Niko Joram

Design of a Dual Band Local Positioning System

Beiträge aus der Informationstechnik

Niko Joram

Design of a Dual Band Local Positioning System

VOGT

Dresden 2015

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar.

Bibliographic Information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2015

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „Design of a Dual Band Local Positioning System“ von Niko Joram überein.

Gesetzt vom Autor

ISBN 978-3-938860-96-0

Jörg Vogt Verlag
Niederwaldstr. 36
01277 Dresden
Germany

Phone: +49-(0)351-31403921
Telefax: +49-(0)351-31403918
e-mail: info@vogtverlag.de
Internet : www.vogtverlag.de

Technische Universität Dresden

Design of a Dual Band Local Positioning System

Niko Joram

der Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden
zur Erlangung des akademischen Grades

Doktoringenieur
(Dr.-Ing.)

genehmigte Dissertation

Vorsitzender:	Prof. Dr. techn. Klaus Janschek
Gutachter:	Prof. Dr. sc. techn. Frank Ellinger
	Prof. Dr. sc. techn. Jan Hesselbarth

Tag der Einreichung: 30. Januar 2015
Tag der Verteidigung: 11. September 2015

Danksagung

An dieser Stelle möchte ich mich bei allen Personen bedanken, die diese Arbeit in den letzten Jahren unterstützt haben.

Mein besonderer Dank gilt Prof. Dr. sc. techn. Frank Ellinger, der mich zur Arbeit auf dem Gebiet der integrierten Hochfrequenzschaltungen motiviert hat und es mir ermöglicht hat, meine Dissertation an seinem Lehrstuhl zu bearbeiten.

Sehr verbunden bin ich meinen Mitstreitern Jens Wagner und Belal Al-Qudsi, die sich stets Zeit für umfangreiche Fachdiskussionen genommen haben und mich bei allen wissenschaftlichen, technischen und administrativen Belangen im Projekt unschätzbar unterstützt haben.

Markus Schulz, Elena Sobotta, Axel Strobel und Robert Wolf, meinen Kollegen im Büro, sowie Bastian Lindner, Anja Muthmann, Stefan Schumann und Uwe Mayer danke ich für das kreative Arbeitsklima und die vielen aufschlussreichen fachlichen und privaten Gespräche.

Ich danke Tom Drechsel, Mohammed El-Shennawy, Marco Gunia und Prof. Dr. Udo Jörges für die aufmerksame Durchsicht der Arbeit und die hilfreichen Kommentare und Diskussionen, die zur Verbesserung des Manuskripts beigetragen haben.

Der Gemeinde Eichigt im Vogtland danke ich für die unkomplizierte Bereitstellung der Messszenarien für das Positionierungssystem.

Von Herzen danke ich meinen Eltern, die mich immer unterstützt haben.

Zusammenfassung

Die vorliegende Arbeit befasst sich mit dem Entwurf eines robusten lokalen Positionierungssystems (LPS), welches in den lizenzfreien Frequenzbereichen für industrielle, wissenschaftliche und medizinische Zwecke (*industrial, scientific, medical*, ISM) bei 2,4 GHz und 5,8 GHz arbeitet. Die Positionsbestimmung beruht auf dem Prinzip des frequenzmodulierten Dauerstrichradars (*frequency modulated continuous wave*, FMCW-Radar), welches hochfrequente Rampensignale für Laufzeitmessungen und damit Abstandsmessungen benutzt.

Im Gegensatz zu aktuellen Arbeiten auf diesem Gebiet benutzt das vorgestellte System Daten aus beiden Frequenzbändern zur Erhöhung der Genauigkeit und Präzision sowie Verbesserung der Robustheit. Ein Prototyp des kompletten Systems bestehend aus Basisstationen und mobilen Stationen wurde entworfen. Fast die gesamte analoge hochfrequente Signalverarbeitungskette wurde als anwendungsspezifische integrierte Schaltung realisiert. Verglichen mit Systemen aus Standardkomponenten erlaubt dieser Ansatz die Miniaturisierung der Systemkomponenten und die Einsparung von Leistung. Schlüsselkomponenten wurden mit Konzepten für mehrbandige oder breitbandige Schaltungen entworfen. Dabei wurden Sender und Empfänger bestehend aus rauscharmem Verstärker, Mischer und Frequenzsynthesizer mit breitbandiger Frequenzrampenfunktion implementiert. Außerdem wurde ein Leistungsverstärker für die gleichzeitige Nutzung der beiden definierten Frequenzbänder entworfen.

Um Spezifikationen für den Schaltungsentwurf zu erhalten, wurden in der Fachliteratur vernachlässigte Nichtidealitäten von FMCW-Radarsystemen modelliert. Dazu gehören Signalverzerrungen durch Kompression oder Intermodulation, der Einfluß der automatischen Verstärkungseinstellung sowie schmalbandige Störer und Nebenschwingungen. Die Ergebnisse der Modellierung wurden benutzt, um eine Spezifikation für den Schaltungsentwurf zu erhalten.

Die Schätzung der Position aus gemessenen Abständen wurde über eine erweiterte Version des Gittersuchalgorithmus erreicht. Dieser nutzt die Abstandsmessdaten aus beiden Frequenzbändern. Der Algorithmus ist so entworfen, dass er effizient in einem eingebetteten System implementiert werden kann.

