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Time-of-Flight WLAN Indoor Tracking System

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Abstract

In this thesis we implemented a localization system based an a time-of-flight (ToF) approach. We improved on a existing WiFi-Echo technique and implemented this on several access points. Furthermore we developed a system which coordinates the distance measuring and produces them automatically. Finally we implemented and investigated different algorithms for estimating the position using multilateration. Our results show that, we can achieve a median positioning error 5.5 meters and a 75-percentile error under 8 meters. Which is comparable to other existing system based on the signal strength of WiFi-Signals [5]. To the best of our knowledge, this work is the first to show that ToF localization with WiFi-Signals using off-the-shelf hardware can provide competing results to an RSSI based approach. The advantage of our system is, that we don't require environment fingerprinting and the scheme is robust to interference.

Acknowledgment

First of all I want to thank Prof. Dr. Plattner, my supervisor, for giving me the opportunity to carry out this project and for his support. Further I want to thank my two tutors, Dr. Giustiniano and Dr. Lenders, for the great support and guidance during the course of the thesis. I also want to thank Maurizio Rea, another master student, for the countless valuable discussions and insights.

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Chapter 1

Introduction

Knowing the location of the user opens a lot of possibilities for useful applications. The first thing that comes in to mind is navigation. But the options are limitless. One can think of applications for security, entertainment, and much more.
For outdoor localization there exists a go-to solution: GPS. It is accurate, cheap and always available. For this reasons it is widely used in smart phones, navigation devices, cameras and much more. But indoors often we have no connection to the satellites and therefore no accurate location. For this reason indoor localization is hot a topic in todays research and in the industry. There exists solutions which can provide a very high accuracy but there are based on special-purpose devices, e.g solutions based on ultra wide band (UWB), or solutions that require extensive calibration or fingerprinting of the environment.

1.1 Motivation

There exists no low-cost and accurate indoor localization system. This is where we want to step in and provide such a solution. We want to use off-the-shelf devices to keep the costs low. Furthermore we want to be able to track all 802.11 certified devices.
Most currently existing systems with a similar goal and also based on 802.11 devices use the signal strength of the received signals to determine the distance. The signal strength is affected by the properties of the channel and the environment. Especially multi-path, fading and interference is a problem for this approach.
In order to remove some of this influences we decided to use another method for the distance estimation. We used a time-of-flight approach, which, like GPS, measures the time the signal travels from one device to another and uses this information to determine the distance.
Further we reduced the influence of outliers in the distance estimation on the estimated position of the target.

1.2 Related Work

Localization can be done based on different point-to-point distance estimation (ranging) techniques. The most commonly used are [6]:

- **RSSI** (Received Signal Strength Indicator) is a metric for the received strength of the signal, which can be used for determining the distance. The stronger the signal is, the shorter the distance. RSSI is available in most RF receivers.

- **ToF** (Time of Flight), also called ToA (Time of Arrival), uses the travel time of a RF signal to determine the distance between receiver and transmitter. Since RF Signals travel at speed of light, we can calculate the distance.

- **TDoA** (Time Difference of Arrival) is similar to ToF. The difference is, that it uses one transmitter and multiple receivers of the same signal. With the difference in the arrival time of the signal at the receiver one can calculate the position of the transmitter.

Ranging techniques → Wireless technology ↓	RSSI	ToF	TDoA	DTDoA	AoA	Proximity
Ultrasonic	x	✓	✓	x	✓	Obstacle Avoidance
Infared	x	x	x	x	x	✓
Bluetooth (IEE 802.15.1)	✓	x	x	✓	x	✓
RFID	✓	✓	✓	x	✓	✓
WiFi (IEE 802.11)	✓	✓	✓	✓	✓	✓
IEEE 802.15.4a DSSS	✓	✓	x	x	✓	✓
IEEE 802.15.4a UWB	✓	✓	✓	x	✓	x
IEEE 802.15.4a CSS	x	✓	x	x	x	x
60 GHz	x	x	x	✓	x	x

Table 1.1: Wireless technologies for indoor localization versus ranging techniques [6]

- **AoA** (Angle of Arrival) uses special antennas, such as antenna arrays, to determine the angel of arrival of the receiving signal.
- **DTDoA**(Differential Time Difference of Arrival) DTDoA (Differential Time Differences of Arrival) uses the difference of TDoA measurements. In order to overcome the synchronization between transmitter and receivers, an additional anchor is introduced. This anchor transmits a special message to start the TDoA measurement. With this approach one can calculate the time offsets of the anchors [7].
- **Proximity** operates with low power signals. If one of these signals is received, the transmitter must be close.
- **Hybrid** techniques use a combination of these techniques.

In table 1.1 we show for which ranging techniques and wireless technologies range-based localization systems exist. Our system is based on WiFi and uses ToF.
This thesis is based on a previous semester project at the ETH [2]. In this work the basis of the distance estimation and the data generation is developed. We improved the ranging method, uses a different scheme for the data retrieval. This work was focused on distance estimation and did no localization. The WiFi-Echo technique used in this work and in our thesis is first developed in a project carried out at the University of Palermo [1]. They also did localization with similar precision as we achieve. The difference in our work is, that we introduce a system for localization. Another Master Thesis on the same project was produced at the same time [3]. The focus of this thesis was more on the ranging method, while we focused on the system.

1.3 Overview

In chapter 2 we describe the problem we solve in more details and highlight the challenges we faced. In chapter 3, we give an overview of the system we implemented. We describe the used hardware and software and the used mechanisms and algorithms. In chapter 4 we show the environment, in which we operate the localization system. Results are given in the chapter 5, a conclusions are made in chapter 6 and finally an outlook is presented in chapter 7.

Chapter 2

Localization

In order to successfully determine the position of a target one has to address several problems. In this chapter we want the present these problems and high-lite the challenges we faced. Figure 2 shows a simple testbed, which can be used for localization. Here we have several so called anchors. Anchors are fixed at a know position and determine the distance to the targets. The data is then transfered via some backbone network to the a server, which calculates the position of the targets using multilateration.

2.1 Distance Estimation

The basis of doing localization is estimating the distance. As we mentioned before we used a time-of-flight approach. So the first thing to have is an accurate time measurement. The greatest challenge with this is, that we deal with two different type of error sources we can have. On one hand we can have multi-path, witch enlarges the path of the signal and therefore also our time measurements, on the other hand we have quantization effects and noise generate in the receiver and sender due to different processing times. We can have either one of these errors or both together.

2.2 Measurement Generation

For every sample of a distance estimation we need to generate a signal and measure the time it travels. Here the greatest challenge is to make sure we can generate these signals from all the anchors to the target. Also an important question is how fast we can generate samples, because this determines how fast we able to determine the position of the target.

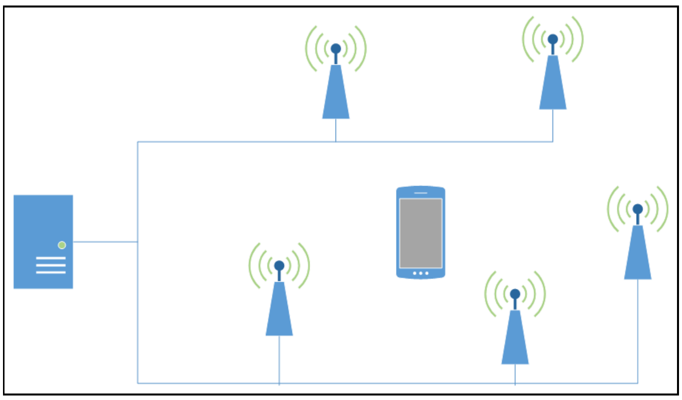


Figure 2.1: Simplified testbed for localization

2.3 Data Access

The time measurements are generated in the firmware of the wireless card, but the calculations of the position are done in the server, because the off-the-shelf hardware we use as anchors should be cheap and therefore is not very powerful. The challenge here is to be able to read the measurements fast enough from the device and then transfer these via the backbone network to the server for the calculations.

2.4 Positing

When we have solved the other problems we can face the localization of the target. Here we have a number of different distance estimations to the target from the anchors. The challenge here is to decide which links to use for the localization and how to deal with outliers.

Chapter 3

Design of the Localization System

In this chapter we introduce and describe our solution. We start with giving an overview over the system, then describe the hardware and software used and finally present the different parts in more details.

3.1 Overview

In figure 3.1 one can see an illustration of the system. It is contained of 10 wireless access points, which we placed in the environment described in 4.3. These act as anchors and can be seen in figure 4.1. They are responsible for measuring the distance to the targets and deliver the samples of the distance estimation to the server. The server is connected to the anchors via Ethernet as backbone network. In figure 2 the server is the box called ESXi VMWARE. It consists of two processes. One is MMeas and controls the anchor for generating the measurements and the other is MLat, which does the trilateration for the position of the targets.

3.2 Used Hardware and Software

3.2.1 Anchors

As anchors we choose the embedded devices soekris net5501 [4]. These are equipped with a 500 MHz AMD Geode LX single chip processor with CS5536 companion chip and 512 Mbyte RAM. They are equipped with 4 Ethernet ports, but do not have a wireless card. Therefore we installed external wireless cards in the Mini-PCI type III sockets. We used Broadcom AirForce54G 4318 cards. We used the open source firmware OpenFWWF [8] and the open-source driver b43 [9]. As operating system we installed Ubuntu server 10.04 [12], but we could have used any other Linux distribution as well. In order to be compatible with the previous work [2] we used the same kernel 2.6.32.60.
For using the soekris embedded devices as WLAN access points we used the software suite hostapd [10] and for operating the card in promiscuous mode which allows us to capture the acknowledgments on the wireless channel we used airmon-ng from the aircrack-ng software suite [11].

