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Distributed
Computing

DAB+ Positioning

Semester Thesis

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Abstract

Vulnerability of GNSS ranging signals in harsh environments where localisation is a desired application has motivated research towards alternative signals sources. Well standardized and globally available Digital Audio Broadcasting network provides a potential signal structure for positioning. This work implements and evaluates localisation performance of a prototype receiver based on signal time difference of arrival.

Contents

CHAPTER 1

Introduction

1.1 Motivation

The potential in signals not originally intended for navigation is often called as a signal of opportunity. This term appears often in conjunction with topics of jamming resilience in navigation and improved availability of ranging signals especially in urban environments. This project aims to demonstrate a complete positioning receiver based on commercially available and affordable software defined radio system and openly available signal processing tools.

1.2 Related work

Signal processing techniques for positioning with DAB+ relate closely to the techniques used in other OFDM based broadcast signal sources. Hence, this project is influenced by the results and experiences made available in previous LTE and DVB-T positioning projects.

1.2.1 GNSS positioning

At the time of conducting this project, GNSS based positioning serves as the primary globally available technology for localization. Due to investments in existing and new satellite constellations, including new signal bands, GNSS offers superior availability to any other existing technology for outdoor localization.

However, the inherent weaknesses of GNSS ranging signals in deep urban, indoor and interference rich environments opens opportunities for local terrestrial broadcast signals with ranging capabilities.

1.2.2 Alternative terrestrial ranging signals

Terrestrial broadcasting networks have been studied as a signal source of opportunity to support localisation in the above mentioned harsh signal environments.

In [1], DVB-T is used as the signal source for ranging. The single frequency network structure with synchronized transmitters shows similarities to DAB+ network structure. Chen et al. demonstrate the performance of a complete signal processing chain including coarse signal synchronization, multipath acquisition based on Matching Pursuit algorithm and detection on first arrival path.

A second example of positioning in terrestrial network is shown by Knutti et al. in [2]. Their work implements channel estimation methods similar to what is used in this work in order to improve TOA measurement resolution and calculation of multipath delays.

Chapter 2

Background

The updated version of Digital Audio Broadcasting [3] is a candidate terrestrial broadcasting technology for positioning in urban environments due to its standardized transmitter technology, affordable receiver hardware and wide coverage in European countries.

2.1 DAB+ transmission

The Digital Audio Broadcasting Plus (DAB+ hereafter) standard was designed in Europe to deliver high-quality audio in Single Frequency Networks (SFN) in the Very High Frequency (VHF) band. The present standard for DAB+ is ETSI EN 300 410 V.2.1.1 dated to January 2017. The following sections introduce the signal structure essentials of DAB+ with respect to the localisation application.

2.1.1 General signal structure

Information sent through DAB+ is spread over frequency and time domain to support the elimination of channel distortions and fading at signal reception, even when working in conditions of severe multi-path propagation.

According to the early DAB standard four distinct transmission modes were available. Three out of four were targeted to Earth-to-Satellite communication or vice versa. However, in the latest DAB+ standard [3] those three modes were removed leaving the mode one as the current mode to which the rest of this documents refers. A major part of the signal description, such as data modulation, is left out from this document due to minor relevance or applicability to time of arrival estimation. In temporal domain DAB+ signal is split into frames each 96 ms long in duration. A single frame consists of 96 consecutive Orthogonal Frequency Division Multiplex (OFDM) symbols being 1 ms long in time. The standard defines a system clock frequency of 2.048 MHz which determines the elementary sample period T in time domain. Throughout this document the unit T refers to 1/2.048 MHz.

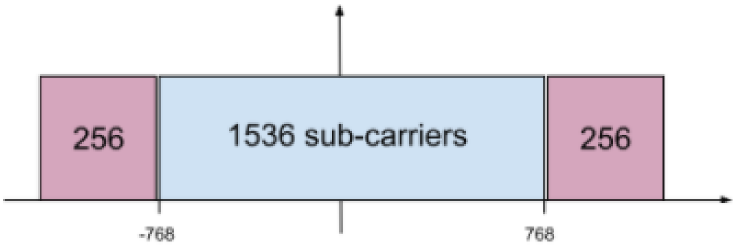

Figure 2.1: DAB+ OFDM symbol.

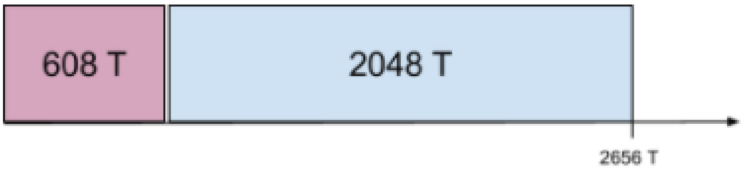

Figure 2.2: Null symbol.

Furthermore the sub-carrier spacing in time units equals 2048 T satisfying the orthogonality requirement. Out of the 2048 sub-carriers only 1536 sub-carries are used leaving the outermost 512 sub-carries idle, as depicted in Figure 2.1. In addition, the center sub-carrier (0 Hz) is suppressed.

2.1.2 Transmission frames

DAB+ frames are structured into three non-equally long sequences called channels: synchronization channel, fast information channel and main service channel. The first channel contains a Null symbol and a Phase Reference symbol, which are discussed later in this chapter as they have a role in signal time-of-arrival estimation. The last channel carries the payload of the main application: audio stream. The following table shows the key parameters which are crucial for a correct receiver implementation for a positioning application.

T_{Null}	T_{PRS}	T_{Frame}
2656 T	2552 T	196608 T

Table 2.1: Parameters of transmission mode I

Each OFDM symbol, excluding the Null symbol, uses a prefix called guard interval to eliminate inter symbol interference. The guard interval shall be removed during baseband signal processing to prevent any noisy samples distorting further processing. Each guard interval is 504 T long.