Messungen zeigen eine maximale Reichweite des Systems von mindestens 245 m. Die Genauigkeit von Abstandsmessungen im Freiland beträgt 8,2 cm. Positionsmessungen wurden unter Verwendung beider Einzelbänder durchgeführt und mit den Ergebnissen des Zweiband-Gittersuchalgorithmus verglichen. Damit konnte eine starke Verbesserung der Positionsgenauigkeit erreicht werden. Die Genauig-

keit in einem Innenraum mit einer Grundfläche von 276 m^2 kann verbessert werden von 1,27 m bei 2,4 GHz und 1,86 m bei 5,8 GHz zu nur 0,38 m im Zweibandverfahren. Das entspricht einer Verbesserung um einen Faktor von mindestens 3,3. In einem größeren Außenszenario mit einer Fläche von 4,8 km^2 verbessert sich die Genauigkeit um einen Faktor von mindestens 2,8 von 1,88 m bei 2,4 GHz und 5,93 m bei 5,8 GHz auf 0,68 m bei Nutzung von Daten aus beiden Frequenzbändern.

Abstract

This work presents a robust dual band local positioning system (LPS) working in the 2.4 GHz and 5.8 GHz industrial science medical (ISM) bands. Position measurement is based on the frequency-modulated continuous wave (FMCW) radar approach, which uses radio frequency (RF) chirp signals for propagation time and therefore distance measurements.

Contrary to state of the art LPS, the presented system uses data from both bands to improve accuracy, precision and robustness. A complete system prototype is designed consisting of base stations and tags encapsulating most of the RF and analogue signal processing in custom integrated circuits. This design approach allows to reduce size and power consumption compared to a hybrid system using off-the-shelf components. Key components are implemented using concepts, which support operation in multiple frequency bands, namely, the receiver consisting of a low noise amplifier (LNA), mixer, frequency synthesizer with a wide band voltage-controlled oscillator (VCO) having broadband chirp generation capabilities and a dual band power amplifier.

System imperfections occurring in FMCW radar systems are modeled. Effects neglected in literature such as compression, intermodulation, the influence of automatic gain control, blockers and spurious emissions are modeled. The results are used to derive a specification set for the circuit design.

Position estimation from measured distances is done using an enhanced version of the grid search algorithm, which makes use of data from multiple frequency bands. The algorithm is designed to be easily and efficiently implemented in embedded systems.

Measurements show a coverage range of the system of at least 245 m. Ranging accuracy in an outdoor scenario can be as low as 8.2 cm. Comparative dual band position measurements prove an effective outlier filtering in indoor and outdoor scenarios compared to single band results, yielding in a large gain of accuracy. Positioning accuracy in an indoor scenario with an area of 276 m^2 can be improved from 1.27 m at 2.4 GHz and 1.86 m at 5.8 GHz to only 0.38 m in the dual band case, corresponding to an improvement by at least a factor of 3.3. In a large outdoor scenario of 4.8 km^2, accuracy improves from 1.88 m at 2.4 GHz and 5.93 m at 5.8 GHz to 0.68 m with dual band processing, which is a factor of at least 2.8.

Contents

1 Introduction

1.1 Motivation

Since the beginning of time people yearn to know their own locations. During the Middle Ages mariners used the stars as references for navigating their ships across the vastness of the oceans. Travelers oriented towards landmarks such as mountains or rivers to find their way home.

Shifting these scenes to modern times, it is observed that the scenarios did not change much. Where people in the past struggled to cross the primeval forests without getting lost, today they are equally fighting to get their bearings in the urban jungle to find the next restaurant or cash point. Moreover, the very principle of location finding, relating oneself to references, remains unchanged. The only minor difference is that mankind is now able to use artificial stars.

The satellite-based global positioning system (GPS) became operational in the 1990s. At first, accurate service was only available to the military. For civilian use, the signal was purposely degraded limiting the accuracy to around 100 m, making it unpractical for modern navigation purposes. In the year 2000, this selective availability was deactivated, paving the way for the widespread use of GPS in car and pedestrian navigation, reaching accuracies around 10 m.

A major drawback of GPS is the limited availability inside buildings due to the weak satellite signals. But with the increasing complexity of buildings with the most prominent example being airports and malls, there is also demand for indoor localization. The first widely available services also available indoors came up in the 1990s and were based on cellular networks with the granularity of a cell size ranging from less than 100 m in urban areas to some kilometers in rural areas [BFH^{+}96]. With the emerging of ubiquitous wireless local area network (WLAN) coverage after the year 2000, signal strength-based localization approaches were introduced, increasing the accuracy to values around 10 m [DS03]. It has to be noted that most indoor systems also work outdoors, which allows to increase the accuracy of locations beyond that of GPS in certain areas with special infrastructure for localization. Modern solutions using special infrastructure can reach accuracies below 1 m [Ubi14, Zig14]. However, indoor environments are usually challenging, because the probability of non-line-of-sight conditions is high and radio frequency (RF) based localization systems suffer from multipath propagation and fading, decreasing the system performance. Contrary to that, the demand for accuracy is usually higher indoors, because areas are more confined.

