive the mobility of mobile subscribers by investigating events in mobile operator networks. They differ from classical behavior analysis in terms of penetration and accuracy. To derive the behavior of the entire population surveys and origin-destination matrices have been used in traffic modeling since the early 1960s [4, 19, 39].

Starting in the late 1990s floating phone data (FPD) has gained interest in traffic estimation and congestion detection. FPD are used due to its high penetration rate e.g. the market penetration in Austria was 159%¹ in 2013. There is a large volume of published studies describing the role of FPD for traffic analysis [9, 28, 41].

The approaches that will be presented here have a higher penetration rate due to the fact that they investigate a whole network whereas surveys can only cover parts of the entire network. Since surveys consists of a limited sample, they only cover a part of the whole population. Another advantage of these approaches is the adaption to seasonal changes. Surveys only depict the behavior at a certain point in time. However both road and mobile network traffic modeling depend on changes in time. By exploring events in mobile operator networks, the behavior can be analyzed for every point in time.

Evaluation of a cellular phone-based system for measurements of traffic speeds and travel times: A case study from Israel

To measure the traffic speed and travel time in Israel Bar-Gera [3] used a proprietary system by Estimotion Ltd. The system works with handover updates to derive the traveled route and traffic speeds. A sequence of locations derived from the handover footprint is matched to road segments

¹Press conference by the Forum Mobilkommunikation [press conference link](#)

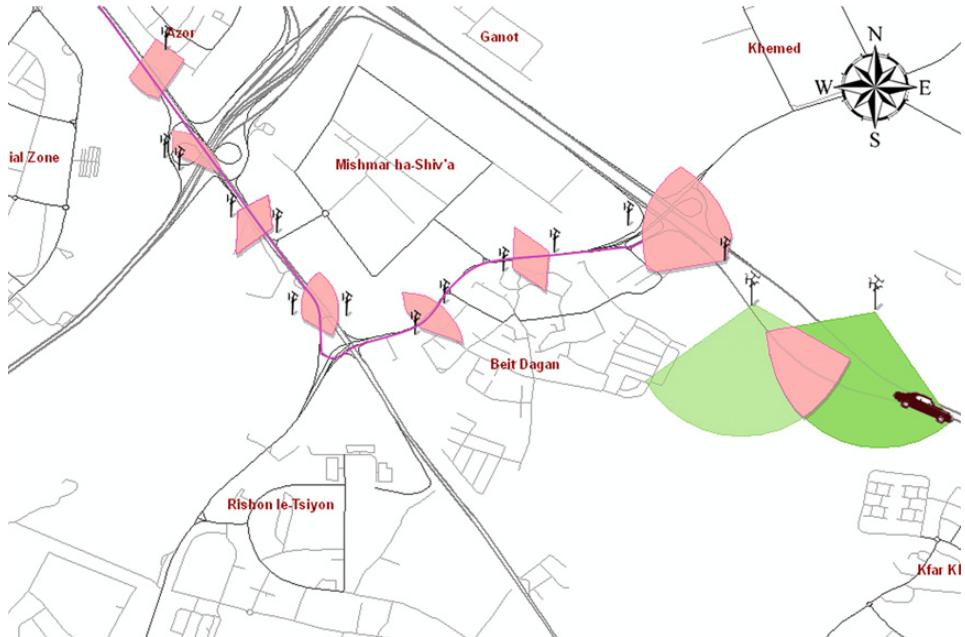


Figure 2.1: Handover sequences and footprints generated by a moving vehicle [3]

which appear to be the most likely on the road network. An example of a handover sequence and its footprints on the road network is shown in Figure 2.1. Despite the fact that this is a proprietary system it gives a good overview of the capabilities of floating phone data. The work by Bar-Gera shows that travel time estimation with phone data can be a replacement for loop magnetic detectors. He investigated a road segment from January to March 2005 and found that the average absolute difference between the two systems is 10.7%. However the whole system has its limitations due to the noise generated by floating phone data. They could reduce the noise by combining travel speeds from subscribers that traveled on the same road segment.

Generating Trajectories from Mobile Phone Data

To derive trajectories from mobile subscribers Schlaich et al. [30] used location area sequences. Location area update events are issued whenever a mobile subscriber enters a new location area. These events are issued in both connected and idle states. Therefore trajectories can be generated even when no call is ongoing. Due to the small number of location areas in the research area, each location area was represented by a unique character. The next step was to generate routes in the research area and store the location area characters for each area they traversed. To estimate a trajectory for a mo-

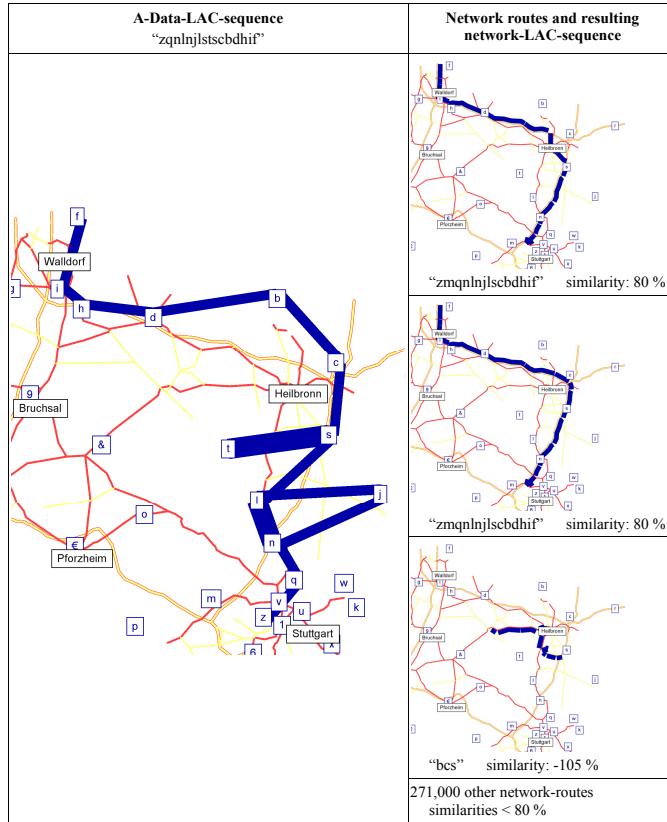


Figure 2.2: Results of comparison between sequences with high similarity by Schlaich et al. [30]

bile subscriber the location area sequence for the subscriber was compared to route sequences that have been generated before. Figure 2.2 depicts the comparison of a mobile subscriber sequence and route sequences with high similarity. The results showed that this technique works well for longer trips around 20 kilometers because trips can only be estimated if the number of different location areas is greater than 3. Schlaich et al. also stated that the presented approach only generates trajectories for SIM cards and not for vehicles. A vehicle can have none, one or more SIM cards therefore a vehicle can generate $0..n$ trajectories where n is the number of SIM cards within the vehicle.

Route Choice Estimation Based on Cellular Signaling Data

To overcome the use of origin-destination matrices Tettamanti et al. [33] used a simulation framework and a route generator to generate trajectories for mobile subscribers. Instead of using location area updates as Schlaich et al. did they used handover updates. Handover updates allow to generate

trajectories not only for a higher road network but also for the minor one. Their approach is based on cell area estimation as each handover update reveals the current cell area. Whenever a mobile phone reaches the boundary of the currently connected cell or when another cell has a higher reception then a handover is made to a cell with a better reception. Tettamanti et al. used Voronoi partitioning to calculate the coverage area for each cell site to estimate a coarse user position.

The main limitation when using handover updates is that a handover update is only propagated when the mobile phone is in connected mode (during a call).

The start and end of the trajectory were set by the centroid of the cell where the call originated and terminated. To derive routes, a traffic modeling simulation framework VISSIM was used. VISSIM was used to generate routes between the start and the end of the call. For each of the generated routes, the euclidean distance between each of the cell sites and the generated route was calculated. To compare different routes equation 2.1 was used as a metric. For each route j , the squared sum of all minimum distances $d_{i,j}$ between the route and the cell site was calculated. The route with the minimum sum was used as a trajectory for the subscriber. In Figure 2.3 an example for four different routes which were generated by VISSIM can be seen. Table 2.1 depicts the results of the above stated equations (see Equation 2.1). In this example route 4 (see Figure 2.3(d)) had the smallest squared sum of all four routes.

$$D_j = \sum_{i=1}^m d_{i,j}^2 \quad (2.1)$$

$$\min(D_j), j = 1, 2, \dots, n \quad (2.2)$$

Route j	$D_j = \sum_{i=1}^m d_{i,j}^2$	Ratio compared to the lowest value
a	5130283	8.2
b	3097741	4.9
c	1356076	2.2
d	627122	1

Table 2.1: Squared deviations for each route as observed by Tettamanti et al. [33]

The research by Tettamanti et al. showed that trajectories can be generated for mobile subscribers by analyzing their handover events. This can be done without using special equipment and can be used to investigate the travel behavior of many subscribers.

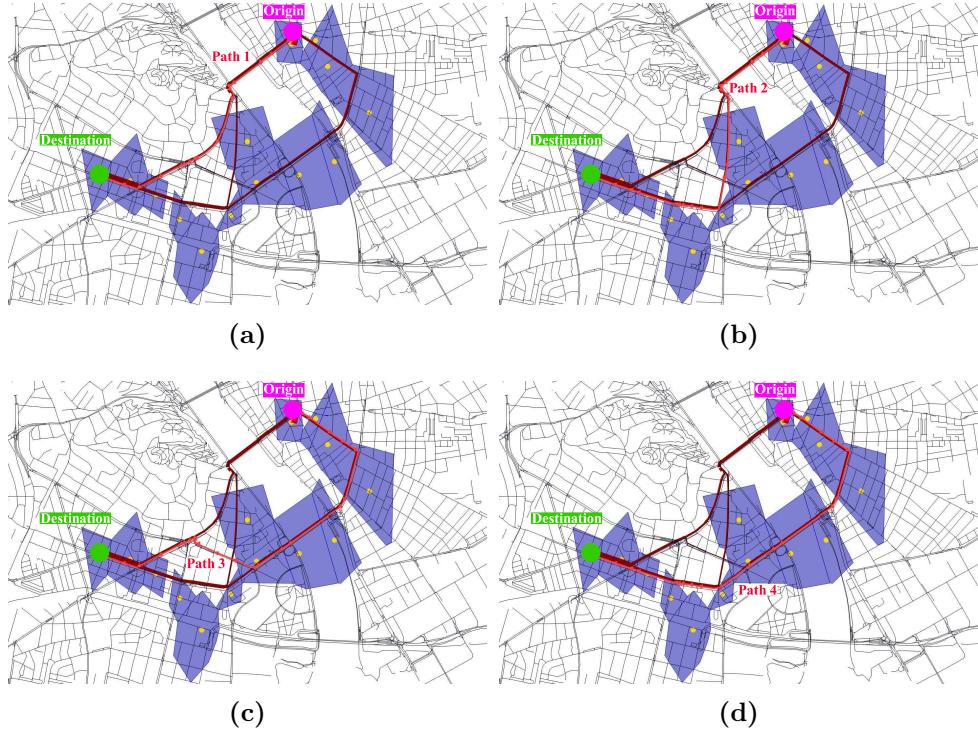


Figure 2.3: Comparison of four different generated routes, the best route was (d) by Tettamanti et al. [33]

RoadCell – Road Traffic Estimation from Cellular Network Signaling

By using cellular network monitoring and therefore mobile subscription data Valerio et al. [37, 38] at the FTW Forschungszentrum Telekommunikation Wien GmbH are investigating road networks in Austria. *RoadCell*² is using the same mobile subscription data source as our system [36]. The aim of *RoadCell* is to recognize situations in the traffic flow by analyzing events in the core network of the mobile network operator. Driven by the fact that each road user is also a subscriber of a cellular network, network operator can be seen as another source to gather traffic information. Their motivation is to provide road operators with an inexpensive toolkit to observe the traffic flow without the installment of costly sensors. Thereby it is possible to not only investigate the traffic flow on the higher road network but also on minor roads where the installment of dedicated sensors is not cost-effective.

The idea is to observe changes in network signaling events and extract

²Project website: <http://www.ftw.at/forschung-innovation/projekte/roadcell> last accessed March 12 2014

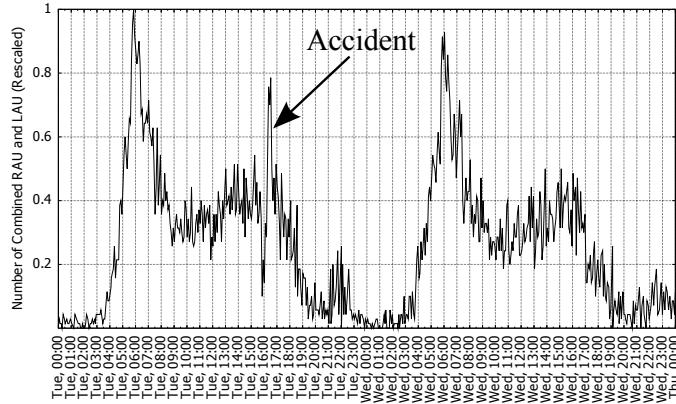


Figure 2.4: Effect of the accident on the number of combined RAU and LAU; tic=300s [38]

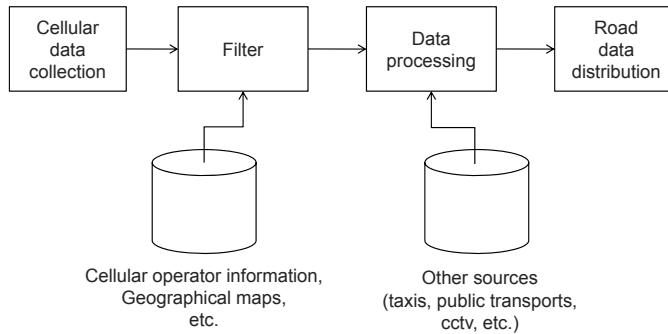


Figure 2.5: RoadCell System Overview [37]

road conditions for example: drop in the handover rate; abrupt change in the LR update; increase in the number of calls/SMS; change in the number of road users. Figure 2.4 shows how an accident effects the amount of Routing Area Update (RAU) and Location Area Update (LAU). An accident is indicated by a sharp decrease in RAU and LAU events followed by a sharp increase in RAU and LAU events.

Figure 2.5 depicts the system overview of the *RoadCell* project. It can be seen, that despite cellular network data, there are additionally data sources used. In order to map a particular event to a road segment, they are using coverage predictions from the network operator. To support data processing they are using third-party sources like floating car data from taxis and public transports which are more accurate, but have a lower penetration rate.

During their research they found out that a combination of passive and active tracking is best to observe road conditions. Passive tracking is done without the involvement of the mobile station. This approach only utilizes

the events captured in the operators core network. While passive tracking offers a high penetration and no increase in network load, it is less accurate than active tracking. Active tracking requires the mobile station and core network to exchange special events that allow the network operator to get an accurate position of the mobile station. This technique is known as Time Difference of Arrival (TDOA). Valerios proposal is to use a combination of both; passive tracking is always used and once the system detects a possible accident active tracking is used for the area in which the accident occurred. This approach improves the accuracy while trying to minimize the additional network load introduced by active tracking.

Differences and Contribution

Our approach utilizes handover events. Consecutive Handovers during a call will be combined to a handover sequence. This sequence will be used to model the subscriber mobility. Handovers allow the subscriber to move from the coverage of one cell site to another while still maintaining an ongoing call or data transfer. By estimating the origin of each handover event a trajectory can be computed. The computed trajectory represents the subscriber route. The time of occurrence of a handover event is used as the timestamp. Timestamps in combination with the route will later be used to compute the average velocity for each route segment between two consecutive handover events. Thus, the system can only compute the average velocity for each route segment; the smaller the coverage area of succeeding handovers is, the more accurate the velocity will be. The main limitation of our approach is that it only works for subscriber in connected mode. Therefore, it can only be used to generate trajectories for subscribers during a call. However, this limitation is not a drawback for network simulation since most of the traffic is produced by connected subscribers. This approach allows mobile network operators to test their mobile networks with simulations based on subscriber behavior. The benefit is that trajectories can be generated for each day of the year. Therefore, this approach can be used to investigate, how changes in the network infrastructure deal with recent scenarios. Annotating the derived route with timing information is an important figure as it influences the network load and traffic.

Chapter 3

Fundamentals

This chapter covers fundamentals that are necessary for a better understanding of the concepts presented in this work. It gives a short introduction into mobile communications systems which our system uses. Mobile communications systems are used in our system to estimate the users coarse location. Furthermore, state of the art analytical mobility models for mobile network simulations are presented. Another section covers the data (provided by A1) our system is using to generate driving trajectories. At last, the process to estimate the coverage area for cell sites with Voronoi tessellation is shown.

3.1 Global System for Mobile Communications

Mobile communication networks are the basis of our modern communication and interaction. However the start of wireless communication began in the late 19th century and was shaped by the work of Hughes, Maxwell, Hertz, Tesla and Faraday.

In 1982, a new mobile communication network was developed by the Group Spécial Mobile (GSM) of the CEPT (Conférence Européenne des Administrations des Postes et des Télécommunications). The main goal of GSM was to develop a Europe-wide standard for digital mobile communication. Over the past two centuries, there has been a rapid increase in the use of GSM all over the world. The present section is based on the books *GSM: Switching, Services and Protocols* by Jörg Eberspächer et al. [11] and *Mobilfunknetze und ihre Protokolle 1* by Bernhard Walke [40].

Besides GSM, there are other mobile communication currently in use. These systems are known as 3G (UMTS, HSPA, WCDMA, etc.) and 4G (LET, LTE Advanced, etc.) networks whereas GSM is a network of the second generation (2G).

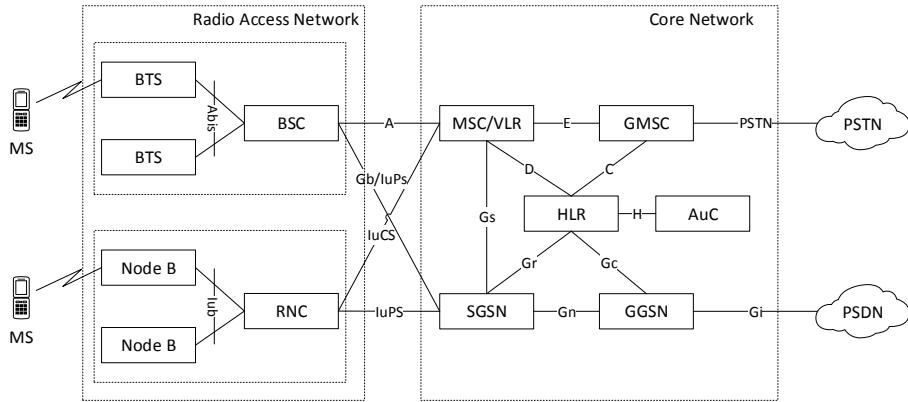


Figure 3.1: System overview of the a GPRS Network

3.1.1 Components - System architecture

GSM consists of a large number of components which are necessary for its operation. However, we will only focus on components that are necessary to understand the functionality of our system. The overview of a GSM network with GPRS capability is visible in Figure 3.1. The various standardized interfaces which are responsible for communication between the components can be seen as well as the different components of the *Radio Access Network* RAN and the *Core Network* CN. The RAN consists of a BTS and BSC in GSM and a Node B and a RNC in GPRS.