2.1.3 Signal synchronization

The DAB+ synchronization channel has multiple functions from which the coarse and fine signal synchronization are the most important in ranging. As mentioned earlier each DAB+ frame starts with a Null symbol which can be used to locate the starting sample of a frame.

Two signal formats for Null symbol exist. The first format disables all the 1536 sub-carriers which means that no signal power is transmitted over the Null symbol. The second format embeds a transmitter identification information which is realized by so called sub-carrier "combs", while maintaining sufficient signal properties for coarse signal synchronization. The two Null symbol formats take turns. A method of a sliding search window can be applied across the received samples to find the sample where the signal energy is minimized. In other words, this is called the coarse frame synchronization.

During the second synchronization stage the Phase Reference symbol (PRS) is used to find a finer start sample within a PRS. Prior to that step, a possible frequency offset between the transmitter and receiver needs to be corrected to ensure better accuracy in signal cross-correlation between the local PRS replica and the received PRS.

2.2 Transmitter network

Switzerland is one of the few countries in Europe with a publicly communicated commitment to replace the existing FM broadcasting network with DAB+ infrastructure. Potentially due to that the DAB+ network coverage in Switzerland is extensive.

This projects utilizes the closest transmitters to city of Zürich. Three organizations Digris AG, Schweizerische Radio- und Fernsehgesellschaft (SRG) and Swiss Media Cast operate those transmitters in channels 7A, 7D and 9D. The three channels can be received simultaneously in 20 MHz wide frequency band.

2.2.1 Transmitter identification

According to the DAB+ standard each transmitter can utilize the Null symbol to transmit its main and sub-identifier encoded in a pattern of enabled and disabled sub-carriers. In other words, the usage of Null symbol for TII resembles frequency division multiplexing. The primary use-case of the transmitter identification information (TII) is to enable a monitoring receiver to distinguish different transmitters. The implementation is optional in the current standard. Such a property can be useful for a positioning receiver to improve signal tracking while the receiver could decode the received TIIs.

A comprehensive, but not complete, list of TII codes used in Switzerland are found on a community held online source [4].

Chapter 3

System Description

3.1 Signal reception

In order to receive at least three distinct transmissions in the city of Zürich, where this work was conducted, a wideband signal reception is required to capture simultaneously multiple DAB+ channels. As an alternative approach, channel hopping was considered as an option if sufficient bandwidth was not available in the software defined radio system (SDR).

3.1.1 Passband signal

The open source signal processing toolkit GNU Radio [5] was chosen for this work. GNU Radio offers the necessary software tools for passband signal capturing and post-processing including drivers to interface USRP B200 SDR. The toolkit is licensed under the GNU General Public License.

Wideband signal capture was done with a sampling frequency of 24.576 MHz, which is sufficient for the DAB+ channels of interest 7A, 7D and 9D without data loss due to bottlenecks is communication interfaces between the SDR and standard PC hardware. The output I/Q sample stream was saved into RAM due to the high data rate.

Offline signal processing functions of GNU Radio were used to conduct the narrow band channelization to produce the desired channels in separate baseband sample files. The channelization involved anti-aliasing filtering and downsampling to compress the output data size.

3.1.2 Baseband signal

Sdrdab [6] was selected as the baseband processing library for Matlab among the few openly available DAB+ signal processing libraries. Initially the library was created at ZHAW (Winterthur, 2011) and later extended by AGH (Krakow, 2015). Sdrdab is originally intended for DAB+ single channel processing and audio decoding together with RTL2832U software defined radio. Thanks to Sdrdab multiple parameters from the DAB+ standard were made available in their Matlab code, such as the PRS replica, frame and symbol lengths and quantity of sub-carriers.

In order to use Sdrdab in multi channel processing a wrapper functionality was implemented to enable synchronous processing of multiple I/Q streams. The wrapper function uses a sequential approach where data per channel is processed at once while time-of-arrival information is saved for later processing stages.

3.2 Channel processing

The first task of the channel processing is to find a coarse synchronization to a frame start. After a successful synchronization the estimated start sample is used to locate a complete Null symbol for optional TII decoding. This functionality is provided by Sdrdab. Later, a Phase Reference symbol is used for coarse frequency and fine time synchronization, both provided by Sdrdab. Eventually, the resolution of fine time synchronization is improved by the implementation of this work utilizing channel order and delay estimation.

The PRS is composed of 1536 sub-carriers with equal transmission power and a particular phase difference scheme. In other words, the PRS makes use of Constant Amplitude Zero Auto-Correlation code where out-of-phase periodic auto-correlations equal to zero. Finally, the PRS is again used to estimate channel order and delay profile to reveal the first path of arrival, which is crucial for correct TOA estimation in multipath rich reception.

3.2.1 TDOA observation

In this work the time difference of arrival was selected as the format of measured observations, similar to [7]. In order to calculate a three dimensional position a minimum of four transmissions from four transmitters are required in signal reception. Due to the present DAB+ coverage in the city of Zürich, three broadcasters from three locations are available: Zürichberg (Zb), Uetliberg (Ue) and Felsenegg (Fe). Such a broadcaster constellation is sufficient for two dimensional (horizontal) localisation.

3.2.2 Channel order estimation

Channel estimation, in general, consists of channel order and delay path estimations. In communication applications the precise channel estimation improves data reception. Likewise, correct channel estimation helps to determine the first path of arrival improving accuracy in TOA estimation and thus increasing positioning accuracy.

This work implements a Minimum Description Length (MDL) algorithm for channel order estimation, as originally applied in [8]. The function of MDL is to determine the dimension of signal sub-space from sample co-variance matrix. In other words, MDL tries to estimate the number of signal sources (e.g. number of propagation paths) from noisy signal. The advantage of MDL emerges from its "blind" applicability where no prior information is required such as parametric thresholds.