To overcome these problems there is on-going research on using multiple data sources to enhance indoor localization performance. One approach is to chart WLAN access points in areas of public interest for location estimation, called finger printing. Since 2001, a large database is built containing locations of countless wireless access points [WiG14]. The *European Integration Project MAGELLAN* [MAG14] researches on seamless integration of indoor and outdoor localization techniques, such as GPS together with approaches based on signal strength or cellular networks. However, those approaches are usually based on existing fixed infrastructure with a large number of nodes.

Obtaining multiple data is also possible from the hardware side of existing localization devices. It was already demonstrated that adding hardware for the measurement of the angle of arrival of RF localization signals can greatly improve accuracy [Gie10]. Improvements in positioning performance were also shown by adding data from readily available inertial sensors such as accelerometers and gyroscopes [AQEJE14*].

This thesis presents the design of a local positioning system with another promising data source which is the use of information from multiple frequency bands. Free space and different obstacles such as various types of walls or windows attenuate and reflect RF signals in different frequency bands differently [ARUS+03]. Having a multi band system allows the selection of the data from the band with best signal quality. Another advantage, especially with today's crowded radio frequency bands, is the resilience towards interferers which can disturb the system in a certain band, but not in another. In a nutshell, redundancy is added to the system, which can improve the robustness in complex indoor environments and allows the use in security-sensitive applications.

1.2 Scope of Application

This work was done in the scope of an European integration project entitled *A holistic approach towards the development of the first responder of the future*, with the acronym E-SPONDER [VGC+10]. The goal of the E-SPONDER project is the development of technologies to provide first responders with information and communication support during large-scale crisis events.

There were several partners involved dealing with the different aspects of the holistic approach, such as

- *EXUS, Greece* was coordinating the project and provides back end software,
- *University of Modena e Reggio Emilia, Italy* deals with network structures for connection of the different parts of the E-SPONDER system,
- *CrisisPlan, Netherlands* is a end-user providing system specifications and a connection of the technical staff to the users,

- *CEREN, France* is another end-user,
- *PROSYST Software, Germany* develops the middle-ware between sensors and user application,
- *Immersion, France* contributes the 3D visualization of the first responder location in the command centers,
- *Rose Vision, Spain* wants to standardize the developed technologies and works on logistics of first responder operations,
- *National Technical University of Athens, Greece* implements the hardware for the network between the users of E-SPONDER,
- *CSEM, Switzerland* provides biomedical sensors and other hardware for the first responders,
- *Smartex, Italy* integrates developed hardware into the garment of first responders,
- *Technische Universität Dresden, Germany* develops a local positioning system to track all involved crisis personnel,
- *YellowMap, Germany* contributes maps and point of interest services for the location visualization,
- *Panou, Greece* is a security and telecommunications specialist, who develops the mobile operations center.

During crisis situations, one important aspect is to continuously track the movements of all involved emergency personnel like fire fighters, police men or paramedics at any time. Since the scenarios vary widely, ranging from airplane crashes, collapsing buildings during earthquakes to fires, satellite-based systems like GPS cannot always be used. Especially for tracking indoors or in complicated urban environments, a dedicated local positioning system (LPS) is necessary to cover vital areas.

The E-SPONDER system consists of three components: a remote emergency operations control center (EOC), on-site mobile emergency operations control centers (MEOCs) and first responder units (FRUs). All of the components are connected by a wireless incident area network to allow information propagation from the operation centers to the first responders and back. The LPS mobile station, which is to be tracked, is integrated into a wireless body area network at the FRU along with biomedical and environmental sensors. Furthermore, since the positioning system is local, several base stations (BS) need to be set up around the incident area to provide reference points. Fig. 1.1 shows how the LPS integrates into the E-SPONDER system.

There are several specifications, which the LPS needs to fulfill to be applicable in the described scenarios:

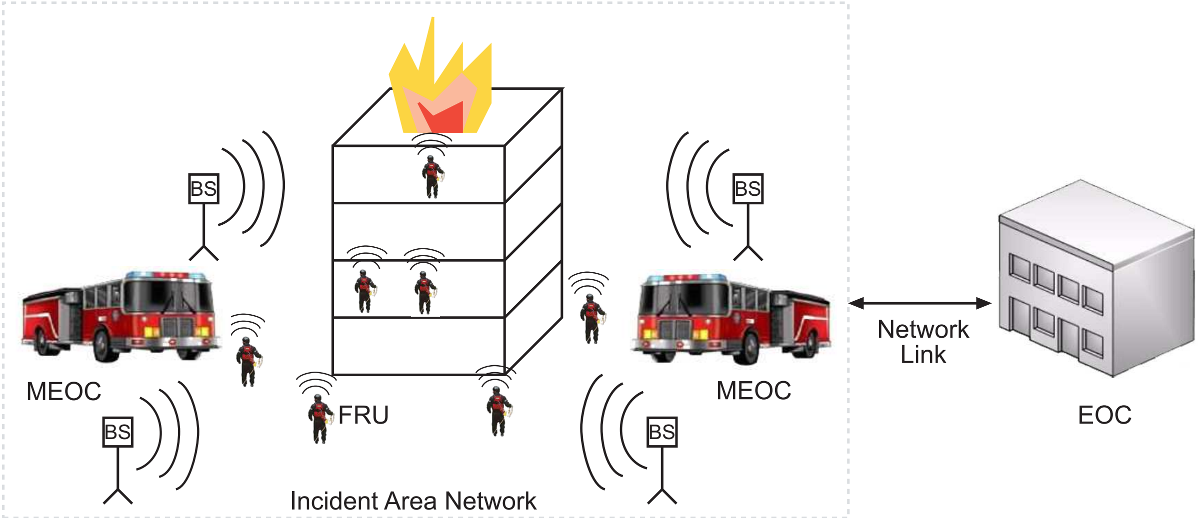

Figure 1.1: Overview of the LPS within the E-SPONDER system

- *3-D Localization:* For effective crisis management, it is necessary to know the altitude of a first responder, which may correspond to a story in a building.
- *Robustness:* Due to the diverse nature of crisis situations, the LPS has work under many different environmental conditions, while still having to provide reliable position information. Typically, multipath propagation can be expected.
- *Real-time Capability:* Movements have to be tracked without excessive delay. An update rate of less than one second is specified, which corresponds to the update rate of a standard GPS receiver.
- *Scalability:* The sizes of crisis events are variable. For managing a forest fire, it may be necessary to have several ten up to a hundred first responders on duty. The system performance must not be influenced by the number of mobile stations. As a consequence, the system has to use an approach similar to GPS, where the mobile stations determine their positions without having to transmit signals to the infrastructure. The propagation of the determined position is then done by the incident area network, which is not part of this thesis.
- *Coverage and Accuracy:* A range of at least $d_{0,\max} = 300\,\mathrm{m}$ with an accuracy of one meter is specified.
- *Deployable Infrastructure:* The LPS base stations have to be set up fast in the event of a crisis. They have to be completely wireless. The battery has to last for at least eight hours of continuous operation.
- *License-free Operation:* To comply with regulations, the system has to work

in a license-free industrial science medical (ISM) band. However, for operation during emergencies, permits, e.g. for increased output power, could be obtained.

1.3 Objectives and Structure

This work presents a structured approach for the design of local positioning systems using the frequency-modulated continuous wave (FMCW) principle. The key points of the investigation are as follows.

- *Theory:* Important effects, which can be observed in hardware implementations, like distortion, noise and interference are modeled and used to determine the parameters for the system components to fulfill the set specifications.
- *Design:* Methods for the design of all major components of a positioning system are presented. The designs are verified by integrated circuit implementations. The main focus lies on concepts, which are capable to support multi or broad band operation. A fully integrated transceiver chip including a complete multi-channel dual-band localization system testbed is developed, which combines all analogue building blocks and digital post-processing.
- *Verification:* Signal processing algorithms for synchronization and position estimation are developed and applied for the verification of the performance of the developed system using data from multiple frequency bands.

The focus of this thesis is on circuit and system design. It is not intended to provide a thorough discussion on signal processing and position estimation algorithms. However, since it is necessary for verification, state-of-the-art algorithms will be applied and referenced, but detailed only as much as necessary for the overall understanding.

The thesis is structured as follows. After presenting the scope of application in the current chapter, the fundamentals of localization systems are discussed in chapter 2, followed by a classification and market overview.

Chapter 3 is dedicated to the system theory of frequency-modulated continuous wave (FMCW)-based localization systems, providing a translation from system specifications to circuit specifications. Furthermore it describes a basic synchronization algorithm for two stations. Then, the implementation and verification of a test system is detailed, consisting of an analog front end with off-the-shelf components and a digital back end, which implements the synchronization algorithm. This chapter is concluded with an overview of the system specifications and derived circuit specifications.

In chapter 4, the design of integrated circuits and their assembly to a dual-band localization system, consisting of base stations and tags, is described in detail.

Major components and their design are presented including a low-noise amplifier, mixer, power amplifier and phase-locked loop.

Chapter 5 presents measurement results of the developed system in different scenarios. The thesis is concluded by a summary and an outlook to further areas of work to improve the system.

2 Fundamentals of Localization

2.1 System Classification

Localization is the process of determining the physical positions of targets with a specific degree of accuracy in indoor or outdoor environments [LT09]. Local positioning refers to localization within a confined area using local infrastructure, which is the LPS. There are several technologies used for localization:

- *Optical localization* is mainly applied in geographical surveys using total stations. It is based on light being sent out by a station and reflected at a target. The station evaluates the time of flight (ToF) and phase shift of the reflected signal to determine the distance. It allows very high accuracy with the drawbacks of expensive and bulky equipment as well as the inability to operate in non-line-of-sight environments.
- *Ultra sound based localization* uses sound signals with frequencies in the range of several ten kilohertz, also evaluating the ToF. The most popular application is the use in car parking sensors. The components are cheap and the system simple to implement. Because of the low propagation speed in the range of 340 m/s, accuracy of the distance measurement can be in the millimeter range. Major disadvantages are the low range, the inability of the signal to penetrate obstacles and the strong temperature dependency of the propagation speed.
- *Localization using inertial measurement units* has recently become popular because of cheap available accelerometers, gyroscopes and magnetometers implemented as microelectromechanical systems (MEMS). Inertial localization systems use a process known as dead reckoning. Based on a starting point, e.g. from a GPS measurement, the system tracks its location from this point using attitude and acceleration information [AQEJE14*]. Applications include aviation navigation but also personal navigation devices, where the systems are employed to bridge times, where the GPS signal is not available. However, accuracy is limited by accumulating errors.
- *Radio location systems* are another large class. There are ToF based systems which are also known as radars, but also approaches that relate the distance to a target to a received signal strength indicator (RSSI) or include the angle of arrival (AoA) of the signal in the location estimation process. Radio frequency signals can penetrate non-metallic obstacles and the influence of temperature, humidity or dust is negligible, which makes this class of

systems an excellent choice for robust localization. Disadvantageous is the limited accuracy resulting from the high propagation speed of approximately $3 \cdot 10^8$ m/s and the fact that radio channels suffer from multipath-induced fading.