Mobile Station

Mobile stations (MS) are the equipment used by mobile subscribers to access services provided by the network operator. The mobile station consist of two components, first the *Mobile Equipment* and second the *Subscriber Identity Module* (SIM). The SIM grants a mobile subscriber access to the network and allows to initiate or receive calls. For management purposes GSM assigns the following numbers and identities to a MS:

- **IMSI** International Mobile Station Identity
- **TMSI** Temporary Mobile Station Identity
- **MSISDN** Mobile Station International ISDN Number
- **MSRN** Mobile Station Roaming Number

Base Transceiver Station

The *Base Transceiver Station* (BTS) provides the radio channels for signaling and user traffic data within a cell. The mobile station establishes a

connection with the BTS over the air interface. The BTS consists only of a few parts, the high-frequency equipment (transceiver and receiver) and the signaling and protocol processing unit. The control remains in the BSC.

Base Station Controller

A *Base Station Controller* (BSC) is used to manage one or more BTS. It is directly connected to a MSC. Together with the BTS, the BSC forms the *Base Station Subsystem* (BSS). For example, the BSC executes the handover protocol and switches a MS to a new BTS.

Mobile Switching Center

The *Mobile Switching Center* (MSC) together with the databases (HLR, VLR) forms the *Mobile Switching System* (MSS). The MSC is responsible for the switching in the network. For example, the MSC performs signal routing, routing path search and service processing. Additionally the MSC has to pay attention to the allocation and administration of radio channels and the mobility of subscribers. A *Public Land Mobile Network* (PLMN) can consist of several MSCs where each is responsible for a dedicated area. Furthermore, the MSC is connected to a *Gateway Mobile Switching Center* (GMSC) which forwards voice traffic between fixed and mobile networks. The GMSC enables the subscriber to call subscribers in different MSCs or PLMNs.

Visited Location Register

The *Visited Location Register* (VLR) stores information of all MS who are located in the serving area of the associated MSC. A VLR can be assigned to one or more MSCs. A MS can be registered in a VLR of its home PLMN or a foreign one when a roaming agreement exists.

Home Location Register

Typically, there is one *Home Location Register* (HLR) per PLMN and one VLR for each MSC. The HLR stores all permanent and temporary subscriber information for all registered subscribers. Moreover, it stores a coarse current location of each MS. The HLR operates as a central register needed by the MSC for routing of subscribers.

3.1.2 Radio Resource Management

The GSM standard [12] distinguishes between two modes of operation first idle and second connected mode. The *Radio Resource Management* (RRM) is necessary to manage the physical and logical channels.

Idle Mode In idle mode there is no dedicated channel assigned to a MS. However, the MS listens on signaling channels (BCCH and CCCH). The higher layers are only informed when a MS reaches the boundaries of a location area.

Connected Mode In this mode there are two dedicated channels assigned to the MS, the first one is SACCH and the second one is either FACCH or SDCCH. The radio resource management provides the following service to a connected MS (a full list can be found in ETSI GSM 04.08 [12]):

- Transfer of messages on any data link layer
- Establishment/release of multiframe mode on SDCCH, FACCH or SACCH.
- Automatic cell reselection and handover to maintain the RR-connection

Handover

A handover is the transfer of an established connection to a new BTS. A handover is necessary for various reasons. First of all, a handover decision is made by the GSM network and not by the MS. As mentioned before the handover protocol is implemented in the BSS. The BSS decides to initiate a handover based on BSS criteria (channel quality, received signal level, distance between MS and BTS) and network criteria (e.g. traffic load of the network).

Handovers are only performed when the MS is in connected mode. If the MS is in idle mode and reaches the boundaries of the cell a location area update is performed if the new cell is in a different location area.

The GSM standard does not define an algorithm for handover decision. Therefore, network suppliers are responsible for implementing them. A basic handover algorithm is specified in appendix A of the ETSI GMS 05.08 [13].

Intra-Cell-Handover The channel within the cell will be changed, e.g. when the channel is noisy. The change can either be done to a new frequency or to a new time-slot with the same (old) frequency.

Inter-Cell/Intra-BSC-Handover The channel will be changed between two cells within the same BSC.

Intra-Cell/Intra-MSC-Handover The connection will be changed between two cells in different BSCs, but both are managed by the same MSC.

Inter-MSC-Handover The connection will be changed between two cells that are managed by different MSCs.

The first two handovers can be carried out by the BSC if it supports the handover protocol. If this is not the case then also Intra-Cell-Handover have to be carried out by the MSC.

Ping-pong Handover A ping-pong handover is an undesirable effect where a handover is made to a neighbor cell and after short time back to the original cell [21].

Location Area Updates

Location area updates (LAU) are used to ease the localization of mobile subscribers. Therefore, a MS must initiate a location area update once it leaves the location area. The HLR and VLR both store the current location area. A MS constantly measures the received signal strengths of all surrounding BTSs and reports it to the BSS to the one with the highest signal strength. If it connects to a BTS outside of the current location area then the MS initiates a location area update and tells the CN its new location area. There are two cases which can distinguished:

- change within the same VLR
- change to a new VLR

Location Area

A location area (LA) defines the area within the mobile network in which the mobile subscriber is located. Location areas are used to decrease the signaling necessary to locate a mobile subscriber within the network. Without location areas, the PLMN has to initiate a paging request to all BTSs. By using location areas, only the BTS within the location area have to carry out the paging request.

One or more BTS with the same MSC can be part of one location area, in most cases they are part of the same BSC. Figure 3.2 shows that a location area can consists of several BTS. Each location area is uniquely defined by the *Location Area Identity* (LAI). The LAI (see Table 3.1) consists of the Mobile Country Code (e.g. Austria 232) which identifies the country, the Mobile Network Code (e.g. A1 1) which identifies the PLMN and the Location Area which identifies the location area within the PLMN. Together with the Cell-ID (CID) the LAI forms the Global Cell-ID (GCID). The size of a location area depends on:

- Cell density
- Voice and data traffic
- Network operator configuration

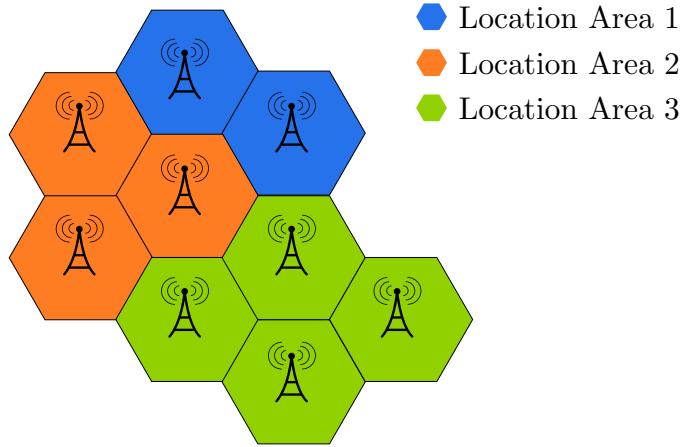


Figure 3.2: Example for three location areas

Location Area Identity		
Mobile Country Code	Mobile Network Code	Location Area Code
3 digits	2 or 3 digits	5 digits

Table 3.1: Parts of the Location Area Identity

Updates

For its operation the MSC (HLR, VLR) needs to know where the mobile subscriber is located. Therefore, location area updates are required. There are two kinds of location area updates first normal updates and second periodic updates. Normal location area updates (NLAU) happen either when the MS is switched on or off during an IMSI attach/detach or when a MS connects to a new BTS in a different location area. Periodic location area updates (PLAU) are defined by the network operator. Each MS has a PLAU timer for this purpose, whenever the timer expires the MS performs a PLAU.

3.1.3 Antennas

Antennas enable wireless communication between a receiver and a transmitter. In GSM, they are the direct air interface between the MS and the Radio Access Network (RAN). Antennas can be designed to transmit or receive signals equally in all directions (omni-directional antennas) or transmit and receive signals in a specific direction (directional or high gain antennas). In GSM networks, a combination of both is used. Omni-directional are mainly used in rural areas to cover a large area whereas directional antennas are used to cover a smaller area with a higher traffic load.

Sector

Sector antennas are a special use case of directional antennas where several directional antennas are combined and each covering a particular sector such as a 120° horizontal pattern. In GSM the most common installations of sector antennas are 60° , 90° and 120° . Based on the traffic load, smaller sectors can be used with larger ones on the same tower (e.g. two 60° antennas with two 120° antennas).

Antenna size

The antenna size or more general its coverage is defined by the antenna gain, the antenna characteristics and the transmit power. In mobile communication networks there are four different types of cells in use that are distinguished by their coverage.

Macrocell Provides the primary radio coverage for mobile networks. Macrocell antennas are mounted on ground-based towers, buildings or other existing infrastructure in order to have a clear view over the coverage area.

Microcell A microcell offers additional capacity within the coverage of a macrocell. Typically, microcell antennas are mounted at street level. Microcells have lower output power than macrocell and therefore a decreased coverage (e.g. 300 to 1000 meters).

Picocell To provide coverage inside buildings or to a high numbers of users. The coverage of a picocell is 200 meters or less.

Femtocell A low-powered, coverage is on the order of 10 meters, base station designed for use in a home or small business [42].

3.2 Mobility Models

Mobile networks permit its subscribers to move freely within the coverage area. To evaluate and ensure the mobility, mobile network operators need to understand the user mobility. A user mobility can be described by a mobility model. A mobility model describes the user behavior and activity using simulation and analytic models. Simulation models are based on realistic mobility scenarios whereas simplified assumptions about the users movement behavior are the foundation of analytic models.

Two major analytic models which are used in mobile network simulation are the *Random Walk* [1, 6, 7] and the *Manhattan Mobility Model* [8, 23].

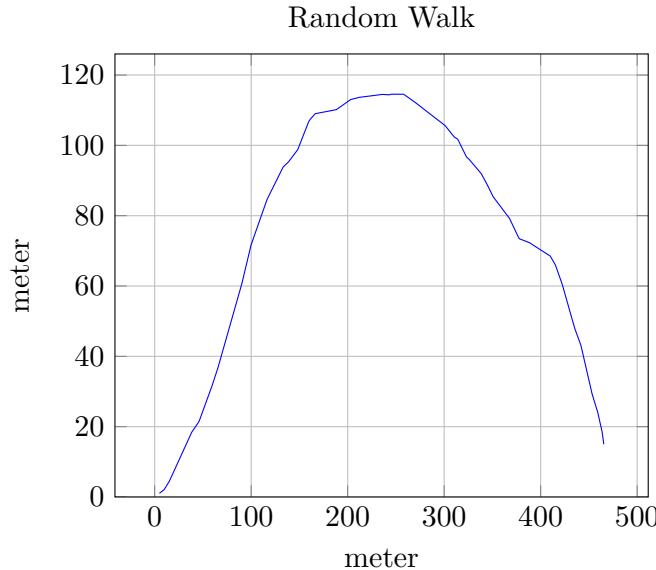


Figure 3.3: Example for a random walk

3.2.1 Random walk

The mobility of entities in nature is unpredictable, therefore a variety of models exists in literature. These models try to describe the mobility for different scenarios. The random walk model is a memory-less system and maintains no record of previous locations and speed. In each iteration dices a new direction and speed within a predefined range [10]. An example for a generated random walk is depicted in Figure 3.3. The speed is limited to the interval 0..5 and angle is limited to $-15..15^\circ$.

3.2.2 Manhattan Mobility Model

In a Manhattan grid scenario streets are aligned in a square grid. It is named after the district Manhattan in the City of New York. Figure 3.4 shows a map of Manhattan and its road network. It can be seen that roads consist of straight lines and each junction forms a right angle.

The Manhattan mobility model can work on any road network [43]. At each junction, the logic is executed which decides if the current street shall be used or a different one. The logic can be modeled as a random number generator with a defined probability density function. For example the probability to drive straight can be 60%, turn right 30% and turn left 10%. The Manhattan Grid mobility model is an extension to the random walk model where participants are not allowed to move freely, but rather move on a defined road network.

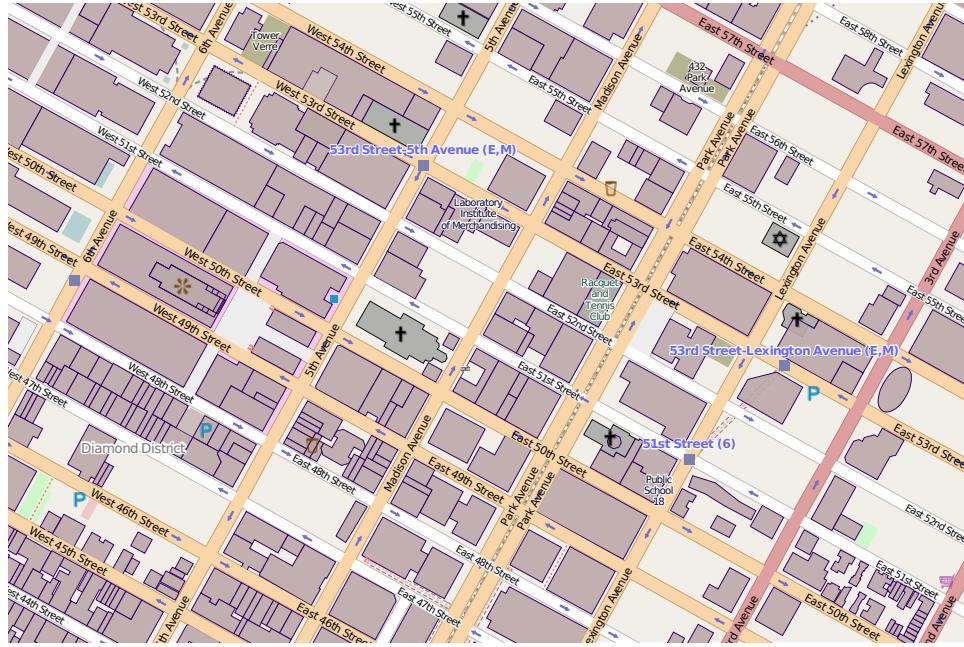


Figure 3.4: Manhattan Road Network

3.3 A1 Data

We are using mobile subscription data from A1. A1 is the largest network operator in Austria with 5.3 million subscribers. The used data was recorded on the network of A1 between Monday, 22nd November 2010 and Sunday, 28th November 2010. The captured interfaces, events and the data structure of the system will be depicted in the succeeding subsections.

Figure 3.5 shows the distribution of handover events for Monday, 22nd November 2010. It can be seen from this that the distribution for handover events changes over time. A strong increase of handover events takes place at 17 o'clock. This is due to the end of work of subscribers. People are leaving from work and start calling their friends while on their way home.

3.3.1 System Overview

Monitoring units need to be installed in the Core Network of A1 to capture useful events. Figure 3.6 illustrates the system architecture used by A1 to capture events. The architecture is almost the same as for a typical GSM system, the only differences are the monitoring units responsible for capturing and forwarding events. In order to intercept the network, the monitoring units are attached to the main interfaces (A, IuCS, Gb/IuPS, IuPS) of the Core Network. The processing unit is responsible for aggregating events and ensuring anonymity.

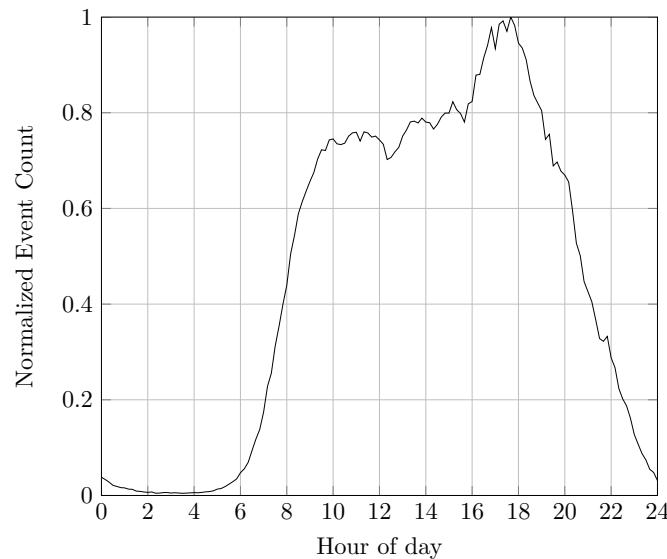


Figure 3.5: Normalized Distribution of Handover Events on Monday, 22nd November 2010

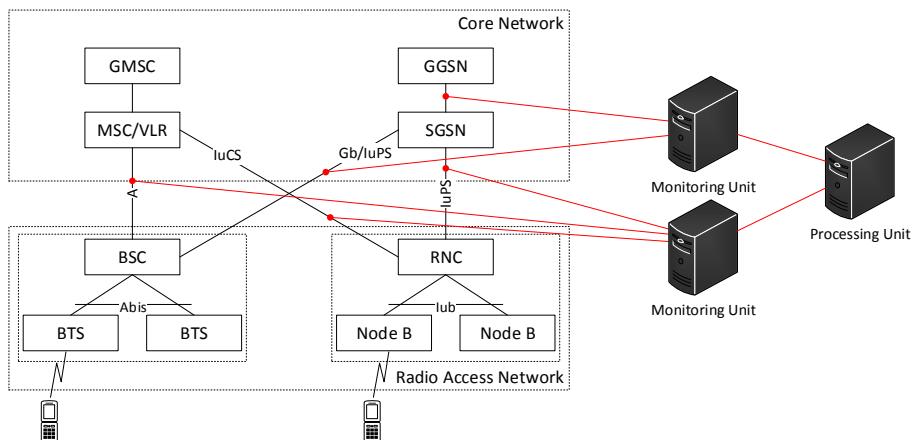


Figure 3.6: System Architecture of the A1 Monitoring System

Interfaces

The monitoring units capture both *Circuit Switched* (CS) and *Packet Switched* (PS) data. Therefore, it intercepts the communication of CS and PS interfaces. The CS interfaces are A and IuCS and they belong to the MSC and enable voice calls and SMS. The PS interfaces are the Gb/IuPS and the

IuPS. Both are connected to the SGSN and enable subscribers to use packet orientated services (e.g. Internet).

3.3.2 Data Structure

Each event captured by the monitoring unit is forwarded to the processing unit for further aggregation. An event is encoded into a binary format and then forwarded to the consumer. Each event has a fixed length (88 bytes) and its structure is shown in Figure 3.8. Because not all fields were used by our system, only the ones used are described.

Anonymous ID

This 32 bytes field contains a unique anonymous identifier of the mobile terminal. It changes every day at midnight, i.e. a device can be followed for maximum 24 hours time span before the assigned anonymous ID changes.

Timestamp

The timestamp represents the exact time of occurrence of the event (i.e., the instant when the event has been captured by the monitoring unit).

Latitude and Longitude

These two fields represent the position of the BTS in which the event occurred. They are both encoded as decimal numbers representing the WGS84 coordinate system in degrees. The decimal number is encoded according to IEEE 754 floating-point double format [20].

Cell ID

This field specifies the cell id in which the event occurred. The cell id is not unique and can therefore be used for more than one cell site.

LAC

This field indicates the location area code in which the event occurred, together with the cell-id it is used as a unique identifier for a cell site.

Event type

Every event includes a field (i.e., Event type) that indicates which type of event has been detected. All possible signaling events are described in Table 3.2.