3.2.2 Targets

For testing we also needed targets. We used Dell Inspiron 5150 laptops with the same wireless cards as the targets. In theory we could have used any different laptop or smart-phone. We decided again to stay compatible with the previous work, where test were always made between devices with this wireless card.

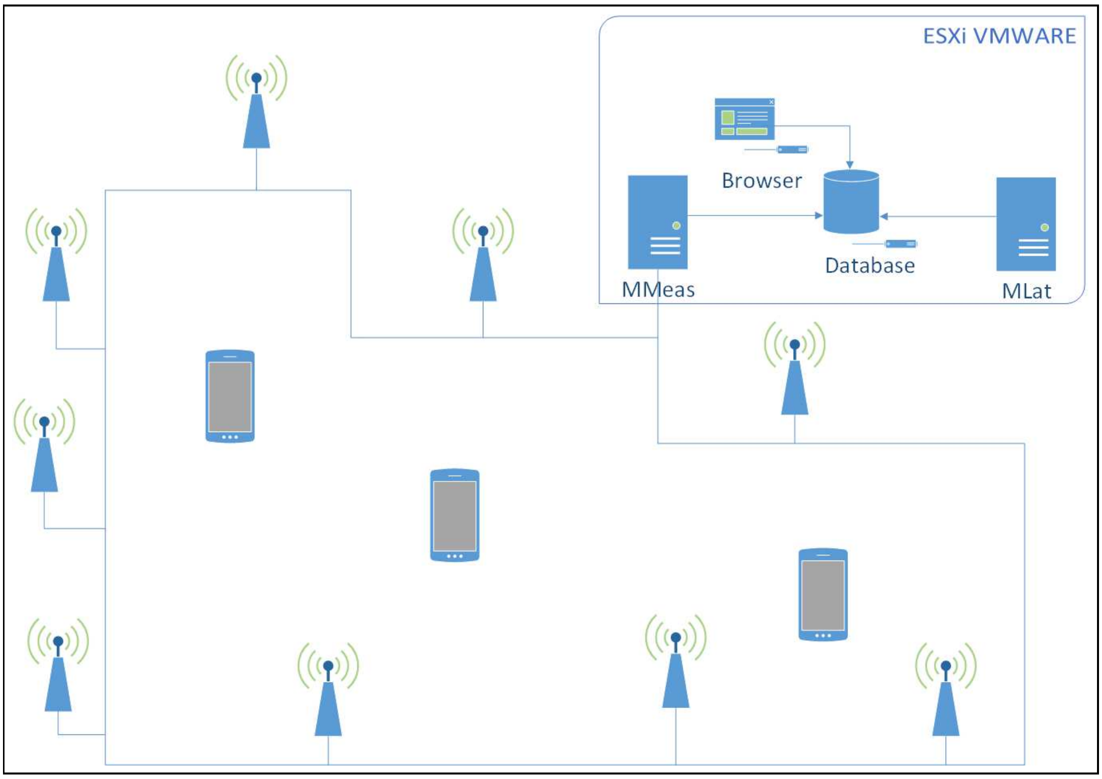


Figure 3.1: Illustration of the testbed deployed at armasuisse in Thun

3.3 Distance Estimation

For a distance estimation 4 different steps are needed:

- Generation ToF-Samples (3.3.1)
- Use the reference values from the calibration to get rid of the dependency of the measurements on the data rate (3.3.2).
- Calculate an estimator $\hat{t}_{ToF}$ for the ToF Value from the samples.(3.3.3)
- Use the relationship $d = \hat{t}_{ToF} \cdot 1.7m$ to determine the estimated distance.

3.3.1 Sample Generation

In this section we describe how a sample Time-of-flight (ToF) measurements is generated. The idea is that we want to use the acknowledgment mechanism of the 802.11 standard.
In figure 3.2 one can see an illustration of the implemented mechanism. For every data packet a round trip time is measured from the start of the transmission to the end of the reception of the corresponding acknowledgment ($t_{MEAS}(d)$)). The time the target waits is defined in the standard as t_{SIFS} and the duration of a acknowledgment t_{ACK} is constant. Therefore the propagation delay can be expressed as

$$t_p(d) = \frac{t_{MEAS}(d) - t_{SIFS} - t_{ACK}}{2}.$$

From this we can see, that the propagation delay is proportional to the measured time for a given distance. The distance than can be calculated with $d = c \cdot tp$. One source of error is the additional noise that is generated by starting and stopping the timer (t_{SET} and t_{STOP}) and by a processing delay. In order to avoid additional delays the time is measured directly in the firmware and not in the driver. The resolution of this measurement is given by the resolution of the General Purpose Timer of the firmware, which is clocked at $88MHz$. If we assume the signal travels at speed of light $c = 3 \cdot 10^8 \frac{m}{s}$, we end up with a resolution for the distance of $1.7m$.

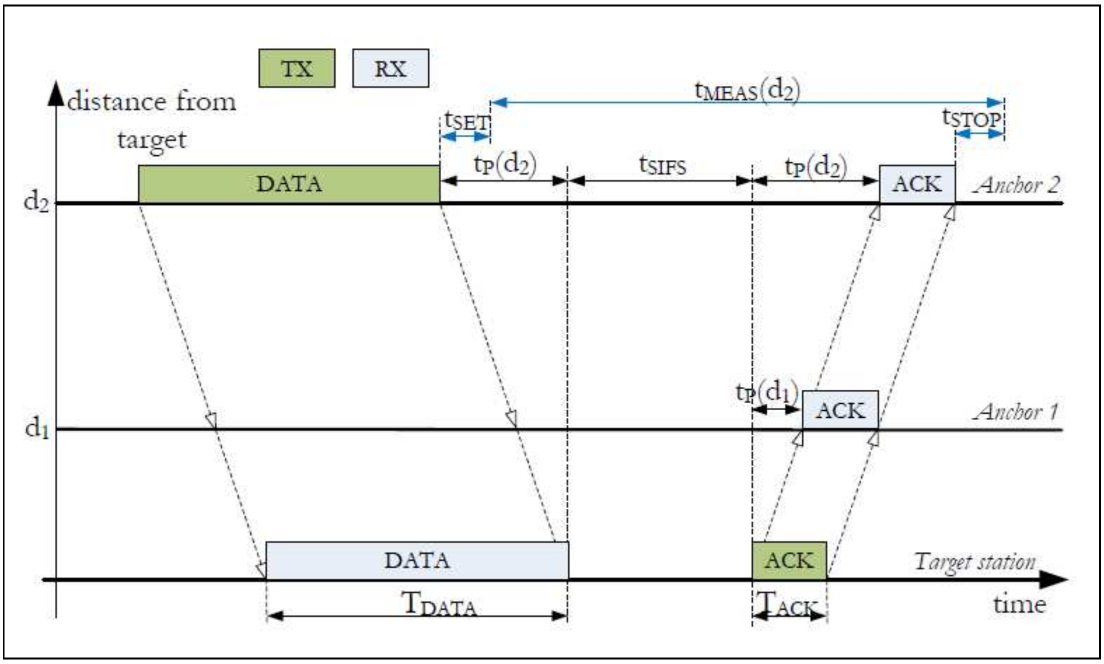


Figure 3.2: Illustration how the ToF measurments are made [1]

Rate	Mode	Reference clock cycle value for $0m$
1Mbps	b	27856.0
2Mpbps	b	22929.0
5.5Mpbs	b	19865.1
11Mpbs	b	18968.7
6Mpbs	g	5234.0
12Mpbs	g	4228.0
24Mpbs	g	3877.0

Table 3.1: Reference values for the Broadcom AirForce54G 4318 wireless card

3.3.2 Calibration

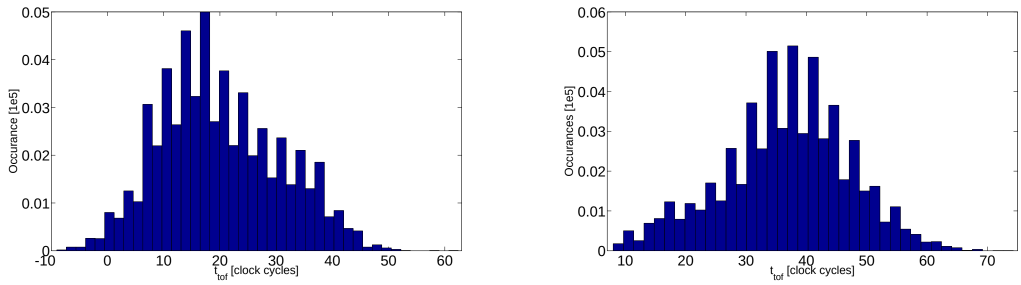
The only calibration we need to do is a per target wireless chipset calibration. We know the distance is directly proportional to the measured time, therefore we can measure a reference value for the distance at $0m$. Since t_{SIFS} and the processing delays are different for the transmission rates, we have to determine the reference for every rate. We did this by using the cables described in section 4.1. We gathered for both cables 10000 samples for every rate and then did a linear regression. As reference value for the distance at 0 we then took the corresponding value of the linear regression. We did this calibration for the basic data rates in 802.11b and 802.11g (table 3.1). With $t_{ToF} = t_{MEAS}(r) - ref(r)$, with $ref(r)$ the reference value from table 3.1, we can eliminate the dependence on the data rate. We showed, that the distance estimation is not influenced by the data rate by fixing the data rate and comparing the results for different data rates (5.1.1). The remaining difference is corresponding to signal travel round trip time. From this point on the clock cycles always correspond to the difference between the reference value and the measured value.