The system developed in this thesis uses the radar approach because of its robustness and the good range. The measurement principle is based on the fact that electromagnetic waves travel at a certain propagation speed and the signal arrives at the target after the ToF, which is then related to the distance between the signal source and the target. There are two radar approaches, which are distinguished in literature: the primary or reflective radar and the secondary or one-way radar [KQ99].

- A typical implementation of a *reflective radar* is a transceiver station, which can transmit and receive signals at the same time. The radar target is usually passive and just reflects the signals sent out by the station. This type of radar is well known through its applications as a ship or aircraft radar. A main advantage of the reflective radar is the simple implementation in hardware, since there is only one transceiver and no active target. Major drawbacks include the high required antenna isolation between the transmit and receive paths and therefore the problem of crosstalk and also a limited range or high required transmit power, since the signal reflection from the passive target has to be strong enough to be detectable by the transceiver. Furthermore, without extra hardware effort (like in active reflector topologies [SE11]) there is no way to easily identify different targets.
- A *secondary or one-way radar system* consists of base stations and mobile stations. Depending on the signaling protocol, the mobile station needs to be a complete transceiver or a receiver only. In any case, signal processing in the radar target is necessary. A prominent example is the GPS, where the mobile station is a receiver only. A key advantage of the one-way system is the increased range with the same signal power compared to the reflective radar, since the signal only travels one way between sender and target. Another benefit is the possibility to identify the targets, because the secondary station contains active hardware and there has to be a signaling protocol. Subsequently, transmission and reception of signals occurs in different time slots and does not have to be simultaneous. On the other hand, the radar target needs additional hardware to implement the radar signal processing and protocol, which increases its size and power consumption.

Another system classification is by the employed signal modulation scheme.

- *Pulse modulation* is done by encoding the signal into short, low power pulses which occupy a certain bandwidth. This modulation scheme is used in ultra wideband (UWB) systems, which can have bandwidths of several gigahertz. A large bandwidth allows a high range resolution as discussed in section 3.2.

However, UWB regulations severely limit the allowed transmit power, which in turn limits the range of such systems and its ability to work in areas with obstacles. Advantageous is the low power consumption.

- *Frequency modulation*, with the most famous system being FMCW radar, uses frequency chirps with a certain bandwidth. The bandwidth is usually confined by regulations to several tens of megahertz in bands below 10 GHz. Hence, for sub-10 GHz systems, range resolution is behind pulse based systems. However, the allowed transmit power in this bands is in the order of several tens of milliwatts, allowing a large range. When using bands with larger center frequencies around 60 GHz to 80 GHz, the range is reduced, but the bandwidth and therefore range resolution increases. Receivers for frequency modulated signals are well researched in literature and therefore easy to implement.

Regarding the specification set in section 1.2, a secondary radar system using FMCW is chosen for the design. Especially the demand for real-time capability and scalability make primary radars such as the mentioned active reflector system unfeasible, since the radar target always needs to transmit data back to the fixed station. Thus, the position update rate will decrease with every added mobile station. FMCW furthermore allows a large range with the possibility to penetrate non-metallic obstacles while having a moderate range resolution.

2.2 Time of Flight Location Measurement Schemes

There are three basic location measurement schemes described in literature, which can be implemented together with a hardware capable of measuring ToF [Gie10, VWG$^+$03, LT09]. In this section, a brief overview of those schemes is given to motivate the decision which one to implement in the system to be developed.

Time of Arrival (ToA) In the simplest case it is assumed that all involved hardware, mobile stations and base stations alike, are perfectly synchronized and the time instance of any signal transmission is known. A signaling scheme could be that each base station transmits a signal in a predefined order, which is received by a mobile station. The mobile stations does not need to transmit. The ToA is then equal to the ToF and directly relates to the distance between the mobile and a certain base station.

The result in the mobile station is then a distance vector with one component for each base station. The location of the mobile then has to be calculated from this distance vector. Geometrically speaking, it means to find the intersection of circles around the base stations in a 2D scenario, as shown in Fig. 2.1, or spheres in 3D. Since the single distance measurements are prone to statistical errors, the circles will not intersect all in one point, but rather leave an area, where the mobile