Further on, a modification to the original MDL is implemented, according to [9], to improve robustness of the channel order estimation. The core idea of the improvement is to apply averaging over the received samples of four consecutive Phase Reference symbols. Eventually, the resulting channel order estimate is used in the channel delay estimation of those four PRS.

3.2.3 Path delay estimation

Path delay estimation is the last and the most influential part of the time of arrival estimation. To enable higher detection resolution in TOA compared to the conventional signal cross correlation, an algorithm named ESPRIT (Estimation of Signal Parameters via Rotational Invariance Technique) was selected and implemented according to the modifications in Vinay et al.. ESPRIT, as introduced in its original form in [10], is one of the few well documented super resolution algorithms for TOA estimation. Compared to the other two investigated algorithms MUSIC [10] and Matching Pursuit [1], ESPRIT is less complex to implement as it eliminates the usage of any search procedure. The principal idea behind ESPRIT is to measure the phase rotation between OFDM sub-carriers. Eventually, the phase rotation can be translated into path delay measured in fractional sample time.

In this work ESPRIT uses the output of the preceding channel order estimation to improve signal and noise sub-space separation in each least squared estimated channel matrix.

3.2.4 Transmitter acquisition

By definition, in Single Frequency Networks (SFN), multiple transmitters are allowed to transmit on the same channel. In preparation for determining first arrival paths in composite signals, all TOA observations shall be grouped and labeled.

In semi-urban or rural areas it is assumed that line-of-sight signals are well detectable from any reflected signal copies in cross-correlation. The implementation of the transmitter acquisition is based on k-means clustering where the total number of clusters is estimated by the number of observed peaks from the cross-correlation shape. As an outcome each measured TOA is labeled by its assumed origin.

3.2.5 First arrival path

Correct detection of first arrival path dictates the final localisation performance. The functionality of this receiver sub-block is as simple as selecting the earliest path delay in each TOA cluster.

The implementation relies on correct selection of TOA clusters. The selection is manually done for each static location. However, it has obvious drawbacks in mobile scenarios where the signal arrival order can change depending on the location of a receiver.

3.3 Position estimation

Typically, the ultimate output of a position receiver is location, time and velocity information. In this work the output of the positioning receiver is considered as a two dimensional location expressed in Cartesian Earth-Centered-Earth-Fixed coordinate system. The implemented receiver is configured to produce one outcome from a fixed quantity of DAB+ transmission frames.

3.3.1 Snapshot receiver

Conceptually a snapshot receiver captures a digitized signal and saves it as a data file for later processing. The duration of the signal dwell time can be chosen arbitrarily long but shall contain enough data samples to allow at least one range measurement. The snapshot concept is especially useful when data cannot be collected in a continuous manner. Hence, the snapshot receiver architecture serves the objective of implementing a prototype receiver on top of DAB+ reception.

3.3.2 Navigation period

The navigation period is defined so that after every four PRS the receiver outputs one position estimate, in other words the location coordinates. This corresponds approximately to one position estimate (epoch) per second, which translates into the navigation rate of 1 Hz.

Each navigation epoch uses measurements only from the four preceding PRS. Hence, every epoch is independent of their successors. This output concept supports the idea of the snapshot receiver.

By increasing the time of the navigation period, one could potentially improve the channel estimation accuracy by introducing more averaging. This, as a trade-off, would make the receiver less useful for localization in mobile scenarios.

3.3.3 Location calculation

As mentioned in 3.2.1 the location calculation relies on TDOA observations which are constructed from TOA adjusted by measured transmitter time offsets.

To calculate a position the following observation pair is constructed

$$TDOA_{2,1} = \left| TOA_2 - TOA_1 \right| \tag{3.1}$$

$$TDOA_{3,1} = \left| TOA_3 - TOA_1 \right|, \tag{3.2}$$

together with the following range equations using the known locations of each involved transmitter

$$R_{21} = \sqrt{(R_x - T_{2,x})^2 + (R_y - T_{2,y})^2 - (R_x - T_{1,x})^2 + (R_y - T_{1,y})^2} \tag{3.3}$$

$$R_{31} = \sqrt{(R_x - T_{3,x})^2 + (R_y - T_{3,y})^2 - (R_x - T_{3,x})^2 + (R_y - T_{3,y})^2}\ . \tag{3.4}$$

As the last processing step an iterative least squares is applied to the objective equations to estimate the receiver coordinates R_x and R_y:

$$f_1 = R_{2,1} - TDOA_{2,1} \tag{3.5}$$

$$f_2 = R_{3,1} - TDOA_{3,1}\ . \tag{3.6}$$

Chapter 4

Results and Evaluation

4.1 Test configuration

Tests for the receiver were carried out in a few locations in the city of Zürich and in the west part of the lake Zürich in Kilchberg. These locations were picked according to their assumed difficulty in signal reception while ensuring transmissions from all the three transmitters Uetliberg, Zürichberg and Felsenegg are well receivable.