3.3.3 Processing of the Data: Dealing with Noise

As mention in chapter 2 we have to deal with two different noise components. One comes from the wireless card and from the starting and stopping of the timer, from now on we call this noise processing noise. The other comes from the multi-path propagation of the signal. For the first type of noise taking the median over the gathered samples is a good measure to deal with it as shown in [2]. But when we increase the distance and introduce non-line-of-sight links the

Value	LOS dominated	NLOS dominated
Measured distance	$16.75m$	$18.42m$
Estimated distance with median	$18m$	$37m$
Optimal percentile	49%	6%
skewness	0.297	-0.205

Table 3.2: Data of two example measurements



(a) line-of-sight dominated situation

(b) non-line-of-sight dominated situation

Figure 3.3: Histograms of two example ToF-measurements

multi-path part of the noise gets more dominant and therefore the median is not the optimal solution anymore. We show this with two example links of 10000 samples each. In figure 3.3 one can see the histograms of the ToF-measurements of these two examples and in table 3.2 some data about these measurements is shown. We calculated for both situations the optimal percentile, this means if we would use this percentile the error for this situation would be minimal. One can see that in the LOS dominated situation the median is very good, since the optimal percentile is 49%, while in the NLOS dominated situation this is not the case. Here the optimal percentile is 6% and therefore a big error is made when we estimated the distance. We further investigated this situations and looked at the skewness of the measurements. Here we have a positive skewness for the LOS dominated and a negative one for the NLOS dominated. This can be explained with the following reasoning: since multi-path only introduces additional delay we expect on NLOS dominated situation a tail on the left, since most measurements are too long, but some are shorter, this leads to a negative skewness. For the LOS dominated the situation is directly the opposite and we expect a positive skewness. In order to confirm this we made measurements for different links. We used the 42 links collected in the first observation of environment at Armasuisse in Thun 4.3.1. We used this data to create a linear regression of the skewness and the optimal percentile (figure 3.4) and calculated the Pearson correlation coefficient between these two metrics. The correlation factor was 0.6, which is a moderate correlation and one can see, that the linear regression has a high dispersion. We assume this comes for the noise in the receiver. We used the linear regression to create a new metric based on the skewness. The idea of this metric, from now called skewness metric, is the take the percentile according to the skewness and the linear regression for calculating an estimate instead of using the median. In the section 5.1 we evaluated the benefit of the skewness metric over the median.

3.4 Access of the Data

Since, as mentioned, we do the time measurement in the firmware we need a mechanism for retrieving this data. This is illustrated in figure 3.5. The wireless card shares one part of the memory (SHM). Every time a measurement is made the firmware writes this into a defined register in this memory. Since the driver has also access to the shared memory block it can retrieve the measurement every time an acknowledgment is received. In order to make sure, that the acknowledgments are reported to the driver, we need to operate the card in promiscuous mode. In the driver we gather additional data about the incoming acknowledgment (see table 3.3) and store them all in a buffer. Once this buffer is full the data is transfered to the user space with the help of UDP sockets. We use UDP sockets in order to be flexible to which destination

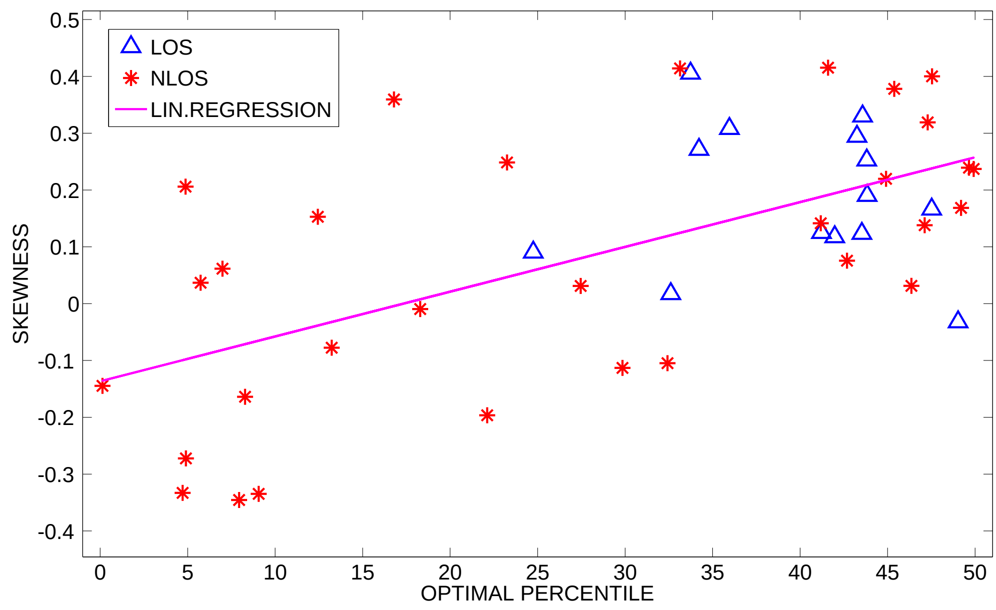


Figure 3.4: Linear regression of the skewness versus optimal percentile

Name	Description
tof diff	ToF-measurement (difference from reference value at distance $0m$)
tof stat	Statistics about the signal (PGA and LNA values)
rssi	Signal strength value (RSSI) of the acknowledgment
data rate idx	A identifier for the data rate of the data packet sent
addr anchor	Mac address of the anchor
addr target	Mac address of the target

Table 3.3: Data gathered in the driver

we can send the buffered data. Depending if the anchor itself makes additional processing or not we can send it to the user space of the anchor or directly to the server.

3.5 Generation of Acks

In order the get a sample of the ToF-measurement we need to generate data and receive acknowledgments for this data. For being able to estimate the position of the target we need to have distance estimations from multiple different targets. In this section we want to describe how we achieved this.

3.5.1 Sending Data to Unassociated Stations

We assume, that the target is connected to one of our access points. Then we can specify the channel and the supported data rates for the communication. Now we have to be able to send data to this target from all the available anchors. In order to be able to this we used raw sockets for sending fake data. Raw sockets allow us to generate the a custom mac header for the packet. In this header we can use the MAC address of the anchor to which the station is connected. The target then will acknowledge the reception of the packet, for which we then can measure the round trip time.

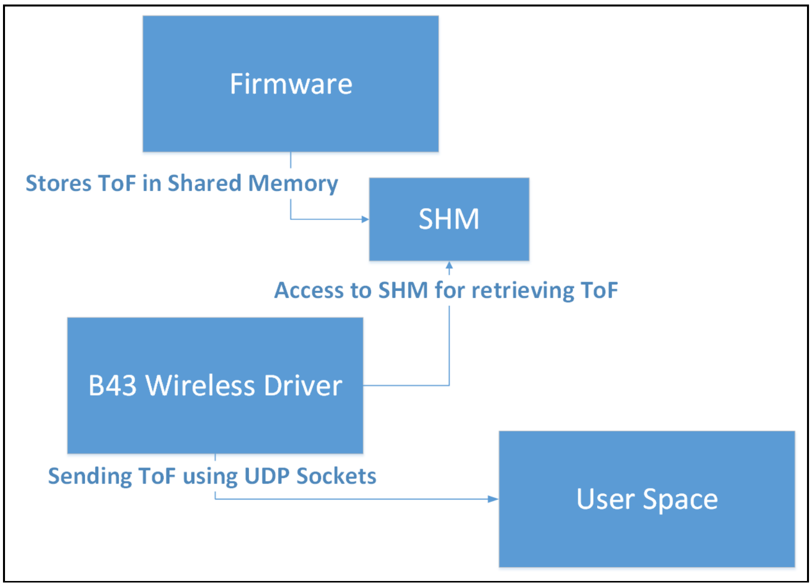


Figure 3.5: Illustration how the ToF measurements are retrieved from the firmware

3.5.2 Distributed Application for Gathering the Measurements

Since the generating of the measurements must be coordinated we implemented a distributed application for this purpose. It consists of 3 parts:

1. **tof_server:** Located on the server and coordinates the measuring and writes the data into a database.

2. **tof_anchor:** Located in the user space of the anchor: Uses raw socket to generate data and tells the driver when it has to record the measurements.

3. **driver of the anchor:** Captures and buffers the measurements. Finally transmits the measurements to the server.

Figure 3.6 is a UML-Sequence diagram of how the flow of the application is. tof_server loops over all combinations of anchors and servers and sends a message via UDP sockets to the tof_anchor of the current anchor to tell it to send data to the current target. Tof_anchor then tells the driver to start capturing the measurements and starts transmitting data to the target. After all the packets are sent it tells to driver to stop capturing and deliver the messages to the server, where they are written into a MySQL database. In the table 3.4 all the parameters are listed that one can use with this application. With the parameters dT_rounds and dT_measurements one can specify whether one wants to make the measurements in bursts or in continuous traffic. In the appendix A one can find a sample of a configuration file, which does set these parameters.