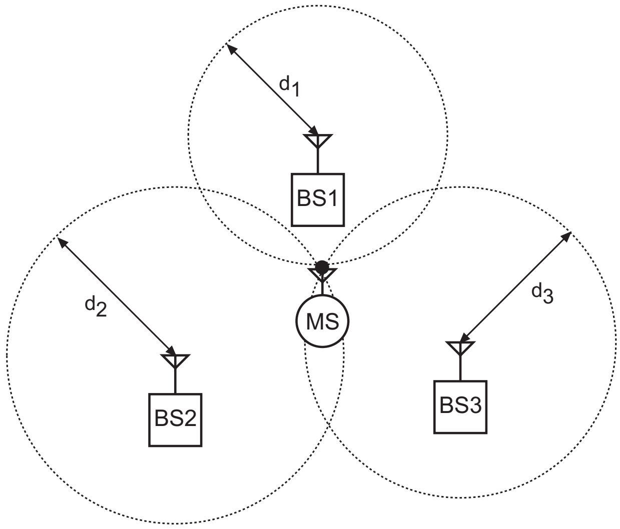

Figure 2.1: Position estimation using RToF or ToA with three base stations

target is probably located. This is the main reason, why a symbolic solution of the intersection problem is not feasible in real implementations. A more practical way is to formulate an error minimization problem, which is done in section 4.8.3 in the frame of a grid search algorithm for position estimation.

However, because of the prerequisite that all involved stations, especially the mobile, have to be synchronized, the time of arrival scheme is rarely applied in actual implementations.

Time Difference of Arrival (TDoA) The TDoA scheme does not require all units to be synchronized as ToA but only the base stations, though the signaling scheme is the same. Base stations transmit signals to the mobile subsequently. Since the mobile is not synchronous to the infrastructure, the measured ToFs do not directly relate to distances, but pseudo ranges. Evaluated are, as the name suggests, pairs of measured time differences between the different base stations. Geometrically, the problem can be considered as intersection of hyperbolas in 2D, as presented in Fig. 2.2, or hyperboloids in 3D. The estimation of the position in a real implementation can again be done similar to ToA.

Since the mobile is passive and not synchronized, TDoA systems allow for an unlimited number of mobile stations without impairing the system update rate. The most prominent example of such a system is GPS.

Round Trip Time of Flight (RToF) The result of the RToF scheme is again a distance vector like in ToA with the same geometrical interpretation. However, for RToF only the two stations just involved in a measurement have to be synchronized coarsely at a time. The signaling scheme is as follows. The mobile

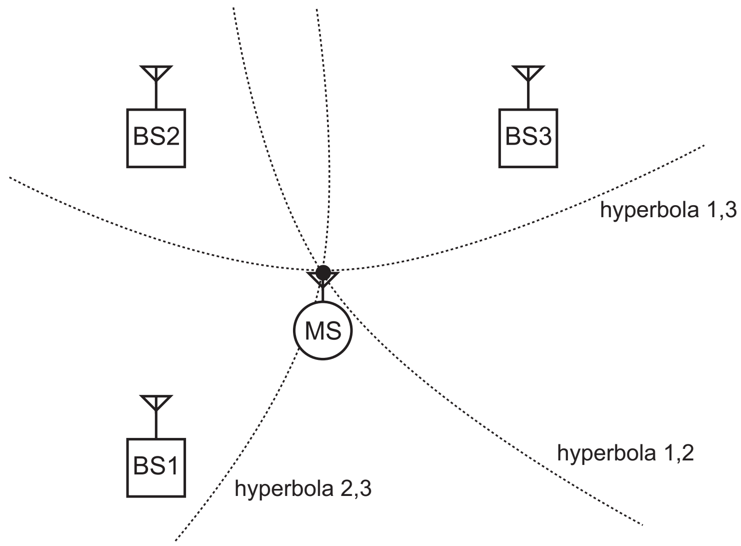

Figure 2.2: Position estimation using TDoA with three base stations

station transmits a signal to a base station, which calculates a pseudo range. The base station transmits a signal back to the mobile station, yielding another pseudo range. From both pseudo ranges, the distance between the two stations can be calculated. The synchronization and distance calculation is detailed in section 3.6. This two-way signaling scheme is repeated for every base station. It is also the major drawback of RToF, because with every added mobile station, the system update rate decreases. Advantageous is, that implementation and position estimation is simpler than with TDoA. The RToF scheme can be applied in TDoA systems to synchronize the base stations.

According to the specifications from section 1.2, the use of TDoA will be favorable to accommodate the need for scalability. However, the developed hardware shall be as flexible as possible to allow the use of any of the above schemes. For the verification of the hardware, RToF is better suited than TDoA because of the simpler protocol, the ability to measure distances wirelessly and directly and the smaller dependency of the location error on geometric conditions [Gie10].

2.3 Performance Measures

Precision and Accuracy The locations measured by a local positioning system exhibit errors, as any measuring device does. The definitions for precision and accuracy basically follow established literature on electronic distance and position measurement systems [Str13, Gie10].

The measuring error d_{e} is the distance of the position $\underline{m} = (x_{\mathrm{m}}, y_{\mathrm{m}}, z_{\mathrm{m}})$ measured by the system to the true position $\underline{r} = (x_0, y_0, z_0)$.

$$d_\mathrm{e} = \sqrt{(x_\mathrm{m} - x_0)^2 + (y_\mathrm{m} - y_0)^2 + (z_\mathrm{m} - z_0)^2} \tag{2.1}$$

For a distance measurement, the sign of the error can be of importance, so for the one-dimensional case, the distance error is defined as

$$d_\mathrm{e} = d_\mathrm{m} - d_0. \tag{2.2}$$

The standard deviation σ_p of a series of N measurements characterizes the precision or repeatability of a single measurement within defined, constant conditions. An example is a measurement series within one scenario, e.g. in a certain room. For a 3D localization system, the standard deviation of each of the three components of the measurement series has to be determined. It can be estimated by

$$\underline{\sigma_\mathrm{p}} \approx \left(\frac{1}{N-1} \cdot \sum_{i=1}^{N} (\underline{m_i} - \overline{\underline{m}})^{\circ 2} \right)^{\circ \frac{1}{2}}, \tag{2.3}$$

with $\underline{m_i}$ being a single 3D measurement and $\overline{\underline{m}}$ being a vector with the mean values for the complete series. The $\circ$ represents the Hadamard notation for component-wise square and root of a vector. This definition, although rarely used, can provide meaningful insights into error sources. For example, the height information is sometimes imprecise, because the base station setup has too little altitude difference.