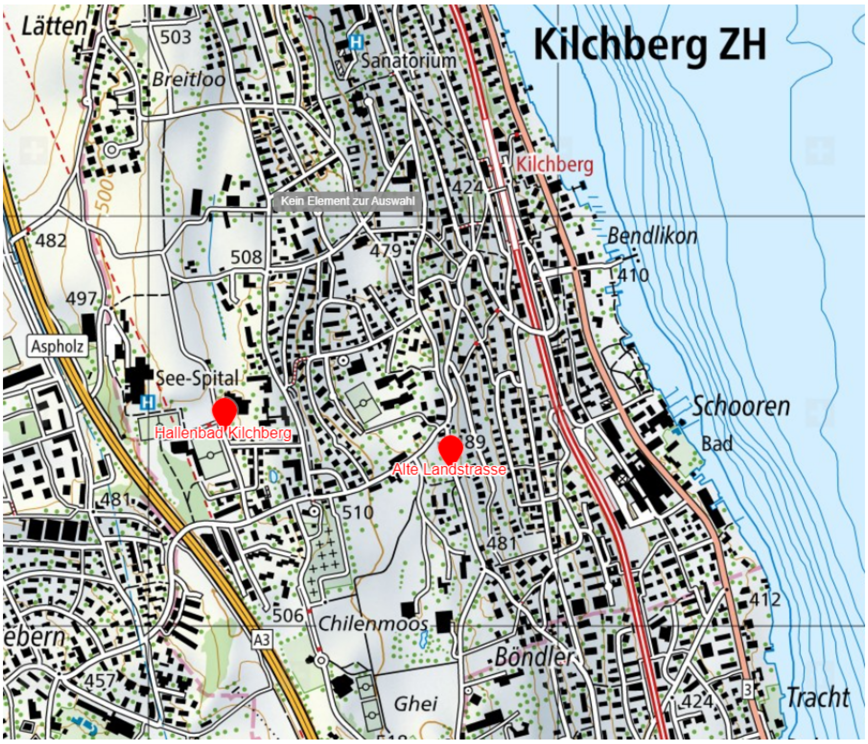

Figure 4.1: Test locations in Kilchberg

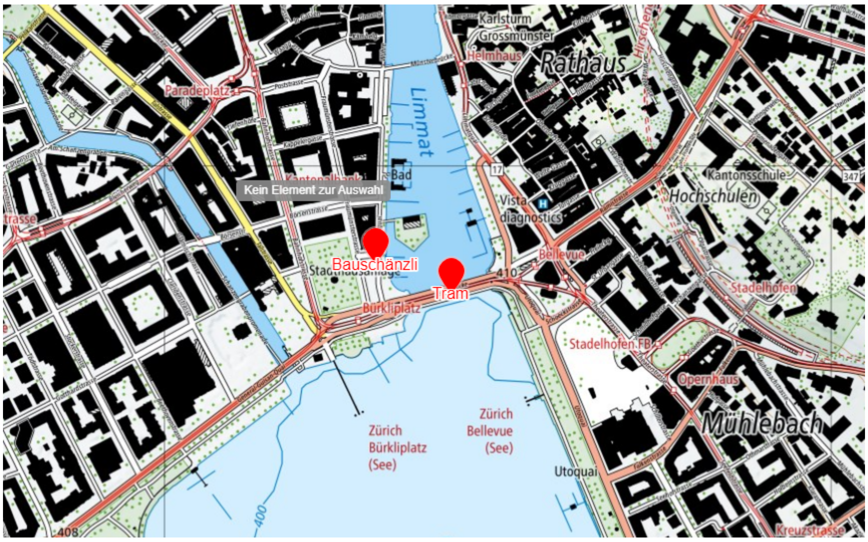

Figure 4.2: Test locations at Bürkliplatz, Zürich

The signal capture was conducted in a duty cycled sequence of ten seconds of recording and three minutes of inactivity. With such an arrangement the data size stays manageable (∼10GB) while the total time can be increased.

4.1.1 Transmitter offset deviation

DAB+ transmitters are assumed to be synchronized in order to allow operation in SFN. A sub microsecond deviation in transmission offsets between synchronized transmitters could be detrimental for a positioning calculation causing a error of several several hundred meters. Therefore, a longer term recording was set to monitor any deviation of TDOA.

The time series in Figure 4.3 and Figure 4.4 represent static TDOA observations. The time series were created in order to observe potential deviation between the transmissions of Uetliberg 7A, Uetliberg 7D and Zürichberg 9D. In this test the TDOAs are calculated by cross-correlating the received PRS with the local PRS replica. Due to this, the results are not used later to calculate transmission offset times which are needed in positioning. The deviation results show no obvious time drift distinguishable from possible error sources in reception, between the transmitters of Uetliberg and Felsenegg. Given the result, it is assumed that TOA measurements from Zürichberg do not deviate with respect to the transmission from Uetliberg and Felsenegg.

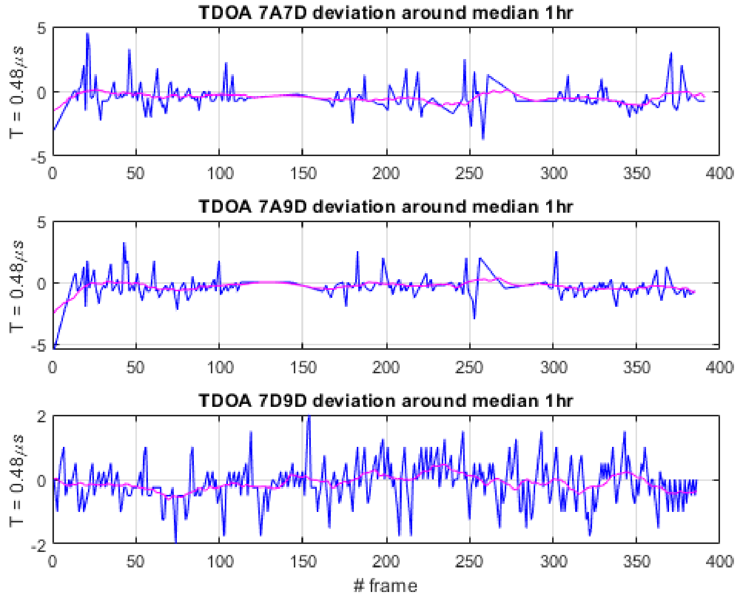

Figure 4.3: Time series of TDOA during one hour between Uetliberg and Felsenegg transmitters.