Name	Description
measurement_id	A unique name for the current measurement setup
output	Type of output (console, file or database)
anchor_ids_id	A list of the anchors that want to be used
targets	A list of MAC Addresses for the targets
nRounds	Number of rounds to make or never stop
nMeasuremnts	Number of measurements to make per round
dT_rounds	Delay between two rounds in milliseconds
dt_measurements	Delay between two measurements in milliseconds

Table 3.4: Parameters for the distributed application for gathering the data

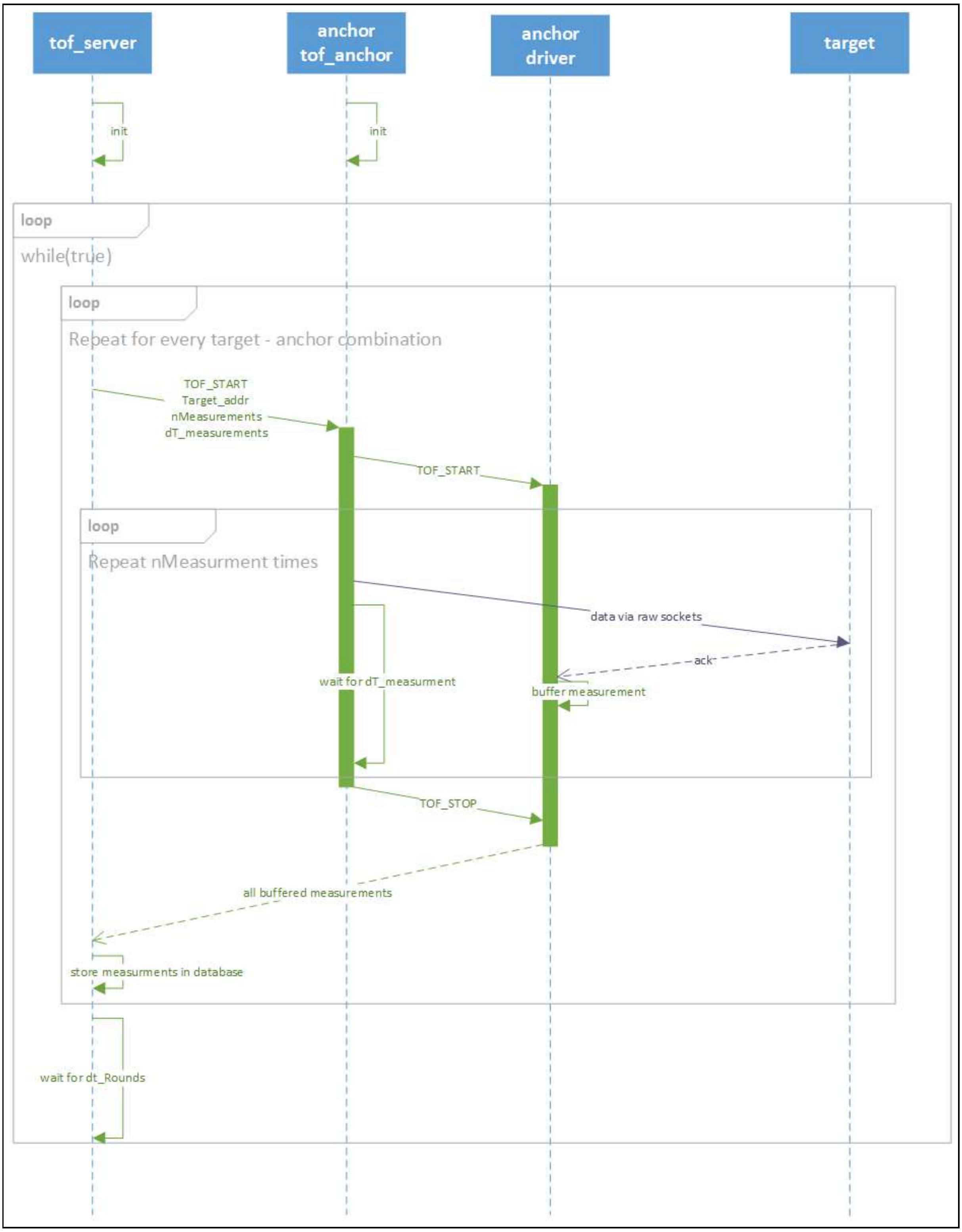


Figure 3.6: UML-Sequence diagram of the distributed application to gather measurements

3.6 Estimation of the Position: Trilateration

First we define a coordinate system on the map shown in figure 4.1 with the origin in the bottom left corner. Since we are interested in localization in one floor we can conisder a 2-dimensional problem and need at least 3 distances. For a estimation of the position we need the find the coordinates that satisfy the following condition:

$$(\hat{x}, \hat{y}) = \underset{(x,y)}{\arg\min} \sum_{i}^{N} (\sqrt{(x - x_i)^2 + (y - y_i)^2} - d_i)^2$$

with N the number of reached anchors (x_i, y_i) the position of the anchor i and the d_i the estimated distance to the anchor i. This means we find the position with the smallest squared error distance. This is a least squares optimization problem. For solving this we consider two different algorithms:

1. Linear Least Squares (Section 5.2.1)
2. Bancroft Algorithm (Section 5.2.1)

Position 5, anchors reached 6

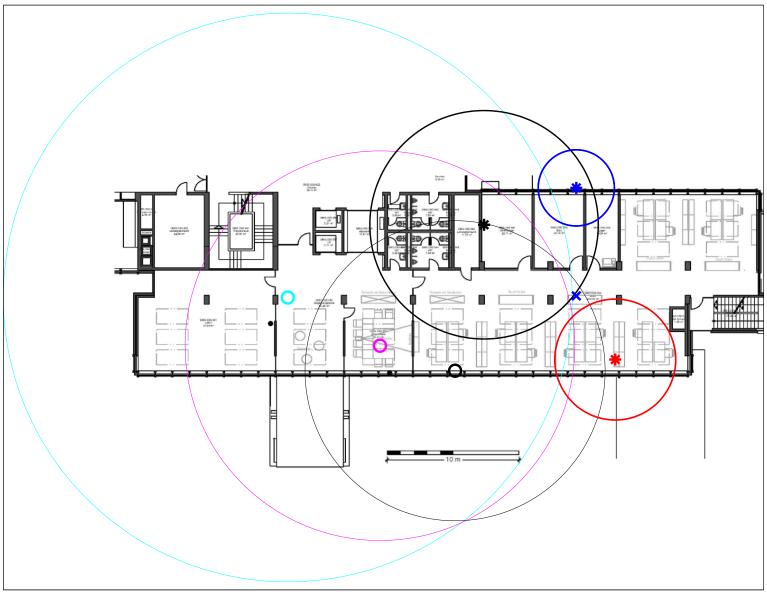


Figure 3.7: Example situation showing the target (blue x), the anchors (o or *) and the measured distances

Chapter 4

Environments

In this chapter we describe the environments used in the thesis.

4.1 Cables

For making tests without any influence of multi-path we used RG-58 coaxial cables. We connected these cables between the wireless cards of the station and the target. One has to take into account, that in the cables the signal travels a lower velocity as in the air. RG-58 cables have a dielectric with velocity factor (VF) of 0.66 [13]. That means the signal travels at $0.66 \cdot c$. We used two different cables with lengths of $0.7m$ and $13.3m$.

4.2 Test Environment at ETH in Zürich

The first tests were executed in the building ETZ at the ETH in Zürich in the G-Floor. This a office floor with a couple of small rooms and one about 50m long corridor. There we did line-of-sight and non-line-of sight tests. The focus for this tests was to improve the distance estimation and test the data generation methods.

4.3 Environment for the Testbed at Armasuisse in Thun

The actual testbed was implement in a building of Armasuisse in Thun. It was also office-floor, therefore we expected the wireless channel to have similar properties to the one in the first scenario. In figure 4.1 one can see a map of this floor. Marked in there are the anchors and the

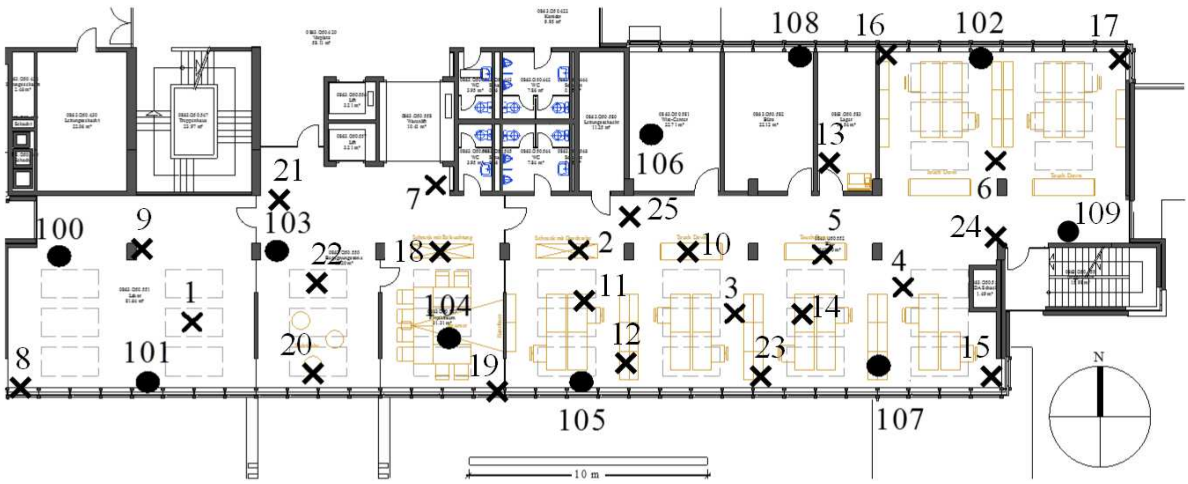


Figure 4.1: Map of the environment at Armasuisse. (● = anchors and X = positions)

Position	Number of anchors reached	Anchors reached
1	5	100 101 103 104 105
2	8	100 101 103 104 105 106 107 108
3	7	101 103 104 105 106 107 108
4	7	101 103 104 105 106 107 108
5	6	103 104 105 106 107 108
6	4	104 105 106 107
7	8	100 101 103 105 105 106 107 108

Table 4.1: Links measured for the first observation at Armasuisse

testing positions we used. As one can see we had a selection of links for different distances for line-of-sight and also for non-line-of-sight and therefore exploiting different multi-path scenarios. We made two observations in this testbed.