To compare different systems, the definition of a one-dimensional standard deviation is useful. It seems reasonable to consider the single components as single measurements, which leads to

$$\sigma_\mathrm{p} \approx \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} [(x_{\mathrm{m},i} - \overline{x_\mathrm{m}})^2 + (y_{\mathrm{m},i} - \overline{y_\mathrm{m}})^2 + (z_{\mathrm{m},i} - \overline{z_\mathrm{m}})^2]}. \tag{2.4}$$

The total precision of the system for comparison is then defined as the mean precision for measurements in M different scenarios.

$$\overline{\sigma_\mathrm{p}} = \frac{1}{M} \sum_{j=1}^{M} \sigma_\mathrm{p,j} \tag{2.5}$$

It has to be noted from (2.3), that the standard deviation or precision does not give any information on the relation of the measurement to the true reference position. This relation is established by the accuracy of the system, which is for a defined scenario given by

$$\sigma_{\mathrm{a}} \approx \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} [(x_{\mathrm{m},i} - x_{0,i})^2 + (y_{\mathrm{m},i} - y_{0,i})^2 + (z_{\mathrm{m},i} - z_{0,i})^2]}. \tag{2.6}$$

Analogous to the total system precision, the total system accuracy is defined as the mean accuracy for measurements in M different scenarios.

$$\overline{\sigma_{\mathrm{a}}} = \frac{1}{M} \sum_{j=1}^{M} \sigma_{\mathrm{a,j}} \tag{2.7}$$

Resolution Another important system parameter is resolution. It describes the separability of two radar targets in terms of a minimum target distance, where both can still be detected. Resolution in a radar system is degraded by multipath propagation of the signal, which overlaps with the wanted line-of-sight signal and increases the location uncertainty. Since the formalization of the system resolution is dependent on its architecture, it will be detailed in section 3.2.

Coverage Coverage of a localization system is the area, in which mobile stations can be localized by the system. It is limited by regulations, the allowed transmit power and the modulation scheme. Furthermore, the scenario will have a severe impact since it may contain obstacles like walls, which attenuate signals. However, coverage can be increased by using additional anchor nodes and combining them in a network. Details on coverage under the condition of additive white Gaussian noise and free space path loss can be found in section 3.4.1.

Deployment The time and infrastructure necessary to set up the system is important for ad-hoc applications like the E-SPONDER system. A static system can be designed to rely on infrastructure such as Ethernet for communication and protocol handling between the base stations. In general, this allows very good overall system performance, since the medium for data exchange has a predictable latency and quality of service. Furthermore, a connection to a power grid can be foreseen, which relaxes power management. Calculation of the position can be done on a server in the network, removing processing load from the stations.

An ad-hoc system on the other hand has to rely on battery power and a wireless channel for communication. All calculations and signal processing has to be done within the stations, which calls for an elaborate power management. A method for quick setup has to be implemented to provide the base stations with their current reference position, e.g. by using integrated GPS modules. Since synchronization of the units is also done wirelessly, accuracy and precision of such systems is usually behind static ones.

Scalability and Update Rate The number of addressable mobile stations and the rate with which positions are provided are interrelated. In a radar system, update rate strongly depends if there is a two-way communication between the nodes. Using a two-way communication, update rate is decreased proportional to the number of mobile stations to be addressed. For one-way signaling, update rate is only decreased starting from a certain number of mobile stations, which is reached when the positions calculated in the mobiles cannot be forwarded by the network anymore due to capacity limitations.

Robustness Robustness describes the ability of a system to handle difficult situations, while still providing useful output. For a positioning system, a difficult situation could be a complex scenario with lots of reflections and attenuation or, related to that, a loss of contact to one or several of the base stations. Robustness of a system can be increased by adding redundancy, such as more base stations or, as described in this work, use multiple frequency bands.

2.4 Commercial Radio Frequency Localization Systems

Table 2.1 gives an overview of localization systems based on radio frequency signals, which are currently on the market. Unless otherwise noted, the parameters are taken from the specification sheets provided by the manufacturers.

A well-known localization system on the market is the *Ubisense 7000 series*. It uses UWB pulses in the range of 6 GHz to 8 GHz to measure ToF and, ultimately, TDoA. It provides a high update rate with good accuracy. The major disadvantage is the fixed infrastructure, which uses cables for synchronizing the base stations. Furthermore, locations are not determined by the mobile units, but by a centralized localization server instead.