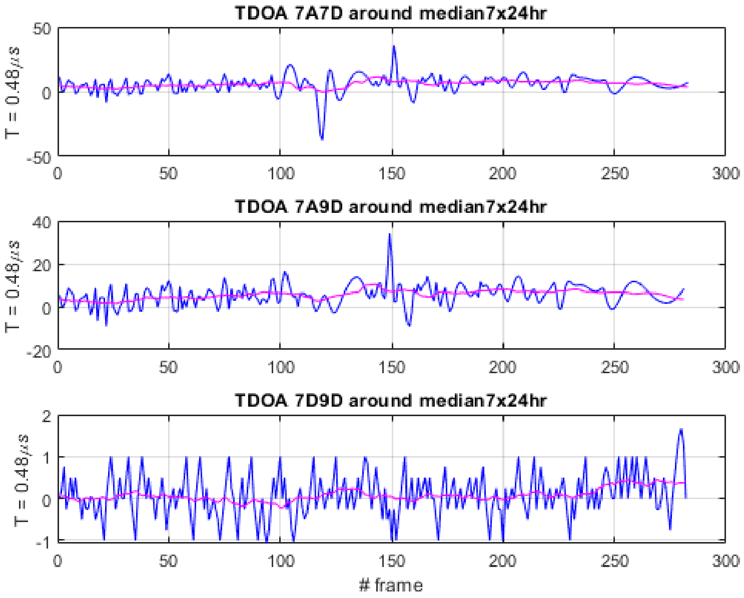

Figure 4.4: Time series of TDOA during one week between Uetliberg and Felsenegg transmitters.

4.1.2 Reference offset and true location

An outdoor location with line of sight connection to all the three transmitters (Zb, Ue, Fe) is used to ensure the best possible reception for offset measurements. The measurements consist a sufficient quantity of PRS samples to average out noise. In this work the reference measurements are 30 minutes long with ten seconds duty cycles.

Calculation of reference TDOA involves the knowledge of a true location of the receiver antenna with respect to the transmitters. A graphical online tool offered by geo.admin.ch [11] provides a simple method to measure distance between two coordinate points on a 2D map. In addition, the map provides the coordinates of each DAB+ transmitter in Switzerland.

4.2 Horizontal accuracy

This section shows the accuracy performance of the receiver. Three out of four tests are static, which means that the receiver antenna stays in the same location. One test is conducted in a moving tram crossing Quaibücke in the city of Zürich. Position accuracy is represented in North-East format (ECEF coordinate system) and in horizontal error distribution.

The highest position accuracy is achieved at the test location next to Hallenbad Kilchberg. The median horizontal error is less than 480 meters, as shown in Figure 4.12, which is approximately four sample time units. This test location is almost optimal for reception of line of sight signals from Ueltiberg and Felsenegg while the transmitter of Zürichberg is slightly shadowed by the near buildings.

The second test location is a half a kilometer from Hallenbad Kilchberg to the direction of Lake Zürich. In contrast to the first test location this location provides a line of sight propagation path to the Zürichberg transmitter. Also, the signal from Felsenegg is not shadowed by any obstacles. The signal from Uetliberg transmitter is partially attenuated by the nearby buildings. At this test location the median position error of 825 meters is achieved.

The third test location depicted in Figure 4.2 is assumed to be the most difficult one in terms of multipath reception. At this location one static and one mobile test recording were made. The static location is just a few tens of meters from nearby buildings which shadow the Uetliberg transmitter. The propagation paths from Zürichberg and Felsenegg remain line of sight. Both of the tests, the static and mobile one, show very large position error. However, the direction of error seems very similar as depicted in Figure 4.9 and 4.10. The recordings were made on different dates having two weeks between them.

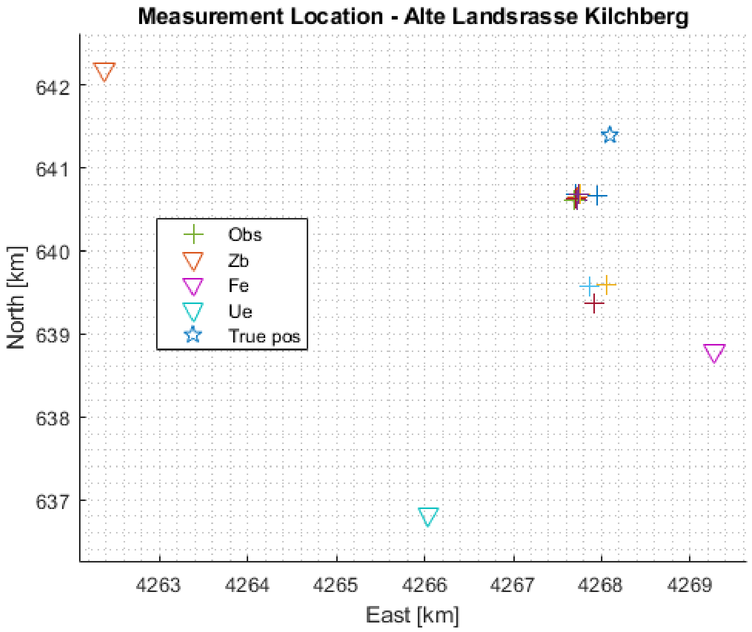

Figure 4.5: Calculated positions w.r.t true position and locations of DAB+ transmitters on Alte Landstrasse Kilchberg.