4.3.1 First Observation

The first series of measurements were made on the eighth of November 2013. We started with the measurements at two o'clock in the afternoon an continued until about six o'clock. We used the anchors 100-108 and the positions 1-7 on the map 4.1. Due to technical difficulties anchor 102 was not functioning and we could not send any data from this anchor to the target. For every position we sent 10000 data packets from all the anchors to the target. Table 4.1 shows which anchors could be reached from which positions.

4.3.2 Second observation

For the second series of measurements we increased the number of positions to 25 and added an additional anchor (109). This observation was made on the fifteenth of January 2014 from eleven o'clock in the morning to about six o'clock in the evening. Also for this position we used 10000 data packets for each link. The anchors 109 and 102 did not function properly on this tests and we could not transmit enough data. The influence of the geometry of the position of the anchors and the target station on the error can be measured with the dilution of precision (DOP) [18]. We calculated the horizontal DOP values for all the positions and decided to remove the ones with a bad value for the following analysis. We removed the positions with a HDOP value higher than 5. In table 4.2 we show an overview of all positions with the anchors reached and the HDOP value. We additionally removed position 6, since we only reached 2 anchors. Therefore we ended up with 20 positions.

Position	Used	HDOP Value	Number of anchors reached	Anchors reached
1	✓	1.25	5	100 101 103 104 105
2	✓	1.00	8	100 101 103 104 105 106 107 108
3	✓	1.09	8	100 101 103 104 105 106 107 108
4	✓	1.59	7	100 101 103 104 105 107 108
5	✓	1.12	8	100 101 103 104 105 106 107 108
6	x	-	2	106 108
7	✓	1.38	6	100 101 103 104 107 107
8	x	6.70	5	100 101 103 104 105
9	✓	2.16	4	100 101 103 104
10	✓	1.07	7	100 103 104 105 106 107 108
11	✓	1.00	8	100 101 103 104 105 106 107 108
12	✓	1.26	8	100 101 103 104 105 106 107 108
13	✓	1.36	5	101 104 106 107 108
14	✓	1.16	7	101 103 104 105 106 107 108
15	x	7.59	8	100 101 103 104 105 106 107 108
16	x	18.66	3	105 106 107
17	x	10.16	6	103 104 105 106 107 108
18	✓	1.18	6	100 101 103 104 106 108
19	✓	1.43	6	100 101 103 104 106 108
20	✓	1.50	5	100 101 103 104 105
21	✓	1.43	6	100 101 103 104 105 106
22	✓	1.29	6	100 101 103 104 105 106
23	✓	1.44	8	100 101 103 104 105 106 107 108
24	✓	3.02	8	100 101 103 104 105 106 107 108
25	✓	1.00	8	100 101 103 104 105 106 107 108

Table 4.2: Links measured for the second observation at Armasuisse

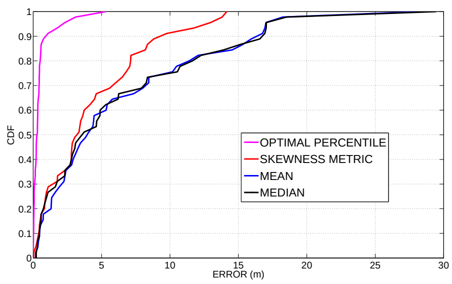
Chapter 5

Evaluation

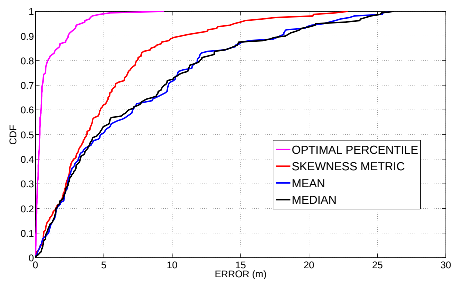
In this chapter we present results we achieved using the system described in chapter 3. We used the environments described in chapter 4.

5.1 Error for Distance Estimation

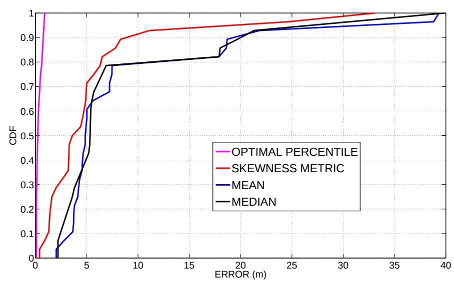
In figure 5.1 we show the empirical cumulative density function of the error in the distance estimation for all different environments. One can see, that in all situations we could reduce the influence of the outliers. While the median error is not changed by much the 90-percentile error has improved by more than $5m$ in all observations. A more detailed evaluation of the distance estimation can be found in [3].



(a) first observation



(b) second observation



(c) ETH

Figure 5.1: CDF of different approaches for the distance estimation

5.1.1 Test with the Cable

Besides for the configuration we used the cable test also for investigation the influence of received power of the signals and the different data rates. In table 5.1.1 we show the results of test for different data rates and different attenuations. For this tests we fixed the data rates on

Name	Attenuation	Data Rate	Median of ToF Difference [clock cycles]	Estimated Length	Measured Length
short	10dB	1Mbps	1	1.12m	0.7m
short	10dB	2Mbps	1	1.12m	0.7m
short	10dB	5.5Mbps	1	1.12m	0.7m
short	10dB	11Mbps	1	1.12m	0.7m
short	30dB	1Mbps	1	1.12m	0.7m
short	30dB	2Mbps	1	1.12m	0.7m
short	30dB	5.5Mbps	1	1.12m	0.7m
short	30dB	11Mbps	1	1.12m	0.7m
short	50dB	1Mbps	1	1.12m	0.7m
short	50dB	2Mbps	1	1.12m	0.7m
short	50dB	5.5Mbps	1	1.12m	0.7m
short	50dB	11Mbps	1	1.12m	0.7m
long	10dB	1Mbps	13	14.59m	13.3m
long	10dB	2Mbps	12	13.46m	13.3m
long	10dB	5.5Mbps	12	13.46m	13.3m
long	10dB	11Mbps	13	14.59m	13.3m
long	30dB	1Mbps	13	14.59m	13.3m
long	30dB	1Mbps	13	14.59m	13.3m
long	30dB	2Mbps	13	14.59m	13.3m
long	30dB	5.5Mbps	13	14.59m	13.3m
long	30dB	11Mbps	13	14.59m	13.3m
long	30dB	1Mbps	13	14.59m	13.3m
long	50dB	1Mbps	13	14.59m	13.3m
long	50dB	2Mbps	13	14.59m	13.3m
long	50dB	5.5Mbps	13	14.59m	13.3m
long	50dB	11Mbps	13	14.59m	13.3m

Table 5.1: Results of the test with the cables

both devices (target and anchor) using iwconfig [14] and attached different attenuators between the cables. One can see, that distance estimation is not influenced by attenuation nor by the different rates. This justifies our calibration method (3.3.2).

5.1.2 Number of Samples

We investigated how many samples we need for generating a robust distance estimation. For this we sliced the measurements of the second observation into smaller portions of 25, 50 and 1000 samples. We than calculated the distance estimation as described in section 3.3 for this number of samples and averaged over it. The result of this can be seen in figure 5.1.2. One can see, that the sample size does not have a big influence on the accuracy of the raging. More details about this can be found in [3].

5.2 Comparison of Distance Estimation Metrics and Positioning Algorithms

In this section we want to investigate the influence of the different distance estimation metrics and the positioning algorithms on the positing error.