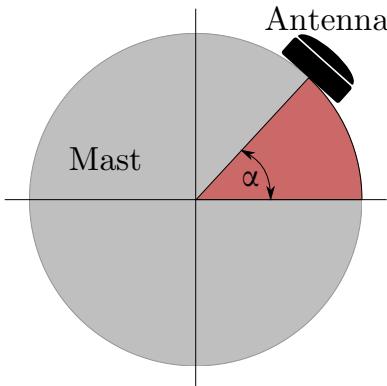


Figure 3.7: Example for an antenna installation

Angle

This field defines the installment of a sector antenna. It is the angle at which the antenna is mounted on the mast. Figure 3.7 illustrates the mounting of a directional antenna on a mast.

Encoding example

The following example illustrates the decoding of the input bit stream.

```
E4A2E4E263A2B54214A2B28E09AE02C36089219123696993EF9E1DF9D8647F18
496DC7340006E61B4030747CF7F849A84048143577861E680000000000000005780200
0000000000002300000000000000000000000000000000000000000000000000000000000000
```

- **Anonymous ID**
Encoded Byte Array = 0xE4A2E4E263A2B54214A2B28E09AE02C360-
89219123696993EF9E1DF9D8647F18
- **Timestamp:** Wed Jan 14 12:06:28 CET 2009, in microseconds: 1231931188452123
Encoded Byte Array = 0x496DC7340006E61B
- **Latitude:** 16,45503187
Encoded Byte Array = 0x4030747CF7F849A8
- **Longitude:** 48,15788168
Encoded Byte Array = 0x4048143577861E68
- **Radius:** 1400
Encoded Byte Array = 0x0000000000000578
- **Input source:** Metawin
Encoded Byte Array = 0x02
- **Reserved:** 0
Encoded Byte Array = 0x00000000
- **Reserved:** 0
Encoded Byte Array = 0x00000000

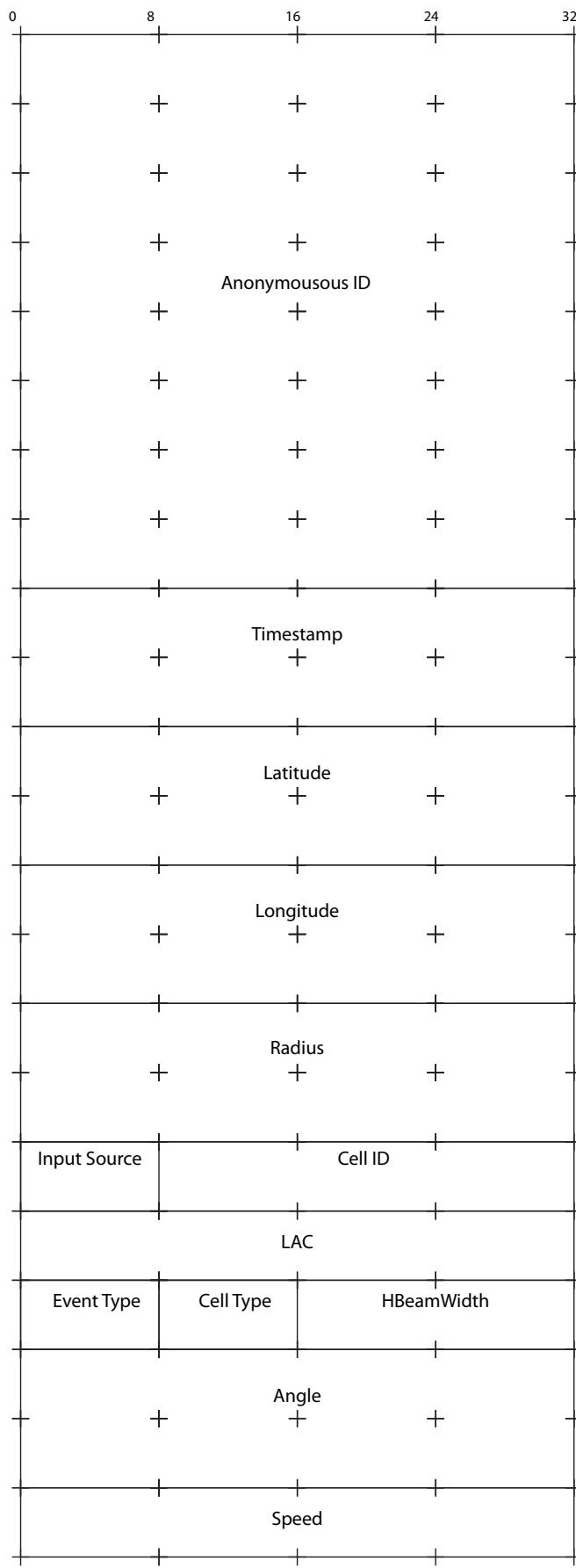


Figure 3.8: Bitstream structure of the A1 Interface

- **Event type:** Emergency Call
Encoded Byte Array = 0x23
- **Reserved:** 0
Encoded Byte Array = 0x00
- **Reserved:** 0
Encoded Byte Array = 0x0000
- **Angle:** 0
Encoded Byte Array = 0x00000000000000000000000000000000
- **Speed:** 0
Encoded Byte Array = 0x00000000

3.3.3 Events

In this subsection, we describe how everyday users activities are visible in the A1 data stream. The events detected by the monitoring units from each terminal depends on the type of terminal. While it is not feasible to cover all events (complete list of events is shown in Table 3.2), we only describe the ones –highlighted in the table– used in our system.

Calls

When a terminal establishes a call with another subscriber a Mobile Originated Call event is created. The receiving terminal will create a Mobile Terminated Call event. Whenever a call is ended (e.g. one subscriber hangs up) an A Disconnect event is created. However in our research of the data stream, there was no evidence of an A Disconnect event.

- MOBILE TERMINATED CALL (0x1D): terminal receives a call
- MOBILE ORIGINATED CALL (0x22): terminal originates a call
- A DISCONNECT (0x18): The call is closed

Location Area Update

Devices are most of the time in "idle" mode where they are switched on but are not involved in any voice/data communication. In this state the device must still be reachable by the network. Thus, when a terminal changes to a cell in a different location area, it sends a Location Area Update message to the core network. This message appears in the data stream as:

- LOCATION UPDATE (0x1F), in case of 2G terminal
- IUCS LOCATION UPDATE NORMAL (0x15), in case of 3G terminal

If a devices does not change its Location Area for a specific time and the PLAU timer expires it sends a keep alive message to the core network.

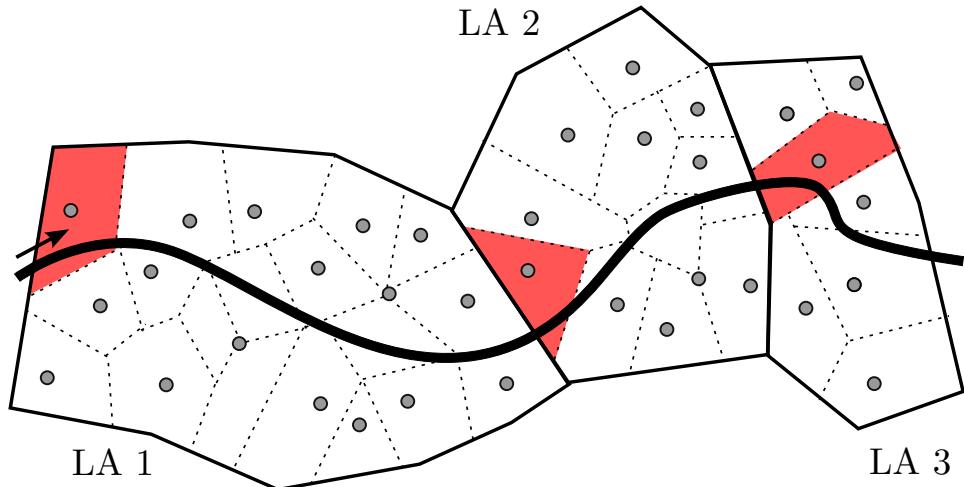


Figure 3.9: Cells and location areas traversed by a subscriber

- IUPS RA PERIODIC UPDATE (0x0C) and IUCS LOC UPD PERIODIC (0x17) in case of 3G terminal (for PS and CS domain respectively)
- LOCATION UPDATE (0x1F) in case of 2G terminals

Figure 3.9 illustrates where a location area update (red cell) happens when a subscriber traverses different location areas on its way.

Handover Cell Update

When a call is established the terminal is said to be in active "connected" state (see 3.1.2). In this state, the network is informed about each change of cell, regardless of the LA to which the cell belongs. A limitation is that the A1 data stream is not able to capture cell changes for 3G terminals (these messages do not reach the core network, but terminate in the radio access network, i.e. they cannot be monitored by the systems). However cell changes for 2G terminals appear as:

- GB CELL CHANGE (0x02), in case of an ongoing data connection,
- HANDOVER CELL UPDATE (0x20), in case of an ongoing call.

HEX	Event Name	Event Description
0x01	GB ATTACH	GPRS terminal attaches to the PS
0x02	GB CELL UPD	GPRS terminal changes cell
0x03	GB OTHERS	GPRS terminal changes cell but message is unclassified
0x04	GB RA UPD	GPRS terminal changes RA
0x05	IUCS PAGING	UMTS terminal is paged in the CS
0x06	IUPS PAGING	UMTS terminal is paged in the PS

0x07	IU OTHER TLLI	UMTS terminal changes cell but message is unclassified
0x08	IU OTHER TMSI	UMTS terminal changes cell but message is unclassified
0x09	IUPS ATTACH	UMTS terminal attaches to the PS
0x0A	IUPS DETACH	UMTS terminal detaches from the PS
0x0B	IUPS RA UPD	UMTS terminal attached to the PS changes RA
0x0C	IUPS COMB RA/LA UPD	UMTS terminal attached to both CS and PS changes LA (and therefore RA)
0x0D	IUPS COMB RA/LA UPD WITH IMSI ATTACH	UMTS terminal attaches to the PS and the current RA differs from the one stored in the SIM
0x0E	IUPS RA PERIODIC UPD	UMTS terminal does not change RA for longer than a timer
0x0F	IUCS DETACH	UMTS terminal detaches from the CS
0x10	IUCS SMS ORIGINATED	UMTS terminal sends an SMS
0x11	IUCS SMS TERMINATED	UMTS terminal receives SMS
0x12	IUCS SETUP	UMTS terminal requests the establishment of a call
0x13	IUCS CONNECT ACK	UMTS terminal establishes a call
0x14	IUCS DISCONNECT	UMTS terminal disconnect a call
0x15	IUCS LOC UPD NORMAL	UMTS terminal attached to the CS changes LA
0x16	IUCS LOC UPD PERIODIC	UMTS terminal does not change LA for longer than a timer
0x17	IUCS LOC UPD	UMTS terminal attaches to the CS and the WITH IMSI ATTACH current LA differs from the one stored in the SIM
0x18	A DISCONNECT	GSM terminal disconnect a call
0x19	A OTHER	unclassified message on A
0x1A	PAGING CS	GSM or GPRS terminal is paged in the CS domain
0x1B	DETACH	GSM or GPRS terminal detaches from the network
0x1C	SMS	GSM terminal sends or receives an SMS
0x1D	MOBILE TERMINATING CALL	GSM terminal receives a call
0x1E	CM REESTABLISHMENT	NA
0x1F	LOCATION UPDATE	GSM or GPRS terminal changes LA or emits aperiodic RA/LA update or attaches to the network
0x20	HANDOVER CELL UPDATE	GSM terminal in active state changes cell
0x21	SUPPLEMENTARY SERVICE	GSM terminal request a supplementary service
0x22	MOBILE ORIGINATED CALL	GSM terminal originates a call

0x23	EMERGENCY CALL	GSM terminal establishes an emergency call
0x24	SETUP	GSM terminal request the establishment of a call
0x25	CONNECT ACK	GSM terminal establishes a call
0x28	CLOSURE	NA
0x29	GB PS PAGING	GPRS terminal is paged in the PS domain

Table 3.2: Description of A1 events

3.4 OpenCoverageMap

OpenCoverageMap was a project and master thesis done by a colleague of mine at the University of Applied Science Upper Austria. Dieter Schlosser [31] goal was to create an open network coverage map for mobile networks. Instead of relying on measurements and coverage reports handed out by network operators he was using smartphones that were doing the measurements. This approach, where users are carrying out work, is known as crowdsourcing [32].

Purpose In our project, we are using OpenCoverageMap data to evaluate our approaches. In order to measure the network, OpenCoverageMap captures events similar to the events captured by A1. The OpenCoverageMap application which is installed on the smartphone periodically records the position (using GPS), the phone state as well as the currently connected cell site. Table 3.3 shows an example of data that was recorded by the OpenCoverageMap application. The GPS information allows us to evaluate a route

Timestamp	Id	Cell-Id	LAC	Latitude	Longitude	State
1328693325	57	9884	5502	48.244381	14.260003	2
1328693326	57	9884	5502	48.244305	14.259999	2
1328693327	57	9884	5502	48.244230	14.260001	2
1328693328	57	9884	5502	48.244156	14.260005	2
1328693329	57	9884	5502	48.244082	14.260009	2

Table 3.3: Data recorded by OpenCoverageMap for the user 57

estimated by our system with the actually traveled route (see Section 4.4 for more information).

Data Structure OpenCoverageMap does not capture events, therefore, our systems needs to convert the OpenCoverageMap data stream to the same format as the A1 data stream. Call establishment and termination events are generated by comparing the timestamps of each record. OpenCoverageMap

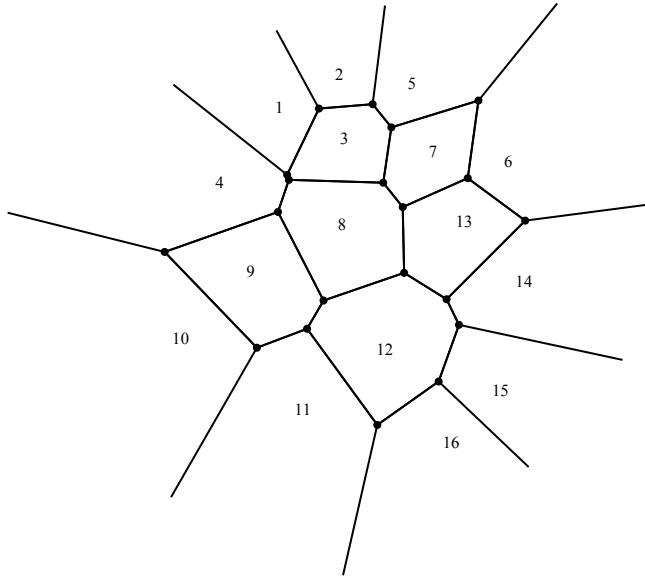


Figure 3.10: Voronoi diagram of 16 random points in a 2D space

logs the state of the MS every second. By iterating over the records and comparing the current state with the previous one, it is possible to extract call establishment and termination events. To generate handover events, an iteration over all records is done, each record compares the cell id and lac with the previous one. If both are similar no event is generated. However, if they are different a handover event is generated. After the conversion is done the OpenCoverageMap event stream looks the same as the A1 event stream.

3.5 Voronoi Tessellation

To generate trajectories for each mobile subscriber their coarse location is needed. For this purpose, we first need an estimation of the coverage area of all cell sites. When a mobile subscriber is connected to a cell site we know that his current position must be within the coverage area of the cell site. A fast approximation of the coverage area can be done with Voronoi diagrams. As mentioned before Tettamanti et al. [33] used Voronoi tessellation to estimate the coverage area.

Voronoi diagrams are widely used in computer science, e.g. pattern matching, space division, cluster analysis, collision detection as mentioned by Aurenhammer [2].

3.5.1 Point Tessellation

The following assumptions are based on *Voronoi diagrams—a survey of a fundamental geometric data structure* by Aurenhammer [2] and *Computational Geometry: Algorithms and Applications* by Makr de Berg [5].

Let $P = \{p_1, p_2, \dots, p_n\}$ be a set of n distinct points, in our case the location of each cell site. The Voronoi diagram of P is a subdivision of the plane into n cells. The property that each Voronoi cell must fulfill is that a point q lies in the cell respective to a site p_i only if $\text{dist}(q, p_i) < \text{dist}(q, p_j)$ for each $p_j \in P$ where $i \neq j$. Each cell defines the coverage area for the n -th cell site. Moreover each cell is a (possibly unbounded) open convex polygon. Figure 3.10 illustrates a Voronoi diagram for 16 random points in a two dimensional space. It can be seen that the outer cells are not closed, they shape an open convex polygon. In Section 3.5.2 we show a method to produce closed polygons.

$$\text{dist}(p, q) = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2} \quad (3.1)$$

3.5.2 Boundaries

Voronoi diagrams are unbounded which means that the coordinates of vertices can be infinite. Unbounded polygons are undesired in a topology computation. If we would use unbounded polygons for coverage estimation, the area for this cell site would be infinite. A simple approach to eliminate this effect is to clip the Voronoi diagram with a rectangular bounding box. However, this approach is only satisfying if the cell site boundaries shape a rectangle. A better approach is to compute the convex hull over all sites and clip it with the Voronoi diagram.

3.5.3 Cell Tower Segmentation

We mentioned before that a GSM network consists not only of omnidirectional antennas but also of sectored antennas. The coverage area of each sector is defined by the angle at which the antenna is mounted on the tower. If we would only consider the location of each cell sites, sectors with different angles would have the same Voronoi polygon and, therefore, the same coverage area. In order to get a better representation of the coverage area for each sector, we moved the location of each sector based on its angle ϕ . The definition of the movement can be found in Equation 3.2. The constant factor means a maximum movement of 3 meters in either direction.

$$x = x + \frac{\cos(\phi)}{50000}, y = y + \frac{\sin(\phi)}{50000} \quad (3.2)$$

Chapter 4

Trajectory Generation Pipeline

In this chapter, the pipeline to generate trajectories for mobile subscribers is introduced. The developed pipeline consists of a five-steps model, which is shown in Figure 4.1. The concept to generate trajectories is the following: The input data is iteratively used to generate trajectories for each subscriber. The output is a trajectory which consists of the route, traveled by the subscriber, as well as timestamps, which defines the point in time when the subscriber was located at this location. Given below each step of the pipeline is described in more detail to better understand how the system operates.

4.1 Input Data

This section focuses on input data that are consumed by the system. The gathering of input data is the first step in the developed pipeline. Moreover input data can be distinguished between four data types, which are used by the system: geographical data, socio-statistical data, mobile subscription data (A1 and OCM), road network data. The different data types are described in the succeeding sections.