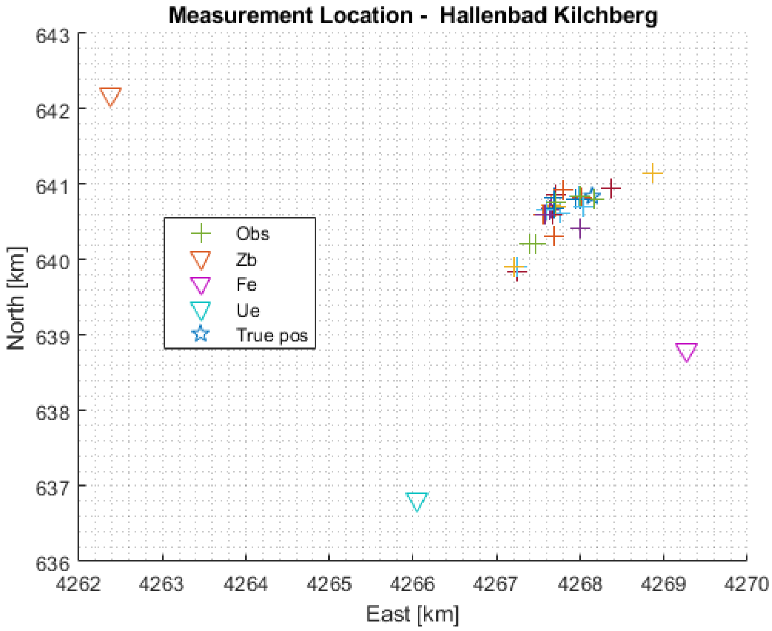

Figure 4.6: Calculated positions w.r.t true position and locations of DAB+ transmitters in the test location next to Hallenbad Kilchberg.

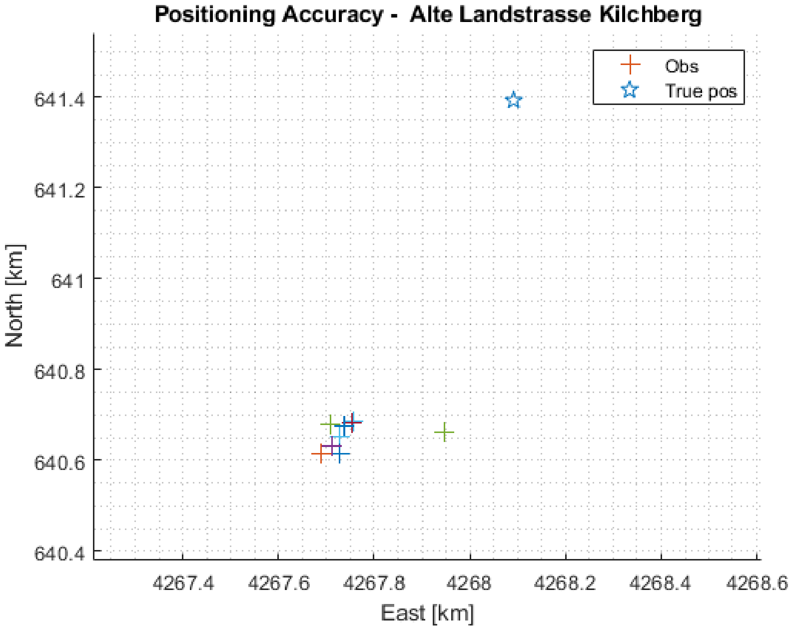

Figure 4.7: Deviation of calculated positions on Alte Landstrasse Kilchberg.

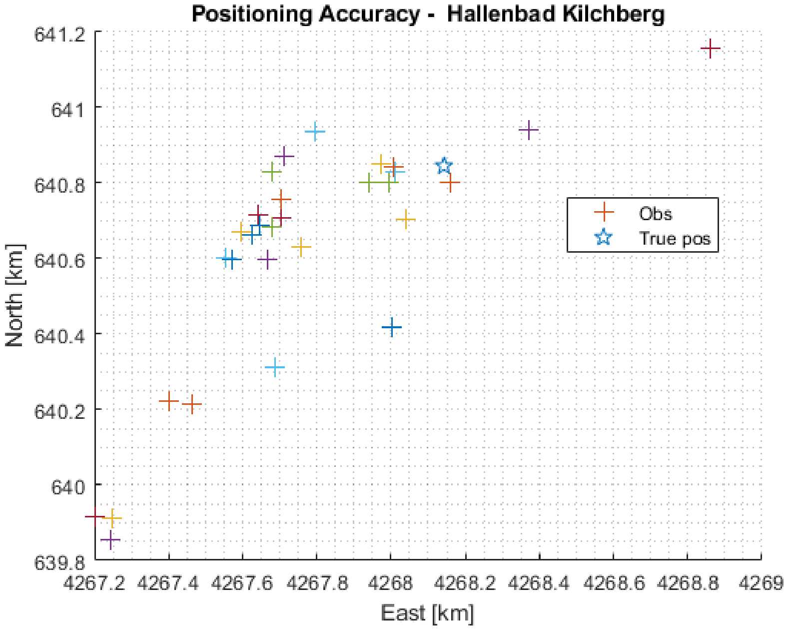

Figure 4.8: Deviation of calculated positions in the test location next to Hallenbad Kilchberg.