5.2.1 Trilateration Algorithms

Linear Least Squares (LLS)

The linear least squares algorithm is well known for curve fitting [15]. It does solve a overdetermined linear set of equations. Our equations are not linear, but we can linearize them. If we

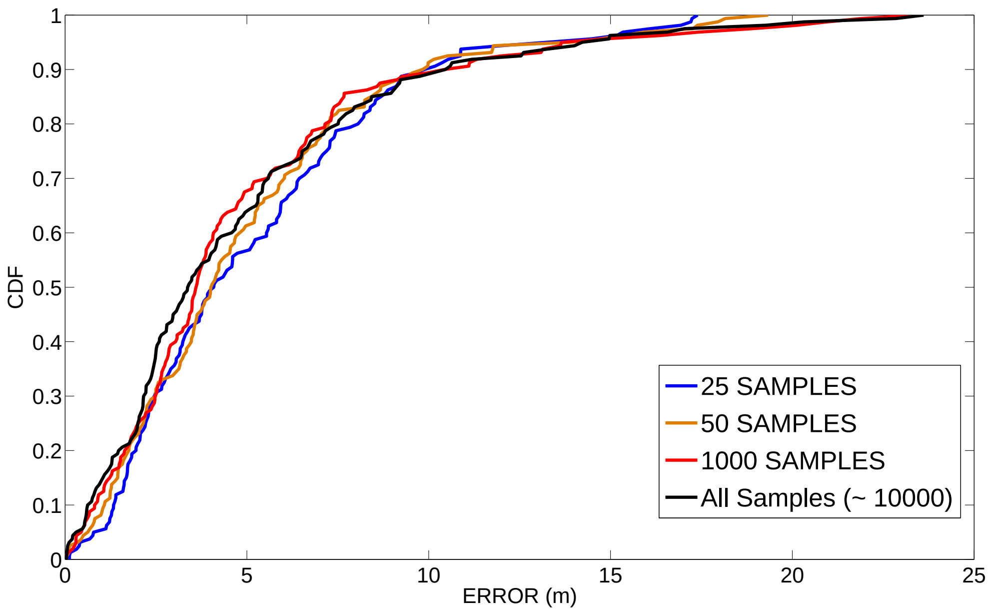


Figure 5.2: Empirical CDF for the distance estimation for different sample sizes (Armasuisse, second observation)

subtract the following constraint

$$\frac{1}{N}\sum_{i=1}^{N}[(x_i - x)^2 + (y_i - y)^2] = \frac{1}{N}\sum_{i=0}^{N} d_i^2$$

we can write the them as $A\hat{p} = b$. Now we have a linear system and can solve this for the estimation vector $\hat{p}$ with

$$\hat{p} = (A^T A)^{-1} A^T b$$

This algorithm has the drawback, that he is highly susceptible to outliers and as shown in section 3.3.3 we have outliers.

Bancroft algorithm

Bancroft algorithm is a algebraic solution to the GPS equations [16]. Since these equations are very similar to our equations, we can use this algorithm. With this method we are able to reduce the problem to a linear least squares. But we have to solve a quadratic equation in order to get the solution. In the case of the GPS equations one solution was located on the surface of the earth and the other not. In our case we just take the solution, which is located inside our floor plan. This algorithm is more robust against outliers than the linear least squares described in section 5.2.1.

5.2.2 Error for Position Estimation

Figure 5.3 shows the empirical cumulative density functions of the positioning error for the all the combinations of median and skewness metric with LLS and Bancroft algorithm for the first observation at Armasuisse (4.3.1). And the tables 5.2 and 5.3 show the errors for all positions. One can see, that the if we use the LLS algorithm and the median distance metric we end up with the highest error. This is because with the median metric we have big outliers in the distance estimation and the LLS algorithm is greatly influenced by this. Using the skewness metric instead of the median for estimating the distance helps a lot, since with this approach we reduce the error of these outliers. If use the Bancroft algorithm however the difference between

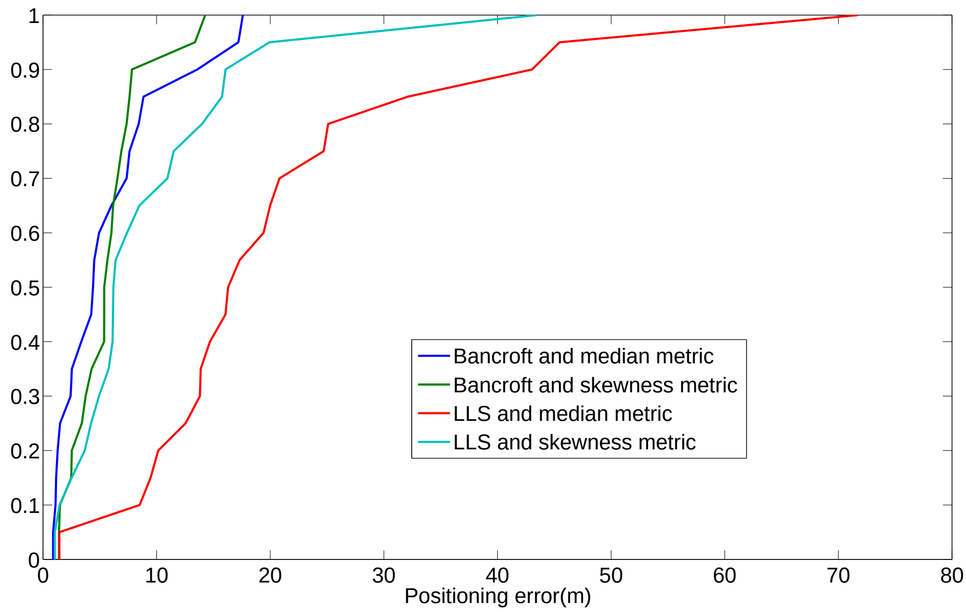


Figure 5.3: Empirical cumulative density function of the positioning error for different distance estimation metrics and positioning algorithms for the second observation at Armasuisse

Position	Median metric and LLS	Median metric and Bancroft	Skewness metric and LLS	Skewness metric and Bancroft
1	13.84m	4.11m	3.25m	5.16m
2	9.34m	5.54m	13.58m	5.84m
3	27.47m	11.66m	5.31m	5.46m
4	9.71	6.41m	11.01m	8.46m
5	1.36m	4.58m	4.12m	5.05m
7	16.17m	6.18m	3.98m	5.20m

Table 5.2: Positioning error different distance estimation metrics and multilateration algorithms for the first observation at Armasuisse

the two metrics is not as evident. Only the 90-percentile error is improved with the skewness metric, but the median error is slightly worse. This can be explained by the fact, that the Bancroft algorithm is very robust against outliers, there fore skewness metric and Bancroft algorithm fight the same problem and only where the errors are very high we benefit from the skewness metric.

5.3 Strategies for Choosing a Combination of Anchors

In this section we investigate the influence of the combination of the anchors we choose on the positioning error. We introduce different strategies for choosing the combination of anchors and find out if we can improve the error using these strategies 5.3.1.

5.3.1 Combination of Anchors

We evaluated two different strategies based on the notion of the predicted error. The predicted error can be defined as [17]:

$$e_{pred} = \sqrt{\frac{1}{N}\sum_{i=0}^{N}(r_i - d_i)^2},$$

Position	Median metric and LLS	Median metric and Bancroft	Skewness metric and LLS	Skewness metric and Bancroft
1	1.43m	1.44m	1.29m	1.40m
2	9.47m	5.78m	2.43m	5.37m
3	19.98m	14.00m	1.15m	1.48m
4	24.70m	19.93m	13.58m	14.27m
5	10.14m	7.39m	7.61m	7.82m
7	45.47m	43.49m	8.84m	5.38m
9	32.09m	1.03m	2.53m	6.89m
10	20.81m	6.16m	17.19m	6.55m
11	8.51m	6.11m	1.10m	5.67m
12	17.30m	2.51m	8.42m	3.75m
13	25.09m	6.20m	4.40m	7.61m
14	14.69m	3.67m	0.89m	3.41m
18	71.7m	15.75m	3.36m	2.48m
19	19.41m	4.92m	4.03m	5.39m
20	16.06m	16.06m	6.02m	6.02m
21	16.28m	6.39m	4.51m	6.16m
22	43.04m	11.50m	1.50m	7.35m
23	13.81m	10.94m	7.35m	2.53
24	12.55m	8.47m	17.57m	13.38m
25	13.87m	4.23m	4.24m	4.27m

Table 5.3: Positioning error for different distance estimation metrics and multilateration algorithms for the second observation at Armasuisse

where $r_i = (\hat{x} - x_i)^2 + (\hat{y} - y_i)^2$ is the distance from the estimated position to the the anchor i and d_i is the estimated distance for anchor i. The smaller the predicted error, the more the anchors agree on the estimated position.
The first strategy is to following: Compute the position of all possible combinations of anchors and choose the one with the smallest predicted error. This allows us the find the position where the involved anchors agrees the most,but since we have to calculate a lot of different positions it is not very efficient.
The second strategy is to start with using all anchors and then iteratively remove the anchor with the highest r_i [17]. As stopping criteria we used three different conditions.

1. Stop when the predicted error is smaller then a certain threshold.
2. Stop when the predicted error increases.
3. Stop when the there are only three anchors left.

This aims to remove the anchors that do not agree on the estimated position.