4.1.1 Geographical Input Data

As mentioned before GSM does not expose an accurate location of the subscriber. In GSM, only the Cell-ID of the current connected cell is known. However, to calculate a route between the start and end of the call a more accurate location is needed. Because the coverage area of cell can be from as little as $500m^2$ up to $50km^2$, boundaries need to be set in which subscribers can be located. The assumption is that the majority of subscribers will start or end their journey in an urban fabric whereas only a small fraction of

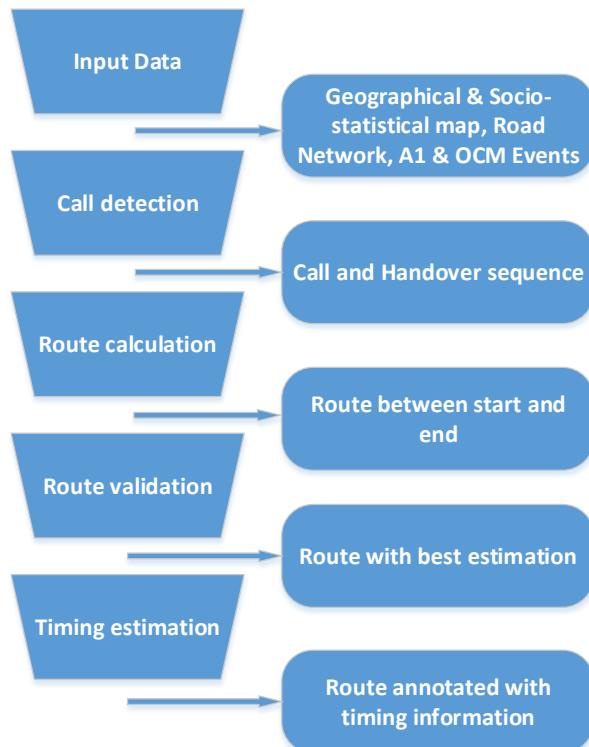


Figure 4.1: Developed trajectory generation pipeline. The trapezoids represent the single steps in the pipeline, the rounded rectangles illustrate the outputs of the particular steps

subscribers will start or end their journey in open land. In the course of this project the geographic information is derived from data from the *CORINE*¹ project which was initiated by the European Commission in 1985. The main purpose of this project was to generate a geographic information system for the member states of the European Union. The *CORINE* land cover (CLC) project is one essential part of the *CORINE* projects which aims to develop a land cover information system for twelve member states of the European Union (Effective 2006). The *CORINE* land cover project distinguishes between five main categories and in total 44 land cover classes. Out of the five only two categories are applicable for the purpose of defining boundaries where a subscriber can be located: *artificial surfaces* and *agricultural areas*. The three remaining categories –*forest and semi-natural areas*, *wetlands* and *water bodies*– can be considered as areas where subscribers are not starting

¹CORINE: "Coordination of Information on the Environment"; <http://www.eea.europa.eu/publications/CORINE-landcover>, last accessed on March 11, 2014

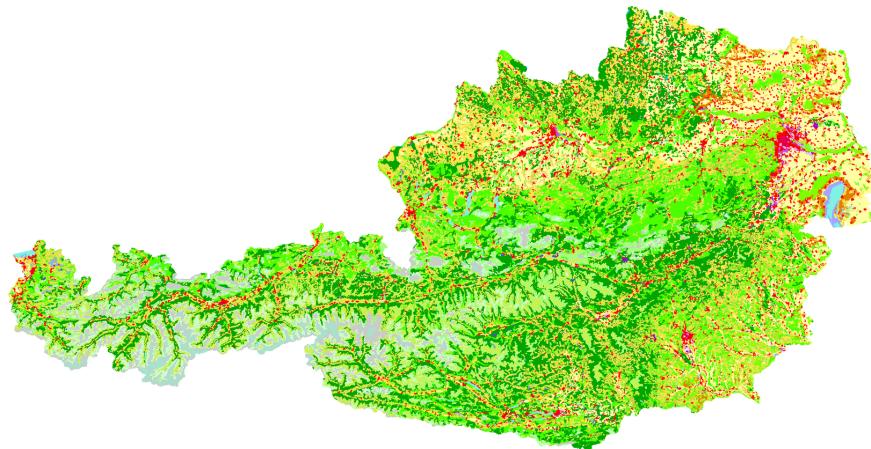


Figure 4.2: Corine land cover map of Austria

or ending their calls. The *CORINE* land cover data for Austria can be obtained from the following service². The land cover data is provided in two different data types, first as a raster image with a grid size of 100 meters and second as a Shapefile. Figure 4.2 illustrates the land cover map³ of Austria. The red spots within the image represents urban fabric areas whereas green denotes to forest and semi-natural areas.

4.1.2 Socio-statistical Input Data

The second type of input data used in the generation pipeline are population density maps. Population density maps belong to the class of socio-statistical maps and provide information about the distribution of population in a geographical area. Gallego et al. [15, 16] describe several disaggregation methods which can be used to generate a population density map of the European Union. Their approach uses information from the *CORINE* land cover project to derive a population density grid with 100 meters grid

²<http://www.data.gv.at/datensatz/?id=9246f37d-da69-4442-9504-ebd006a059bb>, last accessed on March 11,2014

³Image source: http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-2000-by-country/clc00_at_national.eps/image_original, last accessed on March 11,2014.

spacing. The population density grid is used in the developed system to narrow the location of a user within the current connected cell. This works in conjunction with *CORINE* land cover. A more detailed description of the described process will be presented later. The population density grid can be obtained freely from the European Environment Agency (EEA)⁴. Similar to the *CORINE* land cover data the population density grid is available in two data types.

4.1.3 Road Network

The last input data for the developed system is a representation of the road network. Individuals walk or drive on predefined paths: streets, paths, etc. To generate trajectories, the system needs to have a representation of the road network to assign the path of subscribers on the road network. A freely available and open-source road network is provided by the OpenStreetMap⁵ project. The aim of OpenStreetMap is to provide a world wide map which can be used without any royalties. Contributors all over the world are feeding OpenStreetMap with new data. Therefore, OpenStreetMap is very accurate for locations where the number of contributors is high. Figure 4.3 illustrates a map⁶ of Linz, Austria generated by OpenStreetMap. It can be seen that OpenStreetMap provides a large variety of data (e.g. streets, paths, buildings, POI, etc.).

The developed system utilizes the road network from OpenStreetMap to estimate a start and end position of the trajectory as well for route generation. Additionally OpenStreetMap is used to validate the timing estimation for subscribers where no GPS path is available which is the case for A1 subscribers.

4.1.4 Subscriber Information

A1 Dataset

The mobile subscription data which is provided by A1 is used to generate trajectories for subscribers. To generate trajectories, the developed system is fed with an event stream for a special user. This event stream contains all events which have been captured during one day. As we mentioned before in Section 3.3.2 the anonymous user id changes at least every 24 hours. Therefore it is only possible to extract trajectories for one day per subscriber. Each event stream can contain zero, one or n calls. Every call in the event

⁴<http://www.eea.europa.eu/data-and-maps/data/population-density-disaggregated-with-corine-land-cover-2000-2>, last accessed on March 11, 2014

⁵<http://www.openstreetmap.org/about>, last accessed on March 12, 2014

⁶Image source: <http://render.openstreetmap.org/cgi-bin/export?bbox=14.278879165649414,48.31028478774528,14.302825927734377,48.320590159843626&scale=5754&format=pdf>, last accessed on March 12, 2014

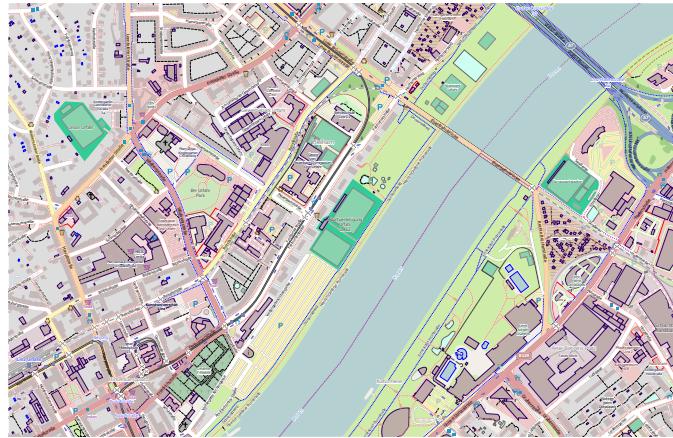


Figure 4.3: OpenStreetMap map of a part of Linz, Austria

stream represents a trajectory.

OCM Dataset

In order to validate our approach we need not only an event stream but also the path traveled by the subscriber. Therefore, the developed system uses an event stream provided by the OpenCoverageMap project. After a conversion to the A1 event format, this event stream can be provided to the developed system. In addition to the A1 event stream, it contains the traveled path which was recorded via GPS on a mobile phone. The GPS tracks allow the system to validate the route finding process as well as the timing estimation. The comparison between the estimated trajectory and the actually traveled route helps to validate the routing. By calculating the speed from the GPS the system can validate how well the timing estimation has been done. More details to the validation process will be provided in Section 4.4.4.5.

4.1.5 Network Coverage

Voronoi Coverage

The developed system needs a representation of the coverage area for each cell site. As described before in Section 3.5 Voronoi tessellation can be used to calculate an approximate coverage area. However, as Voronoi tessellation only takes the location of the cell site and not the physical characteristics (shadowing, antenna gain, reflections, path loss,etc.) the approximation is not very accurate. To calculate the coverage area –the Voronoi polygon – for each cell site, the system is using the location and the angle of the antenna as input data for the calculation. The angle is needed to separate sector antennas which are mounted on the same cell tower.

Coverage Prediction

Because the developed system is based on handover point estimation, an accurate approximation of the coverage area is needed. Besides Voronoi tessellation, a network planning tool is used. The network planning tool not only takes the location of the cell site but also the physical characteristics into account. Characteristics taken into account by the network planning tool are:

- Digital Elevation Model
- Transmit Power
- Path Loss
- Shadowing
- Line Of Sight
- Multi-path propagation

By using the physical characteristics, the calculated coverage area is more accurate than the simple approximation done with Voronoi tessellation. Since this system has no access to the physical properties of the operator, it is using freely available information. This information consists of a Digital Elevation Model of the research area and the transmit power of cell sites.

Digital Elevation Model The network planning tool is using a Digital Elevation Model to calculate properties such as path loss, shadowing and line of sight. These properties are important for the coverage prediction. The European Environment Agency⁷ provides a Digital Elevation Model of Europe. A Digital Elevation Model is aligned in a grid and for each cell of the grid the altitude above sea level is known. The EEA Digital Elevation Model consists of a raster with 25 meters grid spacing. The quality of the coverage prediction is limited by the resolution of the underlying Digital Elevation Model. Therefore by using a better model the accuracy of the prediction can be increased.

Transmit Power The transmit power defines the power level of the transmitter of the antenna. An increase in transmit power Since an increase in coverage since the path loss effect will be minimized. Because the network operator has not provided any information about the transmit power of its BTS the system is using an alternative data source. In Austria the Forum Mobilkommunikation provides a service called *Senderkataster*⁸. The Senderkataster allows to view all broadcast and mobile communication transmitters on a map. In addition to the location it, also depicts the transmit

⁷Data source: http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/ca503256de1b4231b029e4145d0a8b7b last accessed March 19, 2014

⁸Project description: <http://www.senderkataster.at/> last accessed March 19, 2014

power range. The Senderkataster defines the following four categories for transmit power:

- Category 1: < 15 Watt
- Category 2: 15 - 50 Watt
- Category 3: 50 - 100 Watt
- Category 4: > 100 Watt

By querying the Senderkataster with the research area, the system can get the transmitting power. However, the Senderkataster is a voluntary project and relies on the data provided by mobile network operators. This has the disadvantage that not every cell site of a network operator is listed in the Senderkataster.

Data Extraction The Senderkataster service can be queried with simple HTTP requests (see Listing 4.1). The services takes a bounding box of the research area and returns all transmitters within the bounding box. The bounding box is defined by the four parameters –left, right, bottom, top – *EXL*, *EXR*, *EXB* and *EXT*. The coordinates are projected in the WIGeoEU projection (EPSG 7397)⁹. After the request was sent to the service, the service delivers all the transmitters in the following format 301377|314876|2057165. The first parameter is the internal ID of the transmitter, second the X coordinate, and lastly the Y coordinate. The ID can then be used to retrieve additional informations such as the transmitting power, the transmitter type and if it is mounted on a house or a tower.

To retrieve more information about the transmitter a request (see Listing 4.2) to the service with the ID is made. The response to the request is the following: `mobilfunk|301377|GSM/UMTS|d|41,48|1`. The first parameter describes the transmitter, it can either be a mobile radio network or a broadcast transmitter used for terrestrial radio and television. Second is the ID, the third one depicts the used technology (GSM, GPRS, UMTL, LTE), the fourth indicates if the transmitter is mounted on the roof (d) or a tower (e), followed by the transmit power in Watt and the last parameter shows if other transmitter are using the same tower.

Listing 4.1: Request to retrieve station within the boudning box

```

1 http://www.senderkataster.at/functions/getPoints.php5
2 ?EXL=312790.83396198
3 &EXR=315119.16603802
4 &EXB=2056054.8754715
5 &EXT=2057801.1245285

```

Listing 4.2: Request to retrieve transmitter information

⁹Projection string: <http://spatialreference.org/ref/sr-org/7397/html/> last accessed March 19, 2014

```

1 http://www.senderkataster.at/functions/getInfos.php5
2 ?TYPE=mobilfunk
3 &ID=301377

```

Cell Site and Transmitter Position The latitude and longitude coordinates of the A1 data specify the location of the cell tower. On each cell tower there can be one or more transmitters mounted. The network planning tool is using two databases, one for the cell site (tower position) and the second one for transmitters. Each transmitter is assigned to one cell site whereas a cell site can be connected to one or more transmitters.

By querying the A1 data set and only storing unique tuples of latitude and longitude, the system can derive all cell site locations. To get the transmitters for each cell site, the A1 data set is queried for each unique location tuple. A basic transmitter consists of a location, Cell-ID, LAC, transmit power, height and angle. The location is a direct relation to the cell site. The power indicates the transmit power of the transmitter. As there is not information about the installment height of the transmitter it was set to be 20 meters for all transmitters. A higher transmitter height might increase the coverage area for areas shadowed by hills or buildings. The angle defines the mounting angle and indicates in which direction the transmitter is beaming.

Best Server Plot All the above mentioned data is fed into the network planning tool to calculate the best server plot that is used as a coverage prediction. A best server plot calculates the path-loss effect for each transmitter. The path-loss specifies the reduction of power density of an electromagnetic wave as it propagates through space. To calculate the path loss for each transmitter the COST-Hata model is used which extends the urban Okumura-Hata model [18, 22, 24]. The main equations of the COST-Hata model are depicted in Equation 4.1.

$$L = 46.3 + 33.9 \log f - 13.82 \log h_B - a(h_R) + [44.9 - 6.55 \log h_B] \log d + C \quad (4.1a)$$

$$a(h_R) = (1.1 \log f - 0.7)h_R - (1.56 \log f - 0.8) \quad (4.1b)$$

$$C = \begin{cases} 0 \text{ dB for medium cities and suburban areas} \\ 3 \text{ dB for metropolitan areas} \end{cases} \quad (4.1c)$$

L = Median path loss. Unit: Decibel (dB)

f = Frequency of Transmission. Unit: Megahertz (MHz)

hBl = Base Station Antenna effective height. Unit: Meter (m)

d = Link distance. Unit: Kilometer (km)

hR = Mobile Station Antenna effective height. Unit: Meter (m)

$a(h_R)$ = Mobile station Antenna height correction factor as described in the Hata Model for Urban Areas..

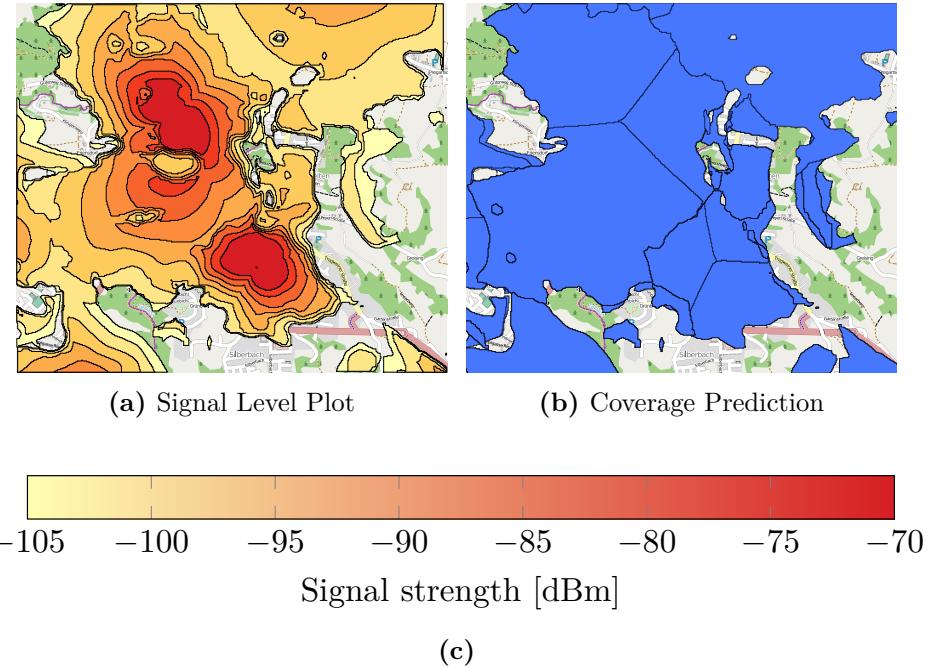


Figure 4.4: A signal level plot (a) with its signal strength (c) and a coverage prediction for Hagenberg, Austria

The path loss was calculated for various distance in the interval [0..5000] meters. Therefore, the path loss effect for each transmitter in the calculation area is known. The coverage prediction simply takes the path loss effect and assigns the best server as the transmitter with the least path loss.

Figure 4.4 shows two different path-loss plots for Hagenberg, Austria. The first one Figure 4.4a depicts the attenuation for each transmitter in the area. The red area indicates a small attenuation whereas yellow indicates a high attenuation. The colorbar in Figure 4.4c indicates the signal strength (dBm) for the above signal level plot.

From these attenuation values, a best server plot – coverage prediction – for each transmitter can be derived as shown in Figure 4.4b. It can be seen that there is an overlapping area between neighboring transmitters. The system is using the predicted coverage area for start and end point estimation and timing purposes.

4.2 Call Detection

This section describes the process of filtering calls within each event stream. The two used event streams – A1 and OCM – are using different events to

signalize call establishment and termination. After this process, the system can generate a trajectory for each call found in the event stream.

A1 Calls To signalize the establishment of a call in the A1 event stream either a *Mobile Originated Call* or a *Mobile Terminated Call* event is issued. The first event is used when a mobile station initiates a call with another subscriber. The mobile station of the other subscriber will issue the second event once the call has been established with the first subscriber.

When either of the involved subscribers terminates the call, a *A Disconnect* event shall be issued by both subscribers. However, during an investigation of the event stream there was no occurrence of this event. Therefore the developed system is using an approach by which it investigates events that have been issued after a call establishment. If the system recognizes either one of the following events: *SMS*, *Mobile Originated Call*, *Mobile Terminated Call*, *Location Area Update* or *IMSI detach* it generates a call termination event before.

OCM Calls Rather than capturing events in the network, the OpenCoverageMap project periodically stores the state of the mobile phone. The state can either be *idle* or *connected*. In order to detect a call, the system has to find changes in the state. If a state change is detected the corresponding event is issued. A call establishment is detected when the state changes from *idle* to *connected*. In contrast to the call establishment, the call termination is detected when the state changes from *connected* to *idle*.