The German company *ZigPos* manufactures a system based on the ZigBee IEEE 802.15.4 standard using signal phase measurements to determine locations with accuracies of several tens of centimeters. It supports up to 255 stations according to the standard, which might be a limiting factor in large-scale crisis scenarios. Major advantages are the completely wireless infrastructure and the possibility of having an integrated sensor network with communications and multi-hop capabilities.

The *nanoLOC* system from *Nanotron* uses a chirp spread spectrum (CSS) modulation for distance measurements in the 2.4 GHz ISM band. The fact sheet from the manufacturer states accuracies in the centimeter range, however, the author's own measurements showed values in the meter range. The measurement was done in a classroom approximately five by five meters using four nanoLOC anchors and one mobile. The system is based on a RToF scheme with two-way ranging between the mobile and the base stations, which limits the update rate and scalability. All system components are completely wireless.

The *Symeo LPR-2D* uses the FMCW principle at the ISM band at 5.8 GHz, which is also applied for the system developed in this thesis. It reaches very good accuracy below 10 cm making use of directional antennas and phased array technology with AoA evaluation. The high update rate allows the use in real time applications, such as crane tracking in mining operations. The stations are wireless and thus easily deployable.

For the sake of completeness, the overview also includes the currently most popular localization system, which is the satellite based GPS. An accuracy for the system of around 8 m is stated with a precision of 4 m, however, it strongly depends on atmospheric conditions and the surroundings of the receiver. In dense urban areas, it may increase to several tens of meters due to signal reflections from buildings. Furthermore, the latitude and longitude values are usually more accurate than altitude. The most obvious advantage of GPS is the localization in a global scale and the availability of low cost receivers. Disadvantageous is, that due to the weak signals, the system does not work inside buildings. To enhance the rather coarse accuracy of GPS, a method called differential GPS can be employed. It makes use of an infrastructure of GPS reference stations with fixed global coordinates. Since their coordinates are known, the error imposed on the satellite signals due to atmospheric conditions can be calculated. The reference stations then forward the correction data to differential GPS receivers via a communications link. Typical accuracies are in the order of 0.2 m [Lei15].

Manufacturer	**Ubisense**	**ZigPos**	**Nanotron**	**Symeo**	**NAVSTAR**
Name	7000 series	eeRTLS	nanoLOC	LPR-2D	GPS
Reference	[Ubi14]	[Zig14]	[Nan14]	[Sym14]	[NAV14]
Technology	UWB, TDoA with AoA	ZigBee, IEEE 802.15.4	Chirp Spread Spectrum, RToF	FMCW, TDoA and AoA	Code Multiplex
Band	6 GHz - 8.5 GHz	2.4 GHz	2.4 GHz - 2.48 GHz	5.725 GHz - 5.875 GHz	1.575 GHz, 1.227 GHz
Accuracy / m	0.3	0.3	4[1]	0.1	8, 0.2 with DGPS
Update Rate	33.75 Hz	10 Hz	3 Hz[1]	25 Hz	1 Hz
Range / m	160	n/a	n/a	400	n/a
Comm. channel	✓	✓	✓	×	×
Infrastructure	fixed, cabled	wireless	wireless	wireless	satellite
Remarks	location server based		test with 4 anchors and 1 mobile	directional antennas, phased array	

1 author's measurement

Table 2.1: Comparison of state-of-the-art radio frequency localization systems

3 FMCW Ranging and Synchronization

3.1 Ranging Basics

This section shall provide an introduction to the FMCW ToF measurement principle according to [Gie10, Str13]. It is based on the reflective radar front end model shown in Fig. 3.1(a). At suitable points during the derivations, the model will be extended to the two-way radar.

The basic ideal reflective radar front end consists of a chirp generator, transmit and receive antennas, a signal multiplier or mixer, which multiplies received and transmitted signals, and a signal processing block containing filtering and calculation of a spectral representation of the base band signal, from which the distance to the target can be determined.

During transmission, a linear frequency chirp with bandwidth B_{fm}, starting frequency ω_0 and duration T_{fm} as depicted in Fig. 3.1(b) is generated. The instantaneous angular frequency $\omega(t)$ is a linear function of time.

$$\omega(t) = \omega_0 + \mu' t \tag{3.1}$$

The transmitting signal is then described by

$$s_{\mathrm{tx}}(t) = A_{\mathrm{tx}} \cdot \cos\left(\int \omega(t)\mathrm{d}t\right) = A_{\mathrm{tx}} \cdot \cos\left(\omega_0 t + \frac{\mu'}{2}t^2 + \varphi_{\mathrm{tx}}\right), \tag{3.2}$$

with A_{tx} being the voltage amplitude of the transmitted signal. The chirp gradient μ characterizes the slope of the chirp whereas μ' is used in conjunction with the angular frequency ω_0. φ_{tx} describes an arbitrary starting phase.

$$\mu = B_{\mathrm{fm}}/T_{\mathrm{fm}} \tag{3.3}$$

$$\mu' = 2\pi\mu \tag{3.4}$$

After being sent, the chirp is propagated in the medium with speed c, and reflected back from an obstacle to the transceiver. The passed time for the signal to arrive again at the transceiver then equals the ToF τ, which is calculated considering the round trip time to the obstacle and back and depending on their distance d_0 to

$$\tau = \frac{2d_0}{\mathrm{c}}. \tag{3.5}$$

The station receives a delayed replica of the transmitted chirp with changed signal