5.3.2 Results

In the figure 5.4 we plotted the empirical cumulative density function for the different strategies. We also included the CDF for using all anchors and the CDF if we use the optimal combination based on the error. This servers as a lower bound, that we cannot achieve. One can see, that two strategies proposed perform worse than using all anchors for the positing. For a possible reasoning we can have a look at an example position. The figures B.1, B.2 and B.3 in the Appendix B show the same position with the distance estimated using the different strategies. The blue cross marks the measured position, the red cross the estimated position and the circles the anchors with the corresponding distances. This is the position with the biggest error we recorded and here it is the most evident why the strategies do not perform well. Because the error in the distance estimation is in the same range as the distance estimations itself, it is possible to find a situation on which less anchors agree more, but is much worse than error for all positions. When we use all anchors for estimating the distances the error can cancel itself out. When we start to remove anchors the probability of this is reduced, what might be another

Position	All reached Anchors	Optimal error	Optimal predicted error	Iterative
1	5.16m	1.32m	1.36m	6.67m
2	5.84m	1.91m	11.62m	6.62m
3	5.46m	1.11m	2.27m	5.47m
4	8.46m	2.76m	18.62m	18.01m
5	5.04m	0.71m	2.95m	12.27m
7	5.20m	0.55m	0.89m	.39m

Table 5.4: Positioning error different strategies for choosing the anchors for the first observation at Armasuisse

Position	All reached Anchors	Optimal error	Optimal predicted error	Iterative
1	1.40	0.93m	0.93m	1.40m
2	5.37	1.57m	3.12m	5.37m
3	1.49	0.79m	2.45m	2.45m
4	14.27	2.84m	26.01m	23.07m
5	7.82m	0.74m	4.54m	13.30m
7	5.38m	2.03m	6.94m	11.22m
9	6.89m	6.89m	9.89m	6.98m
10	6.55m	3.56m	7.48m	10.00m
11	5.66m	0.91m	15.92m	7.57m
12	3.75m	0.95m	26.54m	1.15m
13	7.61m	2.03m	8.16m	8.16m
14	3.41m	0.62m	8.39m	7.83m
18	2.48m	1.79m	2.23m	2.23m
19	5.39m	5.24m	7.37m	7.37m
20	6.02m	6.02m	6.02m	6.02m
21	6.16m	2.58m	3.99m	7.05m
22	7.35m	1.13m	1.98m	13.64m
23	2.53m	2.42m	15.54m	14.95m
24	13.38m	7.25m	8.52m	15.83m
25	4.27m	0.72m	12.88m	3.55m

Table 5.5: Positioning error different strategies for choosing the anchors for the second observation at Armasuisse

reason why these strategies do not work. For these approaches to work we would need better distance estimations or a way to detect bad estimations and remove them beforehand.

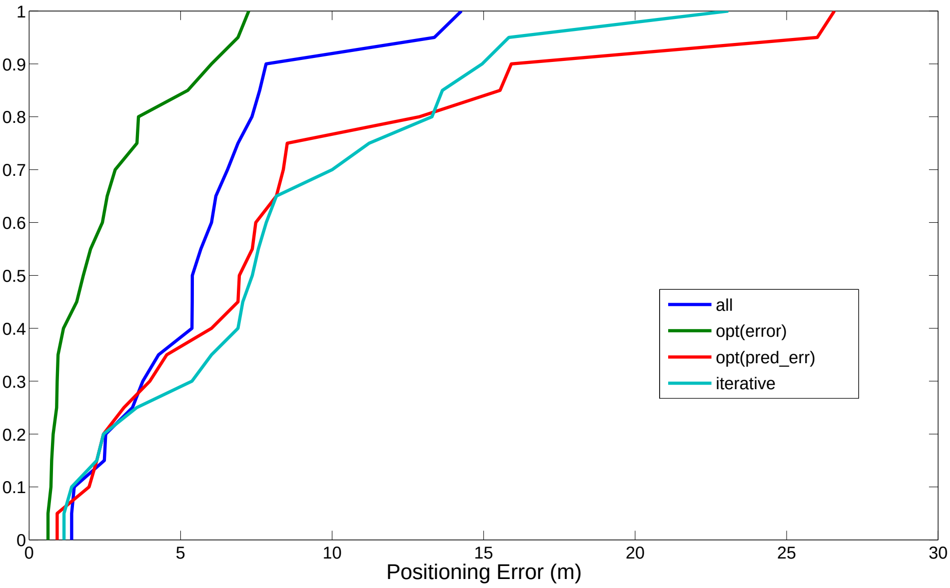


Figure 5.4: Empirical cumulative density function of the error of the positioning for different strategies for choosing the optimal combination of anchors for the second observation at Armasuisse

Chapter 6

Conclusion

In this project we were able to implement a system for localizing mobile devices based on a Time-Of-Flight approach. We could improve the distance estimation, develop a method for generating the measurements and do basic localization. We showed that some more sophisticated strategies for choosing the links to use for the estimation of the position do not give the desired benefit. Our systems achieve a median positioning error of 5.5m and a 80-percentile error of 7.5 meters. This is comparable to what other system achived using the signal strength [5]. We showed, that it is possible to build a localization system using the ToF of WiFi Signals with low-cost off-the-shelf hardware.

Chapter 7

Outlook

In this chapter present we some ways how we think one can improve the implemented system.

- **Different targets:** Test if the systems works for different targets than the one we used. We only used devices with the same wireless card as the anchors. We think it would be interesting to explore if other target chip sets perform different.
- **Investigate in autocorrelation:** Towards the end of the thesis we discovered, that some links showed a high autocorrelation of the ToF-Measurements. Maybe one could exploit this and find a way to remove the bad links or improve the current distance estimation.
- **Browser for showing the position:** Currently the system is missing a automatic way to show the positions. One could think of a browser, where one can see all the currently located devices and their positions.
- **Tracking:** The system is only localizing the targets at the moment. One could think of a implementing a tracking algorithm based on a Extended Kalman Filter.
- **Non Linear Least Squares:** Implement and test a non Linear Least Squares algorithm for the positioning. We think this might improve on the Bancroft algorithm. We think a nLLS would be more efficient and could help improve the accuracy.

Appendix A

Configuration File for the Application for Generating the Measurements

```
measurement_id
test_0

output
# console, file or databases
console
# file

anchor_ids # only the ids (default: all (= 100,101,...,109)
#all
#110
109

targets # mac adresses (needed)
#00:14:a4:77:2c:11 # target 1
#00:14:a4:4f:57:e4 # target 2


nRounds # number of measurement rounds made (default: -1 (=inf))
-1

nMeasurments # measurments made per round (default = 10)
0

dT_rounds # time between rounds in ms (min = nMeasurments*2ms*mTargetrs)
0

dT_measurements # time between measurements in ms (default 1.6)
0
```

Appendix B

Example Figures for the Strategies for Choosing the Combination of Anchors

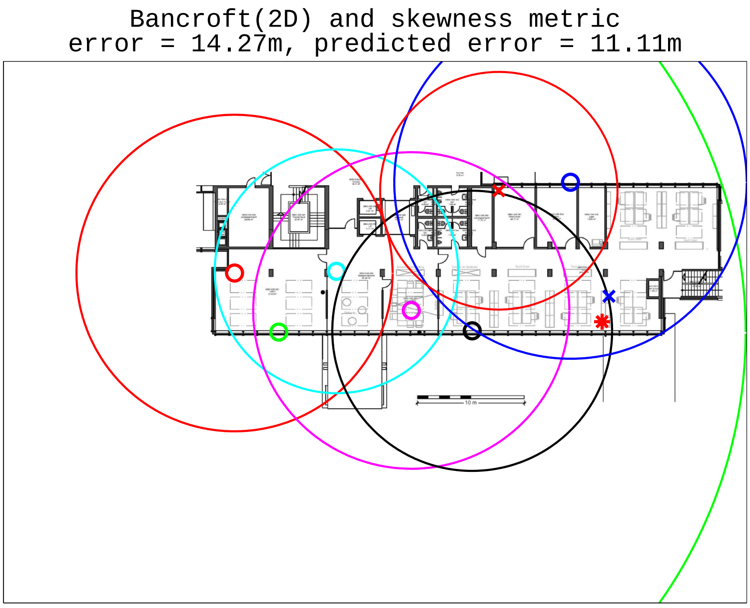


Figure B.1: Example positioning for using all anchors

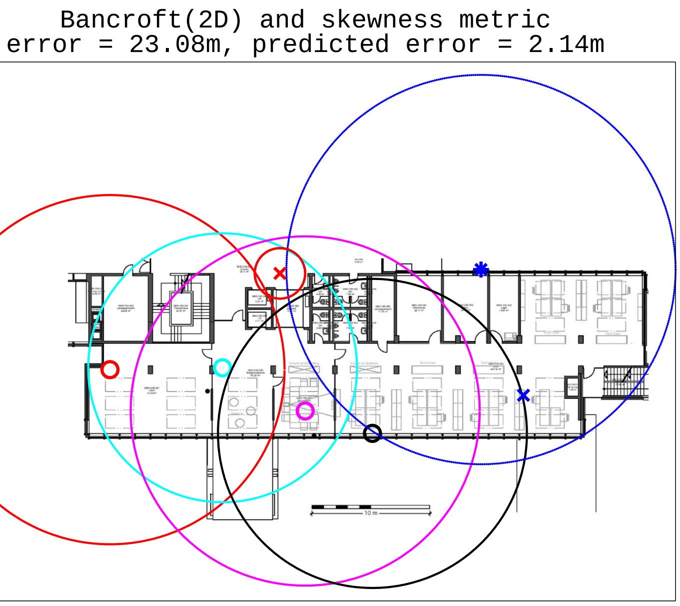


Figure B.2: Example positioning for using the iterative approach

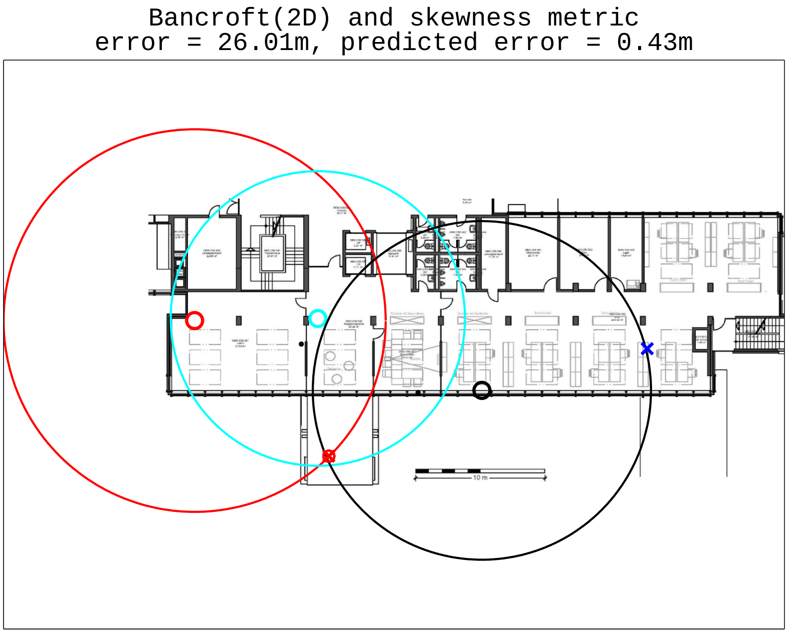


Figure B.3: Example positioning for using the combination with the best predicted error