The detection of call terminations is more accurate for OpenCoverageMap than for A1 where no information is available if a call is still ongoing. Because OpenCoverageMap periodically stores the state of the mobile phone whereas in order to detect a call termination for A1 events the system has to recognize a follow-up event.

4.3 Route Calculation

The following section presents the process of calculating a route for a mobile subscriber. In general each call is used to calculate one route which is later transferred to a trajectory. The process consists of several steps which will be described in the succeeding sections.

Start and End Position Estimation

The first step in the route calculation process is to estimate the subscribers start and end position. As mentioned before GSM only exposes the Cell-ID which only defines a boundary in which the subscriber is located. To narrow this boundaries the system is using geographical input (*CORNINE* land cover) and socio-statistical maps (population density maps).

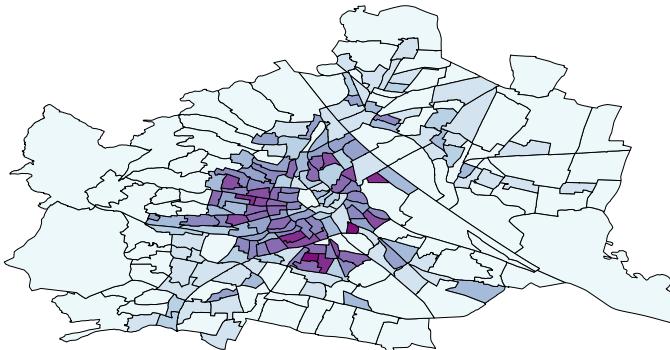


Figure 4.5: Population density map of Vienna, Austria. The population density is higher in darker (purple) than in brighter areas

By using *CORNINE* land cover data the system can define areas where it is unlikely that a subscriber will start or end his journey. This step can be parameterized by giving each of the CLC classes a percentage factor. The percentage defines how likely it is that a subscriber starts or ends a call in this class.

Our second assumption is that subscribers will more likely start or end their call in a higher populated area within the cell boundaries. More subscribers are located in higher populated areas than in less populated ones. Therefore the system is using population density maps in order to better estimate the start or end position. Figure 4.5 shows an example for a population density map for Vienna, Austria. In this example it can be seen that the density is higher in the inner districts than in the outer ones.

Corine Land Cover Clipping

By clipping and therefore removing unwanted areas the system can narrow the boundaries in which a subscriber is located. To clip the coverage area of a cell the system loads the *Corine* land cover map for the particular area. The next step is to clip the cell coverage area with useful *CORINE* land cover categories such as *artificial surfaces* and *agricultural areas*. This technique known as polygon clipping removes unwanted area –*forest and semi-natural areas, wetlands and water bodies* – from the cell.

Population Density Estimation

After removing unwanted areas within the cell coverage area the next step is to estimate the subscribers position. This step is the same for start and end positions. By using the population density information of the coverage area the system dices a position based on the population density. Therefore more subscribers will be located in higher populated areas.

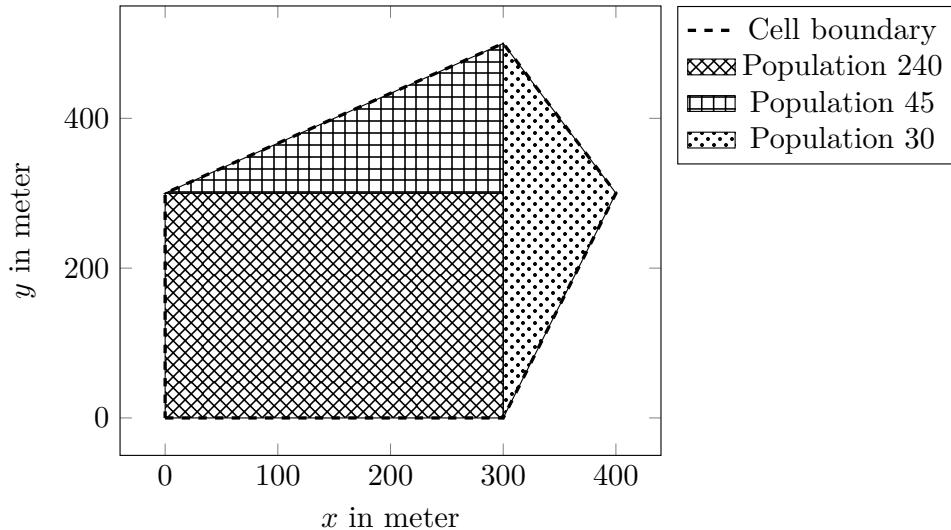


Figure 4.6: A Demonstration of a Population Grid for a Cell Area

Population Density Clipping The first step is to load the population density map for the coverage area. A random number generator with a defined probability density function will be created. The probability density function is derived from the population density map. When the system loads the population density map for the coverage area it will get n polygons with n different population densities. More generally speaking each area with a unique population density is represented by a polygon. Afterwards the random number generator is used to dice an area of interest. By using the population density as a function for the random number generator, areas with a high population density will be picked more often than less populated areas. Once the system picked a polygon based on the random number generator it clips this polygon with the coverage area. This process narrows the boundaries of the subscribers location. Following the subscribers location will be set by dicing a location within the remaining coverage area. Figure 4.6 illustrates an example for different population densities within the boundaries of one cell. We can see that the total population is 315. We calculate a *pdf* for all three population cells based on the ratio of the population and the total population. The calculated *pdf* will be used to estimate the user's start and end position. As an example the probability that the starting point is within the polygon with Population 240 is given by $240/315$. Within the polygon "Population 240" the starting point is selected based on a uniform distribution.

Random Point in Coverage Area Dicing a random location into a rectangular shape is an easy task, however the shape of the remaining cov-

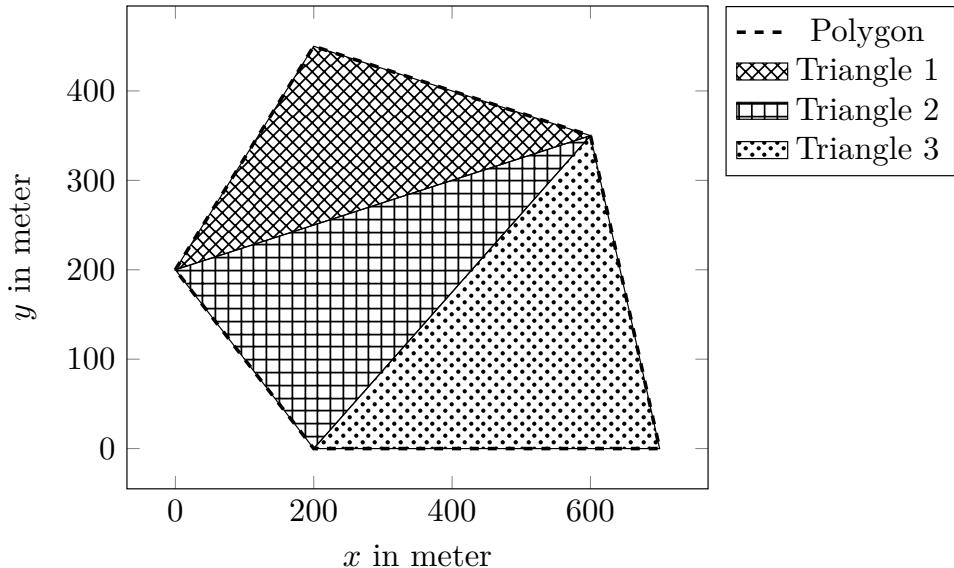


Figure 4.7: Triangulation of a Polygon into 3 Triangles

verage area will unlikely be a rectangular. A simple approach is using the bounding box of the coverage area polygon and dicing coordinate pairs for the bounding box as long as one coordinate pair lays within the coverage polygon. This simple approach has one major disadvantage because it is unpredictable. There is no estimation for how long it would take that one coordinate pair is contained in the coverage polygon.

A more sophisticated approach is to triangulate the coverage polygon into triangles. Triangulation of convex monotype polygons can be done with algorithms by A. Fournier and D.Y. Montuno [14] or Godfried Toussaint [35]. The developed system uses the GDAL project [17] which provides an implementation of polygon triangulation for many platforms and programming languages. Figure 4.7 depicts the triangulation of a polygon into triangles. The polygon is split into 3 triangles by applying Fourniers algorithm.

As already discussed before the developed system needs to uniformly distribute subscribers location with the polygon. A *pdf* will be created by using the area of each triangle as input. A random number generator will use this *pdf* and randomly assign the triangle in which the subscribers location shall be diced.

In Figure 4.8 two different approaches for random triangle point picking are illustrated. The first one is picking a point within the boundaries of the triangle whereas the second one is picking a point in a quadrilateral which consist of the triangle and its mirroring. To pick a point in a triangle the first approach is using Equation 4.2 where a_1 and a_2 are uniform random numbers in the interval $[0, 1]$, v_1 and v_2 are two vertices's of the triangle. As

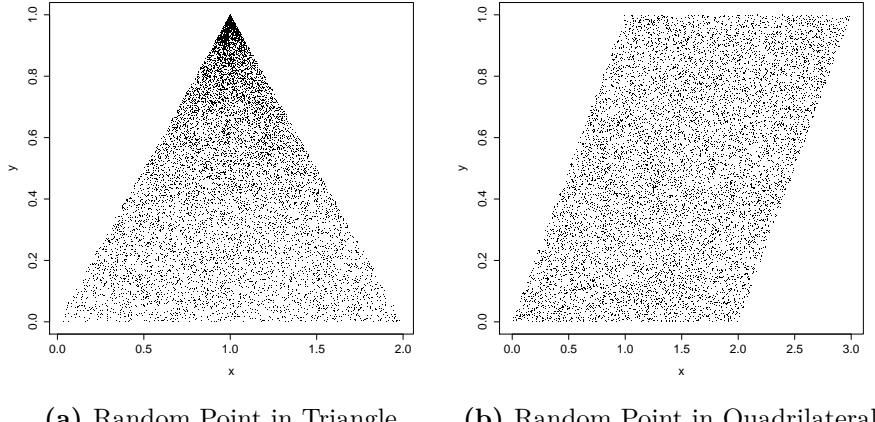


Figure 4.8: Comparison between two different random point picking methods

depicted in Figure 4.8a this approach does not create uniform distributed points within the triangle. The second approach is different from the first one as it does not pick points within the triangle but rather in a quadrilateral made of the original triangle and its mirroring. Figure 4.8b shows that this approach creates uniform distributed points. However the points are created in a quadrilateral instead of a triangle this can be overcome by removing points outside of the triangle. Since our system needs a uniform distribution of points in a triangle, the second approach will be used.

$$p = a_1 * v_1 + (1 - a_1) * a_2 * v_2 \quad (4.2)$$

$$p = a_1 * v_1 + a_2 * v_2 \quad (4.3)$$

Routing

The developed system is using the OpenStreetMap road network and the OSM2PO¹⁰ route engine. After estimating a random start and end position of the subscriber a route between these two points will be calculated with OSM2PO.

OSM2PO OSM2PO is a project developed by Carsten Moeller which allows routing on the freely available OpenStreetMap road network. On the first start OSM2PO is generating a graph network out of the road network.

¹⁰Project description: <http://osm2po.de/>, last accessed on March 18, 2014

The graph network is used internally of OSM2PO and allows a faster route calculation. OSM2PO can calculate the fastest route by using speed limit information or the shortest route with minimum distance.

Route Generation The system first estimates a start and position for the subscriber and calculates the fastest route between these two points. The calculated route contains the geometry of the route, the used roads and the speed limit of each road segment. This information will later be used by the system to validate the route.

4.4 Route Validation

Route validation is necessary to use the best estimation of the traveled route. For each subscriber there will be more than one route generated based on a configuration parameter. The developed system uses two different types of route validation, the first evaluates the route geometry and the second the timing. Each of the validations can be treated separately or in conjunction. By combining the results a better validation can be achieved.

Geometry Validation

Geometry validation is used to evaluate the estimated route with the subscribers handover sequence. In addition when using events from the OpenCoverageMap the system can validate the estimated route with the actual route based on the GPS information.

Squared Sum The first validation the system is doing for each route is to calculate the squared sum between the cell sites of the handover sequence and the calculated route. To compare different routes Equation 4.4 was used. This is the same metric Tettamanti et al.[34] used for their system. For each calculated route j the squared sum of all minimum distances $d_{i,j}$ between the route and the cell site was calculated. Figure 4.9 illustrates the minimum distance between the centroid of a cell site and a calculated route.

$$D_j = \sum_{i=1}^m d_{i,j}^2 \quad (4.4)$$

Hausdorff Distance If the system is using events from the OpenCoverageMap project the actual route traveled by the subscriber is known by storing GPS information. This allows the system to validate the calculated routes with the actual route. The developed system is using the Hausdorff distance named after Felix Hausdorff [29]. The Hausdorff distance measures

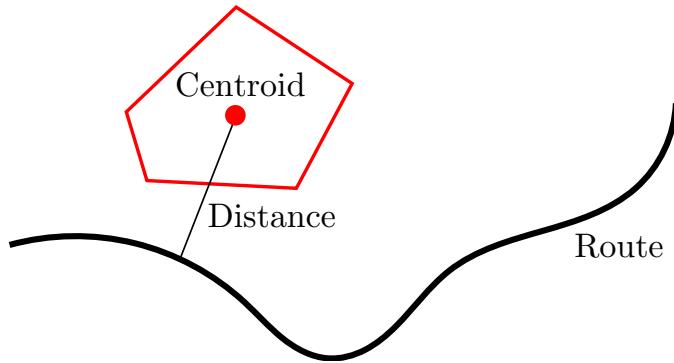


Figure 4.9: Minimum distance between centroid of cell site and route

how far two subsets of a metric space are from each other, it is the maximum of all the distances from a point in one set to the closest point in the other set. In our system the two sets consists of the calculated and the actual route. Figure 4.10 depicts the Hausdorff¹¹ distance between to paths X and Y . Therefore the system is using the Hausdorff distance to measure the similarity between the calculated and the actual route.

Timing Validation

Besides geometry validation the system is taking the time it needs to actually drive the route into account. When the system generates a trajectory for a subscriber it knows the time when the subscriber initiated and terminated the call. This information is used to extract the journey time. A ratio r_t between the actual journey time t_{actual} and the time it takes to travel the estimated route t_{route} is calculated (see Equation 4.5). The ratio gives information if the estimated router is either to fast or to slow. A to fast route can indicate that the route is either too long or that the subscriber was stuck in traffic congestions. On the other hand a slower estimated route can indicate that either the wrong route was chosen or that the subscriber was going faster than the speed limit. Therefore a conjunction of all validations is needed to choose the best approximated route.

$$r_t = \frac{t_{actual}}{t_{route}} \quad (4.5)$$

4.5 Timing Estimation

Whenever a subscriber is in an active call and moves from one cell to another one a handover event is issued. This event exposes a coarse location

¹¹Image source: http://en.wikipedia.org/wiki/File:Hausdorff_distance_sample.svg last accessed on March 16, 2014

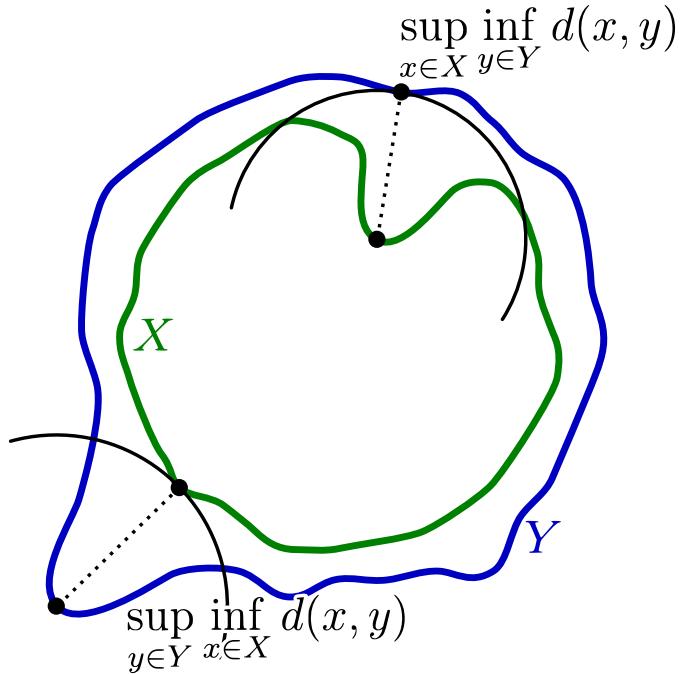


Figure 4.10: Hausdorff distance between two sets

and a time stamp. By using this information the system can derive the velocity of the subscriber. The velocity of a subscriber is an important figure for mobility simulation. Because the velocity together with the estimated route describes the mobility of the subscriber. However as we the system only knows the cell in which the handover event originated – cell to which handover was made – an estimation of the actual handover point is needed. A more precise estimation of this handover point results in a better velocity approximation.

Handover Position Estimation

To estimate handover points the system is using two successive handover events. These two events consists of a time stamp, cell-Id and LAC. From the cell-Id and LAC the system can obtain the coverage area of the two cells. During research of the A1 and OCM data we discovered that there are two types of handover. The successive handover are either connected or apart. Connected handover are handover which coverage areas touches or overlaps each other. An apart handover is a handover where the coverage areas are not touching or overlapping. The difference of the two handover types is illustrated in Figure 4.11. For connected handover it is obvious where the handover happened. For this purpose the system is taking the touching

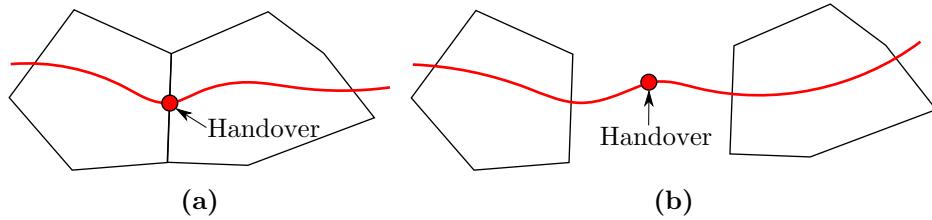


Figure 4.11: Example for connected (a) and apart (b) handover

or overlapping parts of the coverage areas and the intersection with the estimated route. In contrast for apart handover it is not clear where the handover happened. It could either happen at the boundaries of the first cell or the second cell or in between those. A simplification is to use the middle point between the two cells.

Velocity

After the handover points have been estimated the next step is to enrich this information with the timestamps when the handover occurred. As mentioned before in Section 3.3.3 each event contains a precise timestamp when the event was captured by the underlying system. This information together with an estimated route and handover point allows to derive the velocity of the driver. The system knows the time difference between two handover events as well as the distance traveled. The traveled distance is the distance between two successive handover points. By cutting the whole route with the two handover points the system can obtain the route between the two handover points and therefore the actual distance between those. The velocity can then be calculated by dividing the distance s between the handover over the time difference t between the handover $v = \frac{s}{t}$. The calculated velocity represents the average distance between the handover.