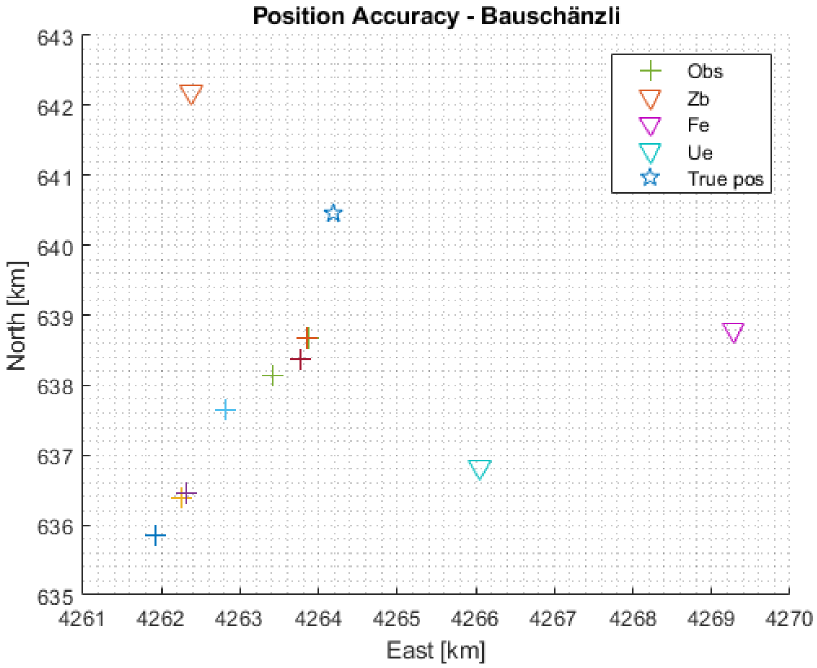

Figure 4.9: Deviation of calculated positions at Bauschänzli Zürich.

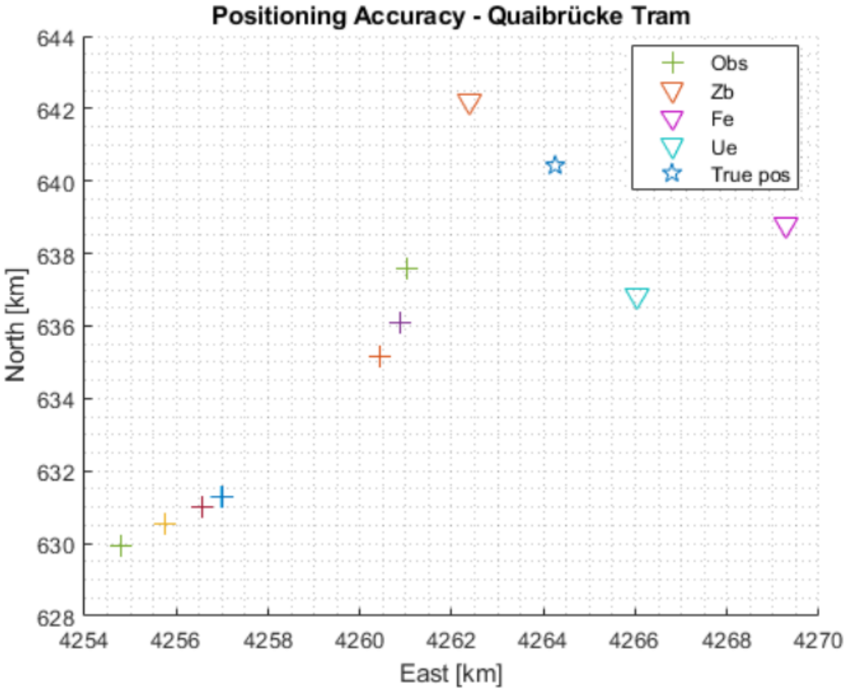

Figure 4.10: Deviation of calculated positions at Quaibücke Zürich.

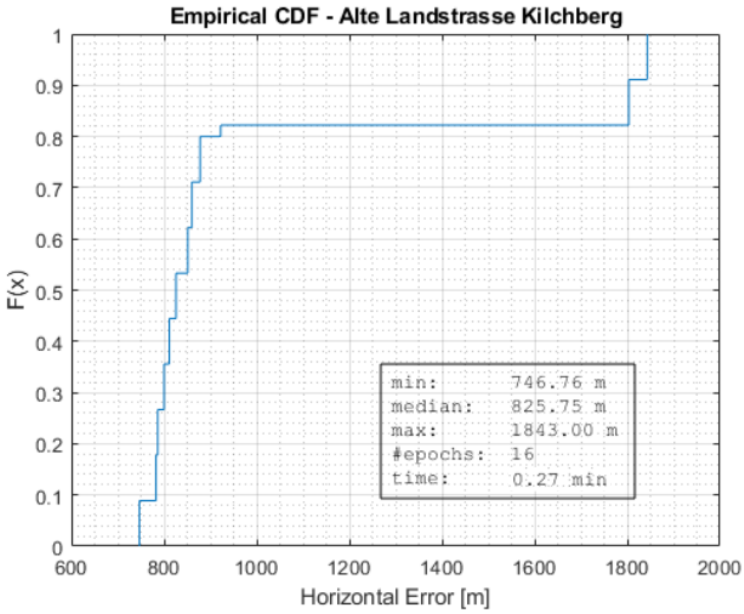

Figure 4.11: Position error distribution on Alte Landstrasse Kilchberg.

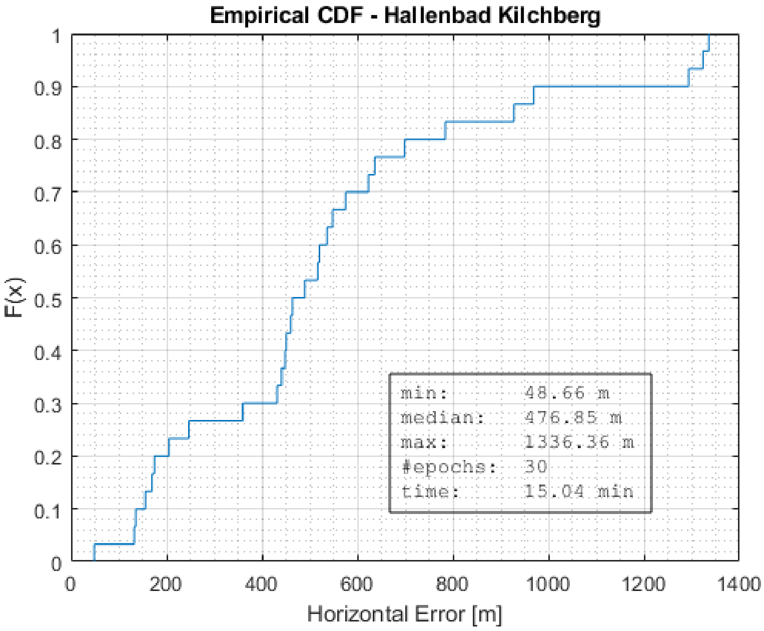

Figure 4.12: Position error distribution in the test location next to Hallenbad Kilchberg.