Appendix C

Task Assignment

Master Thesis Task Assignment of:
Andreas Marcaletti
Time-of-Flight WLAN Indoor Tracking System

Main Advisor	Dr. V. Lenders (Armasuisse)
Second Advisor	Dr. D. Giustiniano (ETH Zürich)
Supervisor	Prof. Dr. B. Plattner (ETH Zürich)
Start Date	12th of August, 2013
End Date	11th of January, 2014

1 Background

Ubiquitous positioning and tracking is considered the key to undisclose new location-based services. Still, there is no pin-point solution that can guarantee high accuracy, low-cost and fast convergence in every environment and application without any calibration at all.

2 Thesis Goal

In a previous thesis at CSG lab, a WiFi echo technique has been investigated to estimate the distance based on time-of-flight measurements [1]. Taking advantage of this approach, the goal of this thesis is to implement a WLAN indoor testbed that permits to localize and track mobile devices, such as smartphones.

3 Tasks

The tasks of this thesis to reach a grade of 5.0 are described in what follows:

- Literature study of existing GPS-based trilateration algorithms; evaluate the code in [2] and whether it could be helpful for the rest of the work.
- The first tests will be done on the same machine (laptop) used in [1]. Understand the code used in [1, 3] and make some simple test to verify the results of [1, 3]. According to the outcome of the previous item, apply and modify the patch in [2] and/or a patch provided by the advisors to send traffic to the mobile device without being associated.

- Port the WiFi echo technique code (as well as any improvements from previous items) to an embedded system with Linux OS and verify the soundness of the setup making simple tests.
- Deploy a small testbed at Armasuisse Thun of up to 5 APs. Place the APs and develop scripts to control the testbed (APs on/off, start/stop sending traffic, send logs to local machine, etc)
- Study the expected dilution of precision (DOP) with the deployed configuration, compare it to the deviation of the ranging measurement, and evaluate the expected precision (2dRMS error) of the 2D position in the map of interest in the testbed [4]
- Develop a trilateration algorithm such as the Extended Kalman Filter (EKF) to estimate the distance to a mobile device. A simple version of the EKF for GPS running on Matlab can be provided by the advisors. The algorithm may run in real-time or offline. Ideally, a more robust implementation will be implemented by post-processing the data, and (if time permits) a simpler version may track the mobile device in real-time. While the final trilateration algorithm will have similarity with what implemented in GPS, it is expected that the student addresses the essential differences between WiFi echo technique and GPS pseudoranges [1, 4].
- Using the above testbed, validate by means of experimental tests the effectiveness of the implementation in terms of metrics such as accuracy, precision, number of messages per second, etc.
- If time permits, study the trade-off between the higher accuracies of the estimated distance when frequent data packets for TOF WLAN are sent and the overhead for the network throughput.

Higher grades can be reached if the work quality goes beyond the expectation above. A considerable independent contribution from the student would lead to a grade of 5.5. Work that would lead to scientific paper may be consider for a grade of 6.0.

4 Deliverables

- At the end of the second week, a detailed time schedule of the thesis must be given and discussed with the main advisors.
- At the end of the second month, a short discussion of 15 minutes with the supervisor and the advisors will take place. The student has to talk about the major aspects of the ongoing work using slides.
- At the end of month four, another meeting with the supervisor will take place. At this point, the student should already have a preliminary version of the written report or at least a table of content to hand in to the supervisor. This preliminary version should be brought along to the short discussion.
- At the end of the thesis, a presentation of 15 minutes must be given at ETH (in English) during a CSG group meeting. The presentations should give an overview as well as the most important details of the work.
- The final report should be written in English but may be written in German. It must contain a summary written in both English and German, the assignment and the time schedule. Its structure should include an introduction, an analysis of related work, and a complete

documentation of all used hardware/software tools. Exceptionally, if the work results in a publication, it may be considered to present the publication as final report. Four written copies of the final report must be delivered to the main advisor along with CD that includes developments undergone during the thesis.

References

[1] M. Bednarek, "Time-of-flight WLAN localization - semester thesis," in *ETH Zurich*.

[2] GRXCA, "WiPos," http://grxca.upc.edu/research/software.

[3] D. Giustiniano, L. Vincent, T. Bourchas, and M. Bednarek, "Deep inspection of WiFi echo technique - Dissecting the origins behind its current limitations," in *Submitted to Infocom'14*.

[4] M. S. Grewal, L. R. Weill, and A. P. Andrews, *Global positioning systems, inertial navigation, and integration*. John Wiley & Sons, 2007.

[5] D. Giustiniano and S. Mangold, "Demo: distance tracking using WLAN time of flight," in *In Proc. of ACM Mobisys '11*, 2011, pp. 349–350. [Online]. Available: http://doi.acm.org/10.1145/1999995.2000029

[6] P. Gallo, S. Mangione, and G. Tarantino, "Widar: bistatic wi-fi detection and ranging or off-the-shelf devices," in *Proc. IEEE WoWMoM'13*, June. 2013.

[7] P. Gallo, D. Garlisi, F. Giuliano, F. Gringoli, and I. Tinnirello, "WMPS: A positioning system for localizing legacy 802.11 devices," in *Transactions on Smart Processing and Computing,*, October 2012.

[8] D. Giustiniano and S. Mangold, "CAESAR: carrier sense-based ranging in off-the-shelf 802.11 wireless LAN," in *Proceedings of the Seventh COnference on emerging Networking EXperiments and Technologies*. ACM, 2011, p. 10.

Bibliography

[1] WMPS: A Positioning System based on the Wireless MAC Processor for localizing legacy 802.11 devices
P. Gallo, D. Garlisi, F. Giuliano, F. Gringoli, I. Tinnirello, 2012

[2] Semester Thesis: Time-of-Flight WLAN Localozation
Maciej Bednarek, June 10, 2013

[3] Master Thesis: Robust Time-of-Flight Ranging Estimation in Indoor WiF
Maurizio Rea, 2014

[4] Description of Soerkis net5501
Soekris Engineering Inc.
http://soekris.com/products/net5501.html,
Last visited at 15.02.2014

[5] Zero-Configuration, Robust Indoor Localization: Theory and Experimentation
Hyuk Lim, Lu-Chuan Kung, Jennifer C. Hou, and Haiyun Luo
INFOCOM 2006. 25th IEEE International Conference on Computer Communications.

[6] Initial version of the EVARILOS benchmarking handbook
EVARILOS Project, April 2013

[7] A 60 GHz OFDM Indoor Localization System Based on DTDOA
F. Winkler, E. Fischer, E. Grass and G. Fischer,
14th IST Mobile & Wireless Communications Summit, Dresden, June 2005

[8] OpenFWWF Website
Francisco Gringoli and Lorenzo Nava
http://www.ing.unibs.it/ openfwwf/,
Last visited at 15.02.2014

[9] b43 and b43legacy Website
Linux Wireless
http://wireless.kernel.org/en/users/Drivers/b43,
Last visited at 15.02.2014

[10] hostapd Linux documentation page
Linux Wireless
http://wireless.kernel.org/en/users/Documentation/hostapd,
Last visited at 15.02.2014

[11] aircrack-ng website
Aircrack-ng, 2009-2013
http://http://aircrack-ng.org/,
Last visited at 15.02.2014

[12] Ubuntu 10.04 Server Guide
Canocial Ltd. 2008
https://help.ubuntu.com/10.04/serverguide/index.html,
Last visited at 15.02.2014

[13] Coaxial Cable Wikipedia Entry
Wikipedia.org
http://en.wikipedia.org/wiki/RG-58,
Last visited at 20.02.2014

[14] Man page of the linux command iwconfig
linuxcommandes.org
http://www.linuxcommand.org/man_pages/iwconfig8.html,
Last visited at 20.02.2014

[15] LLS Wikepedia Entry
Wikipedia.org
http://en.wikipedia.org/wiki/Linear_least_squares_(mathematics)
Last visited at 15.02.2014

[16] An algebraic solution of the GPS equations
Bancroft, S.
IEEE Transactions on Aerospace and Electronic Systems 21 (1985) 56-59.

[17] Evaluating Lateration-Based Positioning Algorithms for Fine-Grained Tracking
Andrew Rice and Robert Harle
DIALM-POMC '05 Proceedings of the 2005 joint workshop on Foundations of mobile computing. Pages 54 - 61

[18] Dilution of Precision Wikipedia Entry
Wikipedia.org
http://en.wikipedia.org/wiki/Dilution_of_precision_(GPS)