Velocity Adaption

The handover position approximation is a static process and does not take the current situation into account. Therefore, it cannot react to dynamic events. These events can be high network load or short-term obstacles that affect the path loss of the transmitter. Since it is not feasible to get an accurate approximation of the coverage area for each cell site, the handover position can be error-prone. This can lead to a deviation of the exact handover position and the estimated one. To minimize this effect the handover position needs to be repositioned in case the estimated velocity is too high. An example for such an adaption is to move the handover position on the route. A deviation between the exact handover position and the approximated can

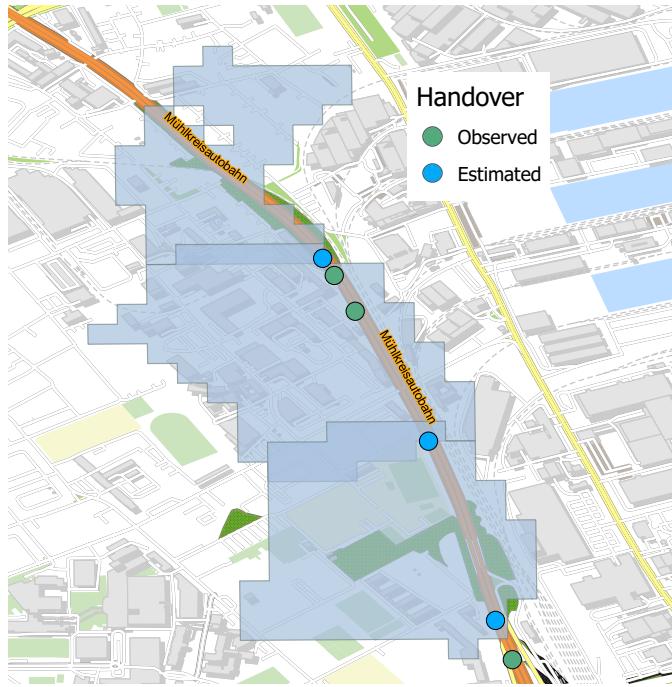


Figure 4.12: Derivation between the observed handover position and the estimated handover position

lead to a higher or a lower average velocity. If the average velocity of one route segment is relative high, then there must exist another route segment with a relative low average velocity. We defined a rule that if the average calculated velocity of a route segment is greater than 50% of the allowed maximum velocity a reposition takes place. Repositioning is done by first calculating the distance a subscriber can move from one handover timestamp H_i to the next one H_{i+1} , considering the allowed maximum velocity. The handover point H_{i+1} is then repositioned so that the distance between H_i and H_{i+1} equals the allowed distance. By decreasing the distance between H_i and H_{i+1} the distance between H_{i+1} and H_{i+2} will increase. This leads to a velocity decrease for the route segment between H_i and H_{i+1} and a velocity increase for H_{i+1} and H_{i+2} .

An example for a handover repositioning is shown in Figure 4.12. The green points are the handover positions observed by the handset. In contrast, the blue points are the estimated handover points. Handover were estimated with the above presented approach. The example illustrates that the second estimated handover is too far from the observed one away. Here a handover is made to a cell whose coverage the subscriber has not yet entered. Therefore, the above presented approach estimated a wrong handover position based on the assumption that; handovers happen at the edge of coverage cells.

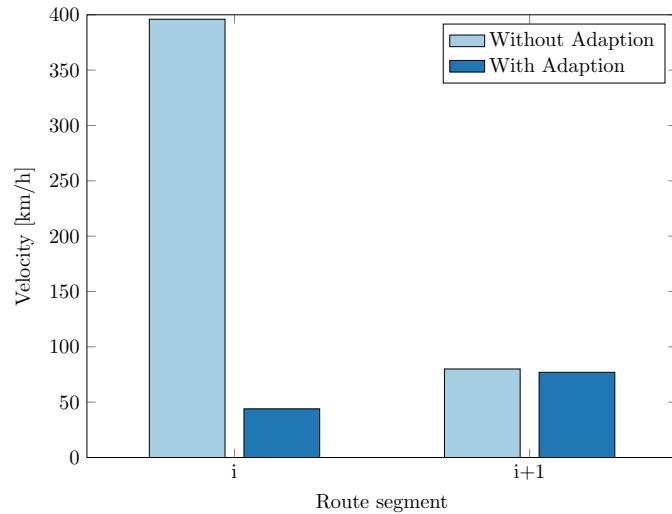


Figure 4.13: Comparison between the velocity without adaption and with adaption

This leads to a deviation between those handover points that resulted in an average route segment (i) velocity of 396 km/h (see Figure 4.13). On the other hand the route segment (i+1) velocity of the successive segment was only 44 km/h due to the increased route segment length. By applying the reposition algorithm the velocity of the route segment (i) was decreased to 80 km/h. The velocity of the other route segment (i+1) was increased to 77 km/h.

While investigating the benefit of handover reposition we discovered that in some cases it is necessary to not only reposition one handover point but two. This needs to be done if the velocity transition from one route segment to another would lead to a high velocity of the second route segment. In such cases it is necessary to equally move the handover (i-1) and handover (i+1). Generally speaking this means that the velocity overrun from route segment (i) will be equally distributed over route segment (i-1) and (i+1).

Chapter 5

Implementation

The following chapter will present the actually implemented system. The implementation is based on Chapter 4 where the concepts for the system have been presented. Through out this chapter all parts of the system and their responsibilities will be explained.

5.1 System Overview

The developer system consists of a set of individual systems. This systems can be grouped in three groups. The first is responsible for storing information such as: mobile subscription data, population and land use information, road network and cell coverage areas. The second is a data abstraction layer which is used to aggregate the data and present it to interested systems via an API. The last group is responsible for processing and generating trajectories. It is using the other systems via the API provided by the data abstraction layer. A brief overview of the implemented system is illustrated in Figure 5.1. It depicts the data store which consists of two different databases, the first is responsible for storing geographic information and the second for storing subscription information from A1 and OCM.

5.1.1 Data Store

The data store is responsible for storing data, this data is either geographic information or subscription data. For geographic data the system is using PostgreSQL with the PostGIS extension. PostGIS extends PostgreSQL with support for spatial data structures and topological queries [25]. Therefore, it allows the system to store the OpenStreetMap road network, population and land use information, the coverage area and the location of each cell site. PostGIS allows the use of advanced spatial queries such as intersections and clipping which is later needed by the system.

Subscription data is stored in a separate MySQL database. It is storing

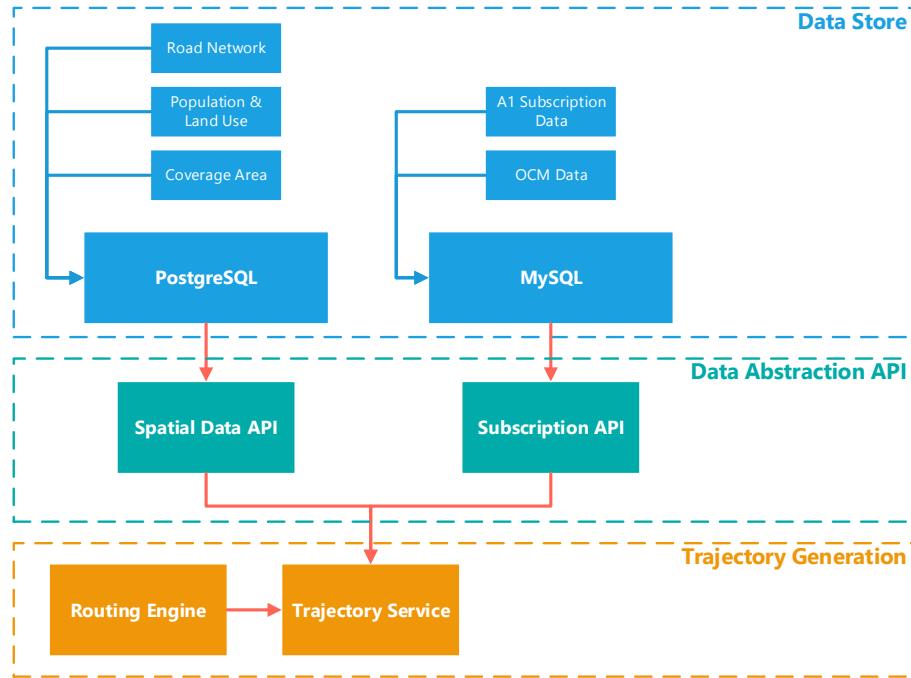


Figure 5.1: System overview of the implemented system

events captured by the A1 system and the OpenCoverageMap project. The database consists of two tables, one for A1 and the second one for OpenCoverageMap.

5.1.2 Data Abstraction API

We first started to develop a system with direct access to the database via the JDBC driver for PostgreSQL¹ and MySQL². But this approach was not sufficient as we experienced a slow data access rate with larger queries. Therefore, we decided to build an abstraction layer which encapsulates the access of the database from the system. The abstraction layer is built with Node.js – a JavaScript framework – and it provides a HTTP API. More details will be provided in Section 5.2.

¹PostgreSQL JDBC driver: <http://jdbc.postgresql.org/>, last accessed March, 28 2014

²MySQL JDBC driver: <https://dev.mysql.com/downloads/connector/j/>, last accessed March, 28 2014

5.1.3 Trajectory Generation

The trajectory generation group consists of two systems. First the trajectory service which is generating trajectories for subscribers and second the routing engine which is responsible for calculating routes between a start and end point.

5.2 Architecture

After a brief overview has been given in the previous section, here the underlying system will be explained in more detail. It will also cover the process of importing the needed data into the database and how this data can be retrieved from the database. Moreover the used data and the communication between the subsystems will be described.

5.2.1 Databases

PostgreSQL Database

To store geographic information PostgreSQL together with the PostGIS extension is used. PostGIS extends PostgreSQL in a way that it follows the Simple Features for SQL specification from the Open Geospatial Consortium. The Simple Features are defined in ISO 19125 [26, 27]. The developed system is using population and land use information stored in the database. This data is needed to estimate a subscribers start and end position within the boundaries of the cell coverage area. In addition to raster data (population and land use) the database also stores the OpenStreetMap road network. Figure 5.2 depicts the internal structure of the PostgreSQL database. The table *at_2po_4pgr* contains the OpenStreetMap road network, *landuse_raster* land use information and *density_raster* population information.

Import Data This section describes the process to import both raster and the road network into the database. Raster data is simply an image where each pixel corresponds to a coordinate in world space. A raster image defines a grid spacing which defines how far in meters pixel are away. A grid spacing of 20 meters means that each pixel covers an area of 400 square meters. Usually environmental and demographic geographic information, is stored as a raster image. On the other hand road networks consists of a vector of points. The road network is stored in the database as Simple Features.

Raster To import raster data into the PostgreSQL database the tool `raster2pgsql` was used. Listing 5.1 illustrates how to import the data. The parameter `s` defines the spatial reference system of the raster image.

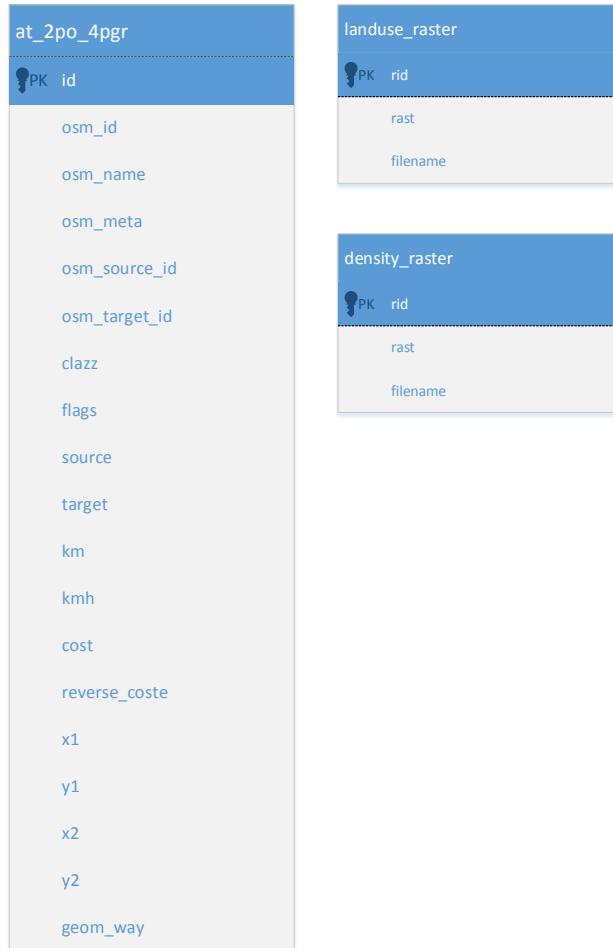


Figure 5.2: Structure of the PostgreSQL database

The grid spacing of the raster image is defined by parameter `t` and is in this case 100 by 100 meters. The tool converts the raster image into an SQL file which can be inserted into the database. To insert the created SQL file into the database the second command is used.

Listing 5.1: Import raster data into PostgreSQL database

```

1  # raster2pgsql -s 4236 -I -C -M *.tif -F -t 100x100
  population > pop.sql
2  # psql -U postgres -d gisdb -f pop.sql

```

Road Network Our system is using the routing engine OSM2PO which operates on the OpenStreetMap road network. OSM2PO can convert the

mfd_events	ocm_all
id	timestamp_android
timestamp	tracks_id
latitude	tel_cellid
longitude	tel_lac
cellID	gps_latitude
lac	gps_longitude
eventtype	gps_altitude
	gps_accuracy
	tel_callstate
	tel_datastate
	tel_networktype

Figure 5.3: Structure of the MySQL database

OpenStreetMap road network to a PostgreSQL compatible SQL file. Listing 5.2 shows the step to import an OpenStreetMap road network – in this case from Austria – into the PostgreSQL database.

Listing 5.2: Import OpenStreetmap data into PostgreSQL database

```

1  # java -jar osm2po-4_8_8.jar prefix=at austri.osm.pbf
2  # psql -U postgres -d gisdb -f at/at_2po_4pgr.sql.sql

```

MySQL Database

The developed system is using data from A1 and the OpenCoverageMap project. Because this data is not related with geographic information a second database is used to store this data. This information is stored in two separate tables because the structure of A1 and the OpenCoverageMap is different. Figure 5.3 depicts the structure of the two tables, the first *mfd_events* stores the A1 data and the second *ocm_all* stores information from the OpenCoverageMap project.

Import A1 To import the A1 data set into the MySQL, the binary event stream needs to be converted first. The conversion takes the binary event stream and converts its to CSV file. Each row in the CSV file represents an event. Later the created CSV file will be imported into the database similar to Listing 5.4.

Convert The conversion is carried out by a Java program which takes the binary data stream as input and outputs a CSV file. First a Java `InputStream` from the input file will be created. This input stream will be passed to a `DataInputStream`. As illustrated in Listing 5.3 a loop iterates over the data input stream and parses the binary information according to the A1 data structure. At last at the end of each iteration the parsed information will be print to the standard output.

Listing 5.3: Example code to parse event data stream

```

1 // create file input stream
2 InputStream is = new FileInputStream("a1.data");
3 // create new data input stream
4 DataInputStream dis = new DataInputStream(is);
5 while (dis.available() != 0){
6     byte[] anon_id = new byte[32];
7     dis.read(anon_id);
8     timestamp=dis.readInt();
9     timestamp_ms=dis.readInt();
10    lac=dis.readInt();
11    cell_id=dist.readInt();
12    latitude=dis.readDouble();
13    longitude=dis.readDouble();
14    radius= dis.readLong();
15    dis.skipBytes(12); //skip reserved fields
16    event_type = dis.readShort();
17    dis.skipBytes(3); //skip reserved fields
18    angle_x=dis.readInt();
19    angle_y=dis.readInt();
20    speed=dis.readInt();
21    //only print useful fields
22    System.out.println(Hex.encodeHexString(anon_id) +";"+
23        timestamp +";"+lac +";"+cell_id +";"+latitude +";"+
24        longitude +";"+event_type +";"+angle_x);
25 }
```

Listing 5.4: Load text file into MySQL database

```

1 LOAD DATA INFILE 'data.txt' INTO TABLE tbl_name
2   FIELDS TERMINATED BY ',' ENCLOSED BY '"'
3   LINES TERMINATED BY '\n';
```

Import OpenCoverageMap The data we got provided by the OpenCoverageMap project was already a CSV file and can be imported into the database with an SQL statement similar to the one in Listing 5.4.

5.2.2 Node.js Data API

To encapsulate the querying of the database from the trajectory service a Node.js API was implemented. It provides a HTTP API which gives access to the data stored in the PostgreSQL and MySQL database. The data API is using the following modules, which can be installed through the script provided in Listing 5.5:

- **express**³ is a web application for Node.js and provides our system with web request routing in a RESTful manner
- **pg**⁴ is a PostgreSQL driver for Node.js
- **mysql**⁵ is a MySQL driver for Node.js

Listing 5.5: Script to install the used Node.js modules

```
1 # npm install express
2 # npm install pg
3 # npm install mysql
```

Listing 5.6: Example for a Node.js app which is using the express framework and the PostgreSQL and MySQL module

```
1 var pg = require('pg');
2
3 var conString = "postgres://postgres:1234@localhost/postgres";
4 var mysql = require('mysql');
5 var connection = mysql.createConnection({
6   host: 'localhost',
7   user: 'mysql',
8   password: '1234'
9 });
10
11 var express = require('express'),
12     app = express.createServer();
13
14 app.get('/mysql', function (req, res) {
15   connection.connect();
16   connection.query('SELECT 1 + 1 AS result', function (err, rows,
17   fields) {
18     res.send(rows[0].solution);
19   });
20   connection.end();
21 });
22 app.get('/postgres', function (req, res) {
```

³Project website with more information about express: <http://expressjs.com>, last accessed March 28, 2014

⁴More information about the PostgreSQL driver pg: <https://github.com/brianc/node-postgres>, last accessed March 28, 2014

⁵Project website with more information and a tutorial about mysql: <https://github.com/felixge/node-mysql>, last accessed March 28, 2014

```

23   var client = new pg.Client(conString);
24   client.connect(function (err) {
25     client.query('SELECT NOW() AS time', function (err, result) {
26       res.send(result.rows[0].time);
27     });
28   });
29 });
30
31 app.listen(3000);

```

Features

The Node.js API provides several features to the trajectory service. It enables the trajectory service to access the two database via an uniform API. This API hides the implementation from the program using it. However, to increase performance the API was split into two parts. The first API resides on the same server as the PostgreSQL and handles geographic request whereas the second one handles subscription data and resides on the MySQL server.

MySQL API provides access to mobile subscription data for both the A1 and OpenCoverageMap data. In addition, the route traveled by a subscriber can be retrieved from the OpenCoverageMap data. This route consists of a timestamp and the latitude and longitude coordinate. All the returned data is encoded as JSON that eases the parsing. Listing 5.7 depicts the request that can be made to the database. The first one retrieves events from A1 for the specified user, the second one retrieves events from OpenCoverageMap and the last one get the route traveled by the OpenCoverageMap user.

Listing 5.7: MySQL API requests

```

1 GET /mfdevents?id=USER_ID
2 GET /ocmraw?id=USER_ID
3 GET /ocmroute?id=USER_ID

```

PostgreSQL API enables the requesting program to access functions of the PostgreSQL database. It provides access to raster data such as population and land use information as well as to retrieve a random point within a specified area based on population and land use information (see Listing 5.8). The bounds parameter is encoded as a list of coordinate – separated by a comma – specifying a bounding box (xmin,ymin,xmax,ymax). In comparison the geom parameter is encoded as Well-known text (WKT) which allows defining more advanced areas as polygons and multi polygons (POLYGON ((30 10, 40 40, 20 40, 10 20, 30 10))).