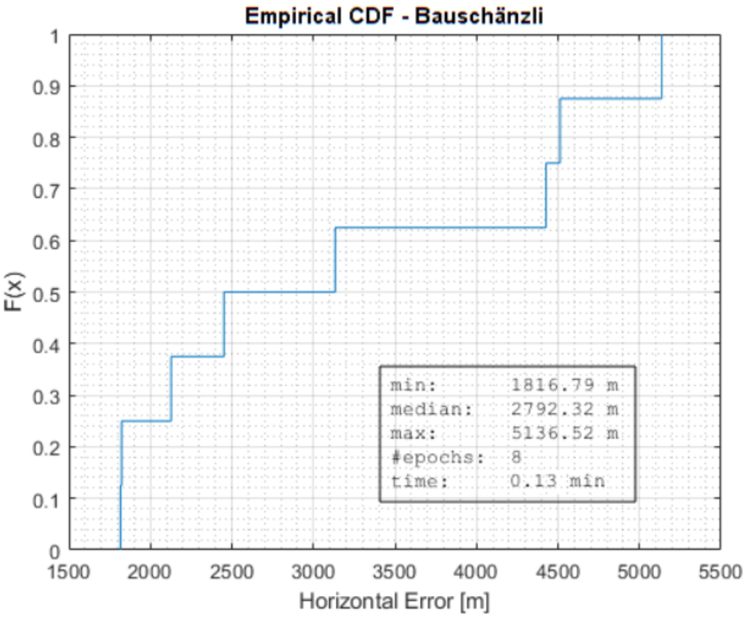

Figure 4.13: Position error distribution at Bauschänzli Zürich.

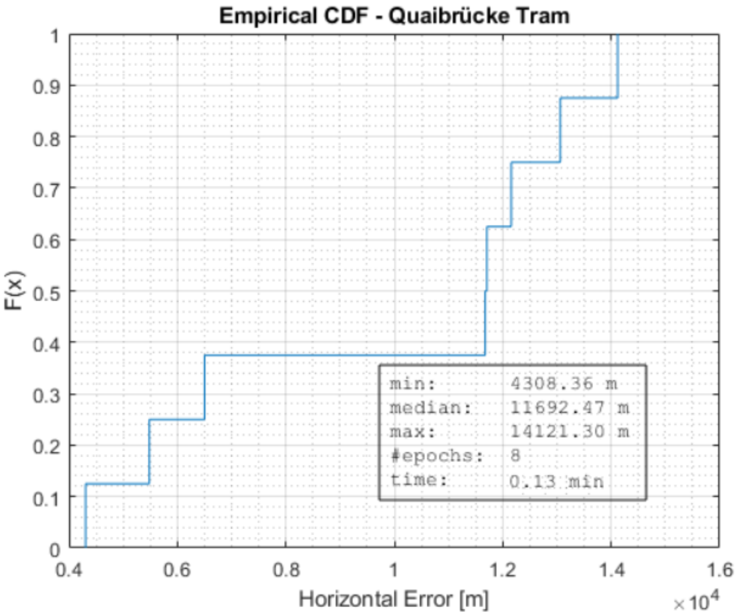

Figure 4.14: Position error distribution on Quaibücke measured in a tram.

Chapter 5

Conclusion

The objective of this work was to implement an offline based positioning receiver utilizing DAB+ signals only. In addition to the signal processing implementation, a part of the work included enabling signal capturing of the current DAB+ channel configuration in region Zürich.

As shown in [7], TOA determination based solely on the cross-correlation properties of PRS can achieve a minimum horizontal position resolution of approximately 150 meters which corresponds to one DAB+ sample period.

Channel estimation provides a potential method to further improve the above mentioned position resolution. Major part of this work focused on finding a suitable method to bring the TOA estimation down to decimeter level. As shown in Section 4.2, only one of the static test locations indicated such potential. However, in the same test location the median accuracy performance is reported as 476.85 m, which is close to the expectations originally indicated in [7].

Despite the potential of the current channel estimation techniques ESPRIT and MDL, further testing is necessary in easy and difficult reception environments to find the weaknesses of both techniques, as pointed out by the measurements in the city of Zürich. A straight forward averaging is implemented to improve robustness which may not work anymore in mobile scenarios where channel properties vary faster.

In addition, the positioning evaluation relies on a correct transmitter offset determination. Optimally, a methodologically independent TDOA monitoring together with a very long term measurement could be established to calculate as accurate offsets as possible.

Chapter 6

Future work

The potential future work relates to the improvements of signal tracking which is a fundamental part of a working positioning receiver.

A clear improvement to the existing receiver implementation would be an advanced signal tracking which distinguishes first arrival paths of several transmitters from possible multipath signals. The improvement would allow substantially faster testing and evaluation without the need of semi-manual tracking configurations. In addition, that update would enable acquisition of several transmissions in a single DAB+ channel. Test locations where multipath signals fold on top of line-of-sight signals create a challenge for the advanced signal tracking.

The transmitter identification information signal could be a source of information to narrow down the search space for transmitter acquisition. A robust method to decode multiple TII codes in a Null symbol would most probably benefit from the phase information of enabled sub-carriers. A quick review on online resources did not reveal such TII decoders so far. However, the findings during this project indicate that the phase assignment in Null symbol may not be according to the DAB+ standard. Therefore, any improvements on this would involve further signal recordings outside Zürich to confirm the observation.

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