Listing 5.8: PostgreSQL API requests

```

1 GET /populationBounds?bounds=BOUNDARIES
2 GET /landuseBounds?bounds=BOUNDARIES
3 GET /randomgeom?geom=GEOMETRY&num=NUMBER_OF_POINTS

```

5.2.3 Routing Engine

To calculate routes on the OpenStreetMap road network, the system is using the OSM2PO routing engine. This engine can either be used as a standalone web server with a defined API or be integrated into a Java application. In our case the engine was integrated into the trajectory service as a library. The benefit of this approach is, that the system has better access to the graph file used by the engine. The graph file is a reduced road network optimized for routing. By accessing the graph file, the trajectory service can retrieve metadata for the calculated route such as speed limits and length of the roads. This information can later be used to validate the calculate route and annotate it with timing information.

Listing 5.9 illustrates how a route between Linz and Hagenberg im Mühlkreis is calculated. The result is an array with segment IDs that can then be used to retrieve the geometry and the speed limits of the segment from the graph file.

Listing 5.9: Example code to calculate a route between two points

```

1 File graphFile = new File("at_2po_4pgr.gph");
2 Graph graph = new Graph(graphFile);
3 DefaultRouter router = new DefaultRouter();

5 //Linz, Austria
6 int sourceId = graph.findClosestVertexId(48.306f, 14.285f);
7 //Hagenberg im Mühlkreis, Austria
8 int targetId = graph.findClosestVertexId(48.368f, 14.513f);
9
10 Properties params = new Properties();
11 params.setProperty("findShortestPath", "false");

13 //calculate path between source and target
14 int[] path = router.findPath(
15     graph, sourceId, targetId, Float.MAX_VALUE, params);

```

5.3 Trajectory Service

The trajectory service is using the data and APIs, mentioned in the previous section, to generate trajectories for each subscriber. By using different data

sources it can estimate trajectories for different data providers in our case mobile network operators. In the current state trajectories can be generated for A1 subscriber and OpenCoverageMap participants. To fulfill its task the trajectory service needs besides the events from the network operator a coverage prediction for each cell site. The trajectory service is using the following data:

- Mobile subscription data
- Population and land use information
- Cell site coverage prediction
- OpenStreetMap road network
- osm2po route engine

Convert Events

The structure of events used in the trajectory generator was inspired by the structure used in the A1 event stream. To integrate other data sources such as the OpenCoverageMap a converter needs to be implemented. The objective of the converter is to transform the event structure to the one used by A1 events.

The OpenCoverageMap does not use the same event structure as A1. Rather than issuing events like call establish / termination or handover events it periodically stores the state of the mobile station. Therefore, this information needs to be transformed to an event structure. The steps to convert the OpenCoverageMap data to the A1 structure are the following: First remove all data where no call is active. Second iterate over this data and check for gaps between succeeding timestamps. Gaps greater than 10 seconds indicate that a call was either established or terminated. Afterwards iterate over the data between the two gaps. Create a call establish and termination event at the beginning and end of the list. If there is a difference between the cell-id and location area of two succeeding entries add a hand over event to the current call. The result will be a list of events with the same structure as the ones captured by A1.

Generation Process

The main aspect of the trajectory service is the implementation of the trajectory generation pipeline introduced in chapter 4. The generation process is implemented as an iterative process. The process contains of the following steps:

1. Data retrieval
2. Call Detection
3. Route Calculation
4. Route Validation

- 5. Timing Estimation
- 6. Trajectory Output

Input Data The input data needed to generate trajectories is consumed via APIs and file access. The mobile subscriber data is accessed via the APIs described in the previous section. Several data provider can be used as long as they follow the same structure or provide a converter that converts the data to the correct structure. Additionally the population density maps and land use information can be accessed via the API. The second type of input data, the coverage prediction is loaded from a file. The coverage prediction consists of entries for each transmitter (see Listing 5.10). Each of these entries consists of an id, location area, cell-id, cell type and the coverage area as a WKT text. The cell coverage will later be used to estimate the start and end point as well as for the handover point estimation. The third and last input data is the road network provided by osm2po.

Listing 5.10: Coverage prediction

```

1 1_5503_62905_11_POLYGON ((14.2873 48.2981,...))
2 2_5503_23115_11_POLYGON ((14.3159 48.2991,...))
3 3_5503_31185_11_POLYGON ((14.3132 48.3026,...))
4 4_5503_31115_11_MULTIPOINT ((14.3176 48.3044,...)))

```

Handover Point Estimation The handover point estimation is using a class that implements the `CellTimeSynchronizeIF` interface. This interface defines the input and output parameter of the handover point estimation. The interface consists of a method to annotate the trajectory with timing information and a method to compute the handover points.

Listing 5.11: Interface for handover point estimation `CellTimeSynchronizeIF`

```

1 public interface CellTimeSynchronizeIF extends
    TimeSynchronizerIF<List<MFDEvent>> {
2     public List<RouteSegment> synchronizeTiming(List<
        RouteSegment> _rs,List<MFDEvent> _events);
     Point[] getHandoverPoints(List<RouteSegment> _rs,List<
        MFDEvent> _events);
4 }

```

The implementation in Listing 5.12 depicts a simple algorithm to compute the handover position. Hereby the midpoint between the centroid of two consecutive handover will be used as the handover position. The handover point estimation can latter be replaced with more sophisticated approaches as long as they correspond to the same interface.

Listing 5.12: Simple implementation of the `CellTimeSynchronizeIF`

```

1  @Override
2  public Point[] getHandoverPoints(List<RouteSegment> _rs,
3      List<MFDEvent> _events) {
4      ArrayList<Point> handoverPoints = new ArrayList<Point>();
5      MFDEvent currEvent;
6      MFDEvent nextEvent;
7      Geometry currGeo;
8      Geometry nextGeo;
9      for (int i = 0; i < _events.size() - 1; i++) {
10          currEvent = _events.get(i);
11          nextEvent = _events.get(i + 1);
12          currGeo = CellLoader.getInstance().getCell(
13              currEvent.getLac(), currEvent.getCellID()).getGeom();
14          nextGeo = CellLoader.getInstance().getCell(
15              nextEvent.getLac(), nextEvent.getCellID()).getGeom();

16          Point handoverPoint=gf.createPoint(new Coordinate(
17              currGeo.getCentroid().getX() + nextGeo.getCentroid().
18              getX()) / 2, (currGeo.getCentroid().getY() + nextGeo.
19              getCentroid().getY()) / 2));
20          handoverPoints.add(handoverPoint);
}
21      Point[] result = new Point[handoverPoints.size()];
22      result = handoverPoints.toArray(result);
23      return result;
24  }

```

Trajectory Output The trajectory service persists the generated trajectory in a file for further usage. The structure of the trajectory file is depicted in Listing 5.13. It consists of the latitude and longitude coordinates as well as the average velocity. The average velocity was computed with the approach described in section 4.5.

Listing 5.13: Coverage prediction

```

1 48.391565;16.106760;21.31
2 48.391553;16.106985;21.31
3 48.391437;16.107714;21.31
4 48.391340;16.108558;21.31
5 ...
6 48.392290;16.170651;85.53
7 48.391478;16.173173;85.53
8 48.391847;16.171947;85.53
9 48.391847;16.171947;85.53

```

Chapter 6

Results

In this chapter, two mobile subscriber trajectories will be presented that have been generated using the developed system. The generated trajectories cover semi-rural and urban areas, which allows evaluating the approach for different scenarios. All results are fully reproducible in case the same subscriber and coverage predictions are used.

6.1 Example 1

The first example covers a semi-rural region. A semi-rural region consist of a rural and an urban area. The following trajectory was recorded on Monday, 26 March 2012. At 08:08:29 in the morning the subscriber established a call. The duration of the call was 7 minutes and 36 seconds. During the call the subscriber traversed the highway A7 from Linz¹ to Engerwitzdorf². Between the call establishment and call termination the mobile station was connected to 22 transmitters which resulted in 21 handover events. Figure 6.1 illustrates the traversed route as well as the estimated handover position for both the network planning tool coverage 6.1a and the Voronoi diagrams coverage 6.1b.

Route

To estimate the subscribers route, 20 random start and end positions within the coverage area of the first and last cell were used. The random positions were derived from a probability density function that was generated by the population density in the area as described in Section 4.3. Table 6.1 depicts the metrics used to choose the best approximation. This metrics are the time-ratio between the journey time and the time it takes to traverse the route as well as the summed square of distances between the route and the

¹GPS position of call establishment Latitude: 48.28086955 Longitude: 14.30415398 <http://osm.org/go/0JhMzsg9I-?m=>

²GPS position of call termination Latitude: 48.3381025 Longitude: 14.4125565 <http://osm.org/go/0JhP~5vT--?m=>

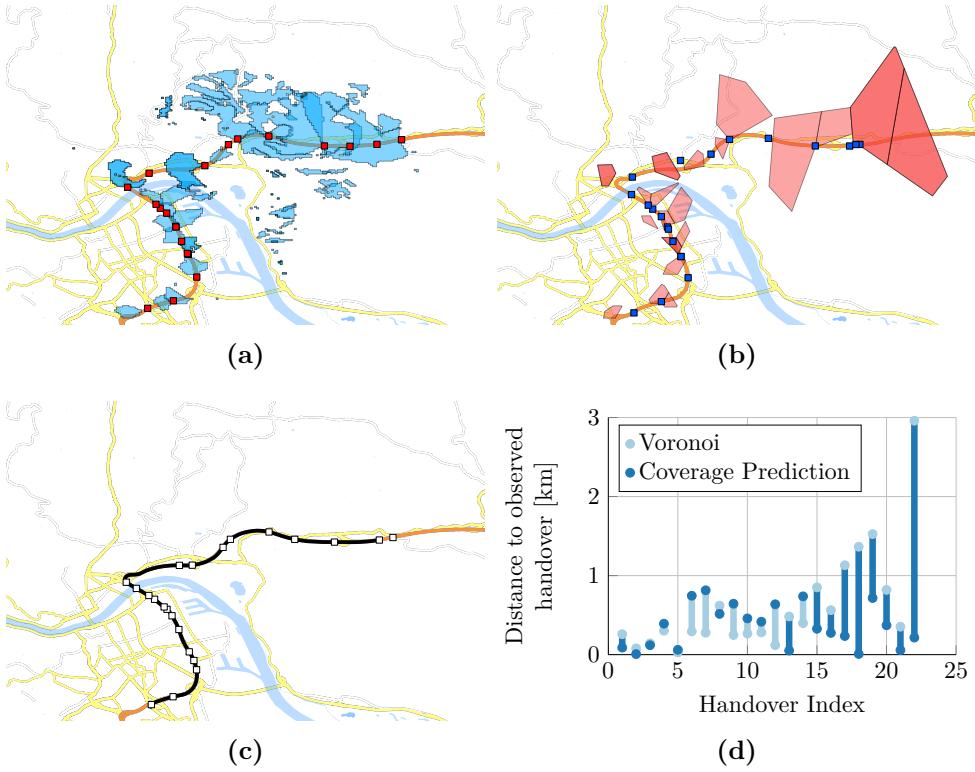


Figure 6.1: Example 1: (a) coverage prediction with network planning tool and estimated handover points, (b) Voronoi diagram coverage and estimated handover points, (c) recorded GPS route and observed handover points, (d) comparison of distance between estimated handover and observed handover

centroids of the involved cell sites. An illustration of all computed routes can be found in Figure 6.2. The time-ratio in conjunction with the squared sum of distances between the route and each coverage area allows the system to choose the best approximated route. In case of subscriber 563 the route with time-ratio 1.00 and $\sum d_i^2 = 0.35$ was picked. To compare the estimated route with the real route recorded with GPS the Hausdorff metric was used. The Hausdorff metric for the chosen route compared with the actual route was 0.990138. That means that the maximum distance between the chosen route and the actual route was very small. Thus, the similarity of both routes is high. A second metric which takes the continuity of both routes into account is the Frechet distance. A Frechet distance of 0 means that both routes are identical. Therefore, the smaller the Frechet distance is, the higher is the similarity. The computed Frechet distance for the estimated route was 0.0134. Even if the estimated route corresponds to the actual route – recorded with GPS – the Frechet distance is not 0. This is due to



Figure 6.2: Example 1: Illustration of 20 routes with different start and end position

the fact that GPS introduces an error which can lead to a deviation.

Time-ratio	Mean distance \bar{d}_i	Variance $\text{Var}[d_i]$	$\sum d_i^2$
0.96	0.09	0.03	1.38
0.97	0.04	0.01	0.36
0.97	0.09	0.03	1.39
0.99	0.04	0.01	0.35
0.99	0.04	0.01	0.35
0.99	0.09	0.03	1.38
1.00	0.04	0.01	0.35
1.00	0.04	0.01	0.35
1.01	0.05	0.01	0.42
1.01	0.09	0.03	1.38
1.02	0.04	0.01	0.36
1.03	0.09	0.03	1.38
1.03	0.09	0.03	1.38
1.04	0.04	0.01	0.36
1.04	0.09	0.03	1.38
1.05	0.04	0.01	0.35
1.05	0.09	0.03	1.38
1.08	0.07	0.03	1.18
1.10	0.07	0.03	1.18
1.10	0.07	0.03	1.18

Table 6.1: Example 1: Statistical comparison of the 20 computed routes

Handover

After the subscriber route was approximated handover points were estimated. The estimation was done for both the network coverage prediction and the Voronoi diagram coverage. Figure 6.1d shows a comparison of distances between the observed handover position and the estimated handover position for both the network coverage prediction and Voronoi diagram coverage. It can be seen that the handover estimation done with Voronoi diagram coverage performed better than the network coverage prediction for the first half of the route. On the other hand the network coverage prediction performed better in the second half of the route.

Velocity

The velocity for each segment has been calculated with the approach introduced in Section 4.5. Due to deviation between the observed handover position and the estimated handover position a velocity over-run and under-run has happened at the beginning and the end of the trajectory. The velocity over-run was eliminated with the adaption algorithm presented in Section 4.5. The effect of the adaption can be seen in Figure 6.3. The first figure shows a comparison of the observed velocity with the estimated velocity when no adaption has been done. On the other hand, the second figure depicts the effect of the adaption algorithm. The velocity overrun that is visible in the first figure between second 310 and 330 has been eliminated.

6.2 Example 2

The second example depicts an urban scenario. The trajectory for this example was recorded on Saturday, 26 May 2012. The subscriber established a call at 12:12:57. The duration of the call was 6 minutes and 33 seconds. During the call the subscriber drove from Linz-Urfahr³ over the minor road network and the highway A7 to Linz-Bindermichl⁴. Between the call establishment and call termination the mobile station was connected to 17 transmitter which resulted in 16 handover events. The traversed route and the observed handover positions are illustrated in Figure 6.4c. The estimated handover positions for both the network planning tool coverage and the Voronoi diagram coverage are depicted in Figure 6.4a and 6.4b.

³GPS position of call establishment Latitude:48.31600 Longitude:14.29023 <http://osm.org/go/0JhNlzh--?m=>

⁴GPS position of call termination Latitude:48.2814 Longitude:14.3029 <http://osm.org/go/0JhMzuVj?m=>

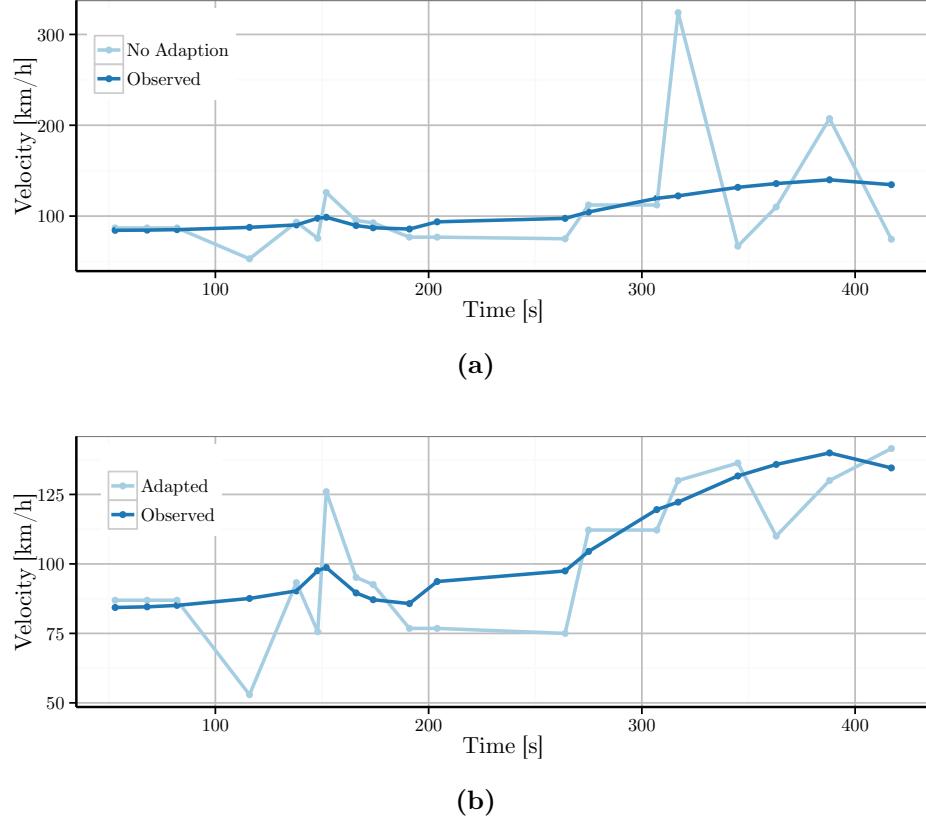


Figure 6.3: Example 1: Comparison of velocity (a) without adaption and (b) with adaption

Route

The same technique described in example one was used to estimate the subscriber route. In Table 6.2 all estimated routes are shown; the most suitable was highlighted. The most suitable route in this example had a time-ratio of 0.97 and a sum square distance of $\sum d_i^2 = 0.40$. The Hausdorff metric and Frechet distance was used again to measure the similarity of the most suited route and the actual traveled route. Figure 6.5 illustrates the 20 routes which have been computed between the estimated start and end position. The Hausdorff metric was 0.933091 which indicates that there has been a deviation with the estimated start and end position and the actual one. However, the Frechet distance was 0.0034 which means that the geometry of both routes is very similar.

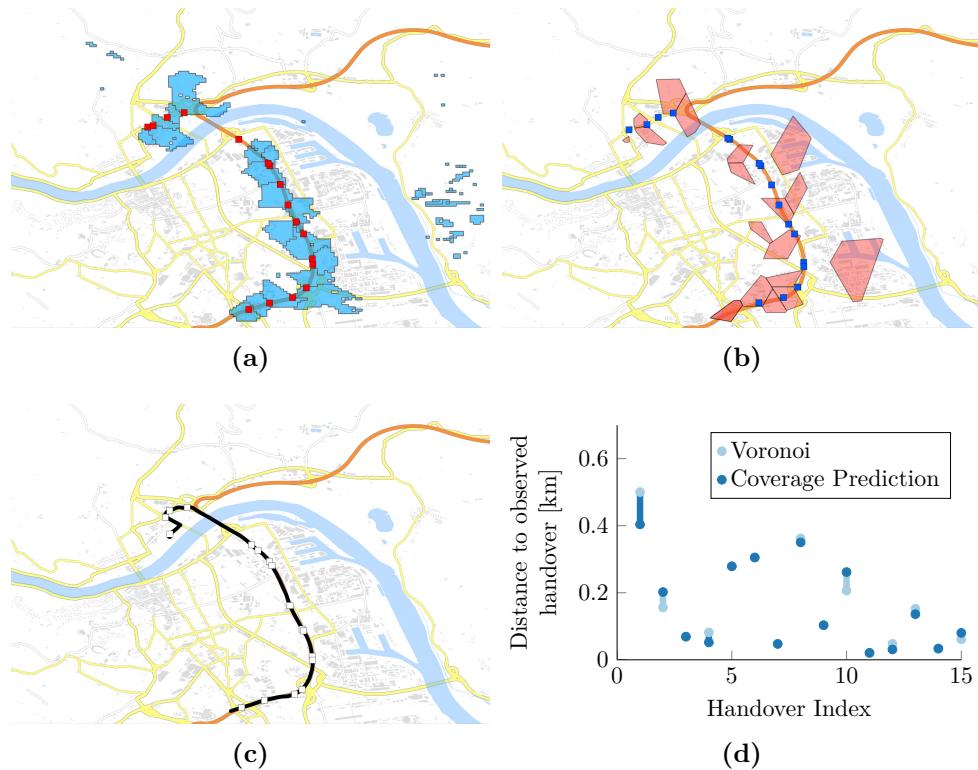


Figure 6.4: Example 2: (a) coverage prediction with network planning tool and estimated handover points, (b) Voronoi diagram coverage and estimated handover points, (c) recorded GPS route and observed handover points, (d) comparison of distance between estimated handover and observed handover

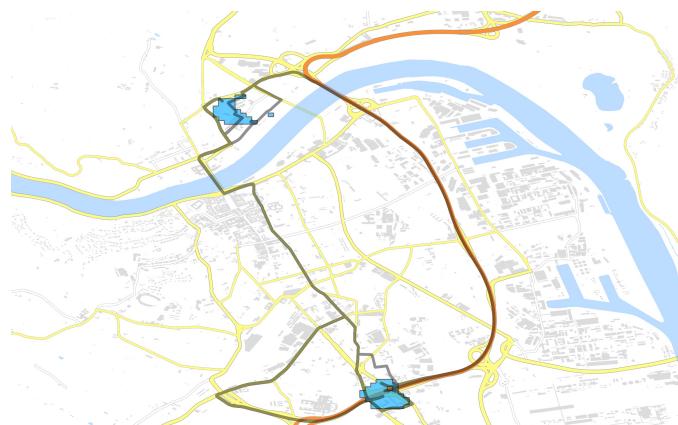


Figure 6.5: Example 2: Illustration of 20 routes with different start and end position

Time-ratio	Mean distance \bar{d}_i	Variance $\text{Var}[d_i]$	$\sum d_i^2$
0.85	0.82	0.39	19.77
0.87	0.80	0.40	19.25
0.90	0.78	0.43	19.13
0.91	0.09	0.02	0.50
0.93	0.78	0.41	19.08
0.95	0.80	0.41	19.50
0.95	0.80	0.40	19.30
0.97	0.19	0.08	2.03
0.97	0.78	0.41	18.88
0.97	0.07	0.02	0.40
0.98	0.77	0.41	18.46
1.01	0.76	0.41	18.34
1.11	0.86	0.40	21.12
1.12	0.83	0.40	20.24
1.12	0.86	0.41	21.32
1.13	0.83	0.41	20.44
1.14	0.80	0.41	19.59
1.17	0.79	0.41	19.06
1.17	0.79	0.41	19.06
1.17	0.84	0.40	20.62

Table 6.2: Example 2: Comparison of time-ration, mean, variance and sum square of the 20 computed route

Handover

In this example the handover estimation with network coverage prediction was more accurate than with Voronoi diagram prediction. This, however, is interesting as it is the opposite of the first example. In the first example Voronoi diagrams performed better in the urban area than the network coverage prediction. The reason for this can be that the subscriber was connected to a different set of cells while driving the same road network. Figure 6.4d depicts the distance difference between the observed handover position and the one estimated with both Voronoi diagram coverage and network coverage prediction.

Velocity

Similar to the first example there was a deviation of estimated and observed handover positions. This deviation introduced an error which led to an increase in speed for the segment where the deviation happened. In Figure 6.6a the speed increase is visible as four spikes. The adaption algorithm was used to remove this speed over-runs. The result of the adaption algorithm can be

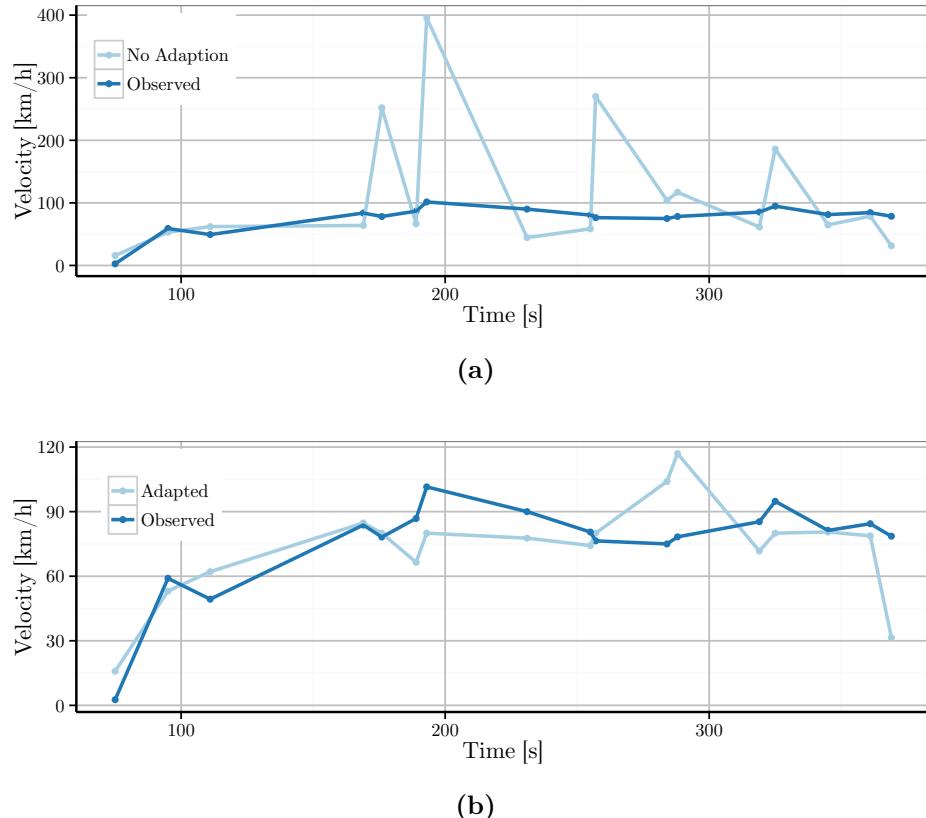


Figure 6.6: Example 2: Comparison of velocity (a) without adaption and (b) with adaption

seen in Figure 6.6b.

Chapter 7

Summary

In this thesis a trajectory generation pipeline for the automated generation of mobile subscriber trajectories has been presented. Mobility simulations are an important aspect in mobile network simulations, since they allow to investigate the effects mobile subscriber have on the mobile network. In the recent years real world behavior models have gained more and more importance in the field of mobility analysis, because they allow simulations in a real environment.

The developed system is using call detail records to estimate driving trajectories for mobile subscribers. The call detail records are used together with coverage predictions and a representation of the road network to estimate the trajectory. Trajectories are generated for subscribers during an active call. Therefore, the location of the call establishment marks the begin of the trajectory. Because GSM does not expose an accurate subscriber location an approximation takes place which takes the population density of the area into account. To derive the average subscribers velocity between two consecutive handover, the presented system calculates a most likely handover position. In order to make the generated trajectories accessible to third-party applications such as mobility simulation framework a simple output format has been chosen. The output format persists the trajectory as a list of latitude and longitude coordinates as well as an average velocity that defines the subscribers movement.

7.1 Résumé

This thesis gives an introduction into GSM in order to provide a better understanding of the working principle of the trajectory generation. Besides that, several approaches of other researches in the field of trajectory generation for mobile subscribers are presented. Based on these fundamentals, the trajectory generation pipeline is explained in detail. First, the input data required by the system will be described. This involves the subscriber

information, the road network and the network coverage prediction. Two different types of network coverage prediction techniques are described and compared with each other. Afterwards, each step involved in the generation process is outlined, consisting of the call detection, route computation, route validation, handover estimation and timing annotation.

7.2 Discussion

At this time, the developed system can be used to estimate driving trajectories for mobile subscriber based on the subscriber information. The estimated routes correspond to the route driven by the subscriber. As shown in chapter 6 trajectories can be estimated for subscribers in urban and semi-rural areas. As seen in the example a major drawback of this approach is the unpredictability of the handover points. Both coverage prediction methods have shown that there exist a deviation between the estimated handover point and the observed one. Therefore enhancement would be to use coverage predictions provided by the network operators. This coverage predictions shall better represent the coverage area. Additionally different coverage predictions can be used for different areas. Therefore, the accuracy of the handover position can be increased. This, however, only affects the timing information, the route finding process is not affected. To overcome this deviation we presented an approach which adapts the handover position. This approach eliminates the velocity overrun and produces reliable velocity values that correspond to the actual velocity of the subscriber.

The greatest limitation of that system is that handover events in GSM are only made when the subscriber is in connected mode. With the increase usage of data services on smartphones, a possible extension would be to investigate routing area updates and handover updates in the GPRS, UMTS and LTE network. Right now these events can not be used because they terminate in the radio access network and are not forwarded to the core network where the monitoring units are placed.

Bibliography

Literature

- [1] Ian F. Akyildiz et al. “A new random walk model for PCS networks”. In: *Selected Areas in Communications, IEEE Journal on* 18.7 (2000), pp. 1254–1260 (cit. on p. 16).
- [2] Franz Aurenhammer. “Voronoi Diagrams;a Survey of a Fundamental Geometric Data Structure”. In: *ACM Comput. Surv.* 23.3 (Sept. 1991), pp. 345–405 (cit. on pp. 27, 28).
- [3] Hillel Bar-Gera. “Evaluation of a cellular phone-based system for measurements of traffic speeds and travel times: A case study from Israel”. In: *Transportation Research Part C: Emerging Technologies* 15.6 (2007), pp. 380–391 (cit. on pp. 3, 4).
- [4] Martin J Beckmann. “On the theory of traffic flow in networks”. In: *Traffic Quarterly* 21.1 (1967) (cit. on p. 3).
- [5] M. de Berg. *Computational Geometry: Algorithms and Applications*. Springer, 2000 (cit. on p. 28).
- [6] Christian Bettstetter. “Smooth is Better Than Sharp: A Random Mobility Model for Simulation of Wireless Networks”. In: *Proceedings of the 4th ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems*. MSWIM '01. Rome, Italy: ACM, 2001, pp. 19–27 (cit. on p. 16).
- [7] Christian Bettstetter and Christian Wagner. “The Spatial Node Distribution of the Random Waypoint Mobility Model”. In: *Mobile Ad-Hoc Netzwerke, 1. Deutscher Workshop Åæber Mobile Ad-Hoc Netzwerke WMAN 2002*. GI, 2002, pp. 41–58 (cit. on p. 16).
- [8] S. Buruhanudeen et al. “Mobility models, broadcasting methods and factors contributing towards the efficiency of the MANET routing protocols: Overview”. In: *Telecommunications and Malaysia International Conference on Communications, 2007. ICT-MICC 2007. IEEE International Conference on*. May 2007, pp. 226–230 (cit. on p. 16).

- [9] N Caceres, JP Wideberg, and FG Benitez. “Review of traffic data estimations extracted from cellular networks”. In: *IET Intelligent Transport Systems* 2.3 (2008), pp. 179–192 (cit. on p. 3).
- [10] Tracy Camp, Jeff Boleng, and Vanessa Davies. “A Survey of Mobility Models for Ad Hoc Network Research”. In: *WIRELESS COMMUNICATIONS & MOBILE COMPUTING (WCMC): SPECIAL ISSUE ON MOBILE AD HOC NETWORKING: RESEARCH, TRENDS AND APPLICATIONS* 2 (2002), pp. 483–502 (cit. on p. 17).
- [11] Joerg Eberspaecher, Christian Bettstetter, and Hans-Jhorg Vhogel. *GSM: Switching, Services and Protocols*. 2nd. New York, NY, USA: John Wiley & Sons, Inc., 2001 (cit. on p. 10).
- [12] ETSI Secretariat. *GSM 04.08: European Digital Cellular Telecommunications System (Phase 2); Mobile Radio Interface Layer 3 Specification (GSM 04.08)*. European Telecommunications Standards Institute, 1994 (cit. on pp. 12, 13).
- [13] ETSI Secretariat. *GSM 05.08: European Digital Cellular Telecommunications System (Phase 2); Radio Subsystem Link Control (GSM 05.08)*. European Telecommunications Standards Institute, 1994 (cit. on p. 13).
- [14] A. Fournier and D. Y. Montuno. “Triangulating Simple Polygons and Equivalent Problems”. In: *ACM Trans. Graph.* 3.2 (Apr. 1984), pp. 153–174 (cit. on p. 41).
- [15] F.J. Gallego et al. “Disaggregating population density of the European Union with CORINE land cover”. In: *International Journal of Geographical Information Science* 25.12 (2011), pp. 2051–2069 (cit. on p. 31).
- [16] Francisco Javier Gallego. “A population density grid of the European Union”. In: *Population and Environment* 31.6 (2010), pp. 460–473 (cit. on p. 31).
- [17] GDAL Development Team. *GDAL - Geospatial Data Abstraction Library, Version 1.10.1*. Open Source Geospatial Foundation, 2014. URL: <http://www.gdal.org> (cit. on p. 41).
- [18] A. Ghasemi, A. Abedi, and F. Ghasemi. *Propagation Engineering in Wireless Communications*. Springer, 2011 (cit. on p. 36).
- [19] Kevin E Heanue and Clyde E Pyers. “A comparative evaluation of trip distribution procedures”. In: *Highway Research Record* (1966) (cit. on p. 3).
- [20] IEEE Task P754. *ANSI IEEE 754-1985, Standard for Binary Floating-Point Arithmetic*. Aug. 1985, p. 20 (cit. on p. 20).

- [21] M. Junius. "Leistungsbewertung intelligenter Handover-Verfahren für zellulare Mobilfunksysteme". PhD thesis. 1995, p. 208 (cit. on p. 14).
- [22] J. Laiho, A. Wacker, and T. Novosad. *Radio Network Planning and Optimisation for UMTS*. Wiley, 2006 (cit. on p. 36).
- [23] J.G. Markoulidakis et al. "Mobility modeling in third-generation mobile telecommunications systems". In: *Personal Communications, IEEE* 4.4 (Aug. 1997), pp. 41–56 (cit. on p. 16).
- [24] A.R. Mishra. *Advanced Cellular Network Planning and Optimisation: 2G/2.5G/3G...Evolution to 4G*. IT Pro. Wiley, 2007 (cit. on p. 36).
- [25] Regina Obe and Leo Hsu. *PostGIS in Action*. Greenwich, CT, USA: Manning Publications Co., 2011 (cit. on p. 49).
- [26] Organització Internacional per a la Normalització. *ISO 19125-1: International Standard : Geographic Information, Simple Feature Access : Part 1: Common Architecture*. ISO, 2004 (cit. on p. 51).
- [27] Organització Internacional per a la Normalització. *ISO 19125-2: International Standard : Geographic Information, Simple Feature Access : Part 2: SQL Option*. ISO, 2006 (cit. on p. 51).
- [28] Zhijun Qiu and Peng Cheng. "State of the art and practice: cellular probe technology applied in advanced traveler information system". In: *86th Annual Meeting of the Transportation Research Board, Washington, DC*. 0223. 2007 (cit. on p. 3).
- [29] R.T. Rockafellar and R.J.B. Wets. *Variational Analysis*. U.S. Government Printing Office, 1998 (cit. on p. 43).
- [30] Johannes Schlaich et al. "Generating trajectories from mobile phone data". In: *Proceedings of the 89th Annual Meeting Compendium of Papers, Transportation Research Board of the National Academies*. 2010 (cit. on pp. 4, 5).
- [31] Dieter Schlosser. "OpenCoverageMap Die freie Mobilfunk-Netzabdeckungskarte". MA thesis. Hagenberg, Austria: University of Applied Sciences Upper Austria (cit. on p. 26).
- [32] J. Surowiecki. *The Wisdom of Crowds: Why the Many are Smarter Than the Few and how Collective Wisdom Shapes Business, Economies, Societies, and Nations*. Doubleday, 2004 (cit. on p. 26).
- [33] Tamás Tettamanti, Hunor Demeter, and István Varga. "Route Choice Estimation Based on Cellular Signaling Data". In: *Acta Polytechnica Hungarica* 9.4 (2012), pp. 207–220 (cit. on pp. 5–7, 27).
- [34] Tamás Tettamanti and István Varga. In: *Periodica Polytechnica Civil Engineering* 54.1 (2010), p. 3 (cit. on p. 43).

- [35] Godfried T Toussaint. “A New Linear Algorithm for Triangulating Monotone Polygons”. In: *Pattern Recogn. Lett.* 2.3 (Mar. 1984), pp. 155–158 (cit. on p. 41).
- [36] Danilo Valerio. *Road Traffic Monitoring from Cellular Network Signaling*. Tech. rep. Vienna Austria: FTW Forschungszentrum Telekommunikation Wien GmbH, Mar. 2009, p. 48 (cit. on p. 7).
- [37] Danilo Valerio et al. “Exploiting cellular networks for road traffic estimation: a survey and a research roadmap”. In: *IEEE 69th Vehicular Technology Conference (VTC), Spring 2009*. IEEE. 2009, pp. 1–5 (cit. on pp. 7, 8).
- [38] Danilo Valerio et al. “Road traffic estimation from cellular network monitoring: a hands-on investigation”. In: *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2009*. IEEE. 2009, pp. 3035–3039 (cit. on pp. 7, 8).
- [39] AlanM. Voorhees. “A general theory of traffic movement”. English. In: *Transportation* 40.6 (2013), pp. 1105–1116 (cit. on p. 3).
- [40] B. Walke. *Mobilfunknetze und ihre Protokolle 1*. Mobilfunknetze und ihre Protokolle. Teubner, 2001 (cit. on p. 10).
- [41] YB Yim and Randall Cayford. “Investigation of vehicles as probes using global positioning system and cellular phone tracking: field operational test”. In: (2001) (cit. on p. 3).
- [42] J. Zhang and G. de la Roche. *Femtocells: Technologies and Deployment*. Wiley, 2011 (cit. on p. 16).
- [43] Biao Zhou, Kaixin Xu, and M. Gerla. “Group and swarm mobility models for ad hoc network scenarios using virtual tracks”. In: *Military Communications Conference, 2004. MILCOM 2004. 2004 IEEE*. Vol. 1. Oct. 2004, 289–294 Vol. 1 (cit. on p. 17).