Victim Localization using RF-signals and Multiple Agents in Search & Rescue

Examensarbete utfört i sensorfusion vid Tekniska högskolan vid Linköpings universitet av

Jonas Ekskog & Jacob Sundqvist

LiTH-ISY-EX–15/4871–SE

Linköping 2015
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Linköping, 4 juni 2015
A common problem in existing Search And Rescue (SAR) systems is that they must be activated by the missing person in order to work. This requires an awareness of the the risk of becoming distressed, which in many cases is not feasible. Furthermore, most of the localization systems require specialized hardware.

In this thesis, the victim is assumed to wear a cellphone that could be located using readily available consumer electronics. A method of estimating the position of a transmitter, given radio signal measurements at different locations, is developed and verified with real and simulated data. A proof-of-concept system is built in which several users can jointly collect received signal strength data at different locations using mobile phones. The system analyzes the data in real-time and guides the users in the search by estimating the origin of the signal.

An outdoor field test is conducted in which the searchers using the system are able to locate the hidden target phone without prior knowledge regarding the position. We are able to localize the victim with an accuracy of 10-20 meters in a timely manner using android smartphones. This shows the potential of a similar system in SAR scenarios. However, more work is needed to make the system viable in real scenarios and to remove some of the delimitations of the current implementation.
Abstract

A common problem in existing Search And Rescue (SAR) systems is that they must be activated by the missing person in order to work. This requires an awareness of the risk of becoming distressed, which in many cases is not feasible. Furthermore, most of the localization systems require specialized hardware.

In this thesis, the victim is assumed to wear a cellphone that could be located using readily available consumer electronics. A method of estimating the position of a transmitter, given radio signal measurements at different locations, is developed and verified with real and simulated data. A proof-of-concept system is built in which several users can jointly collect received signal strength data at different locations using mobile phones. The system analyzes the data in real-time and guides the users in the search by estimating the origin of the signal.

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Linköping, May 2015

Jonas Ekskog and Jacob Sundqvist
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Notation</strong></td>
<td>ix</td>
</tr>
<tr>
<td><strong>1 Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background and motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Goal</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Methodology</td>
<td>2</td>
</tr>
<tr>
<td>1.3.1 Assumptions and delimitations</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Related work</td>
<td>4</td>
</tr>
<tr>
<td>1.5 Combitech Reality labs</td>
<td>5</td>
</tr>
<tr>
<td>1.6 Thesis outline</td>
<td>5</td>
</tr>
<tr>
<td><strong>2 Theory</strong></td>
<td>7</td>
</tr>
<tr>
<td>2.1 Radio signal properties</td>
<td>7</td>
</tr>
<tr>
<td>2.1.1 Signal-to-noise ratio</td>
<td>7</td>
</tr>
<tr>
<td>2.1.2 Free space propagation</td>
<td>7</td>
</tr>
<tr>
<td>2.1.3 Multipath propagation</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Radio propagation models</td>
<td>8</td>
</tr>
<tr>
<td>2.2.1 Log-distance path loss model</td>
<td>8</td>
</tr>
<tr>
<td>2.2.2 Forest propagation model</td>
<td>9</td>
</tr>
<tr>
<td>2.2.3 Wet earth propagation model</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Sensor measurements</td>
<td>9</td>
</tr>
<tr>
<td>2.3.1 Received signal strength</td>
<td>9</td>
</tr>
<tr>
<td>2.3.2 Time of arrival</td>
<td>10</td>
</tr>
<tr>
<td>2.3.3 Time difference of arrival</td>
<td>10</td>
</tr>
<tr>
<td>2.3.4 Angle of arrival</td>
<td>10</td>
</tr>
<tr>
<td>2.4 Positioning techniques</td>
<td>11</td>
</tr>
<tr>
<td>2.4.1 Trilateration</td>
<td>11</td>
</tr>
<tr>
<td>2.5 Regression techniques</td>
<td>12</td>
</tr>
<tr>
<td>2.5.1 Linear least squares</td>
<td>12</td>
</tr>
<tr>
<td>2.5.2 Non-linear least squares</td>
<td>13</td>
</tr>
<tr>
<td>2.6 Numerical techniques</td>
<td>13</td>
</tr>
<tr>
<td>2.6.1 Gauss-Newton</td>
<td>13</td>
</tr>
</tbody>
</table>
3 System overview

3.1 Mobile application module
   3.1.1 Existing system
   3.1.2 Extensions

3.2 Admin module

3.3 Simulation module
   3.3.1 Agent movement
   3.3.2 RSS observations

3.4 Analysis module
   3.4.1 Implementation of Gauss-Newton algorithm

3.5 Planning
   3.5.1 Scanning phase
   3.5.2 Locating phase

3.6 Cloud service

4 Field test

4.1 Localization tests

4.2 Coverage tests

4.3 SAR tests

4.4 Drone tests

4.5 Hardware

5 Results

5.1 Localization results

5.2 Coverage results

5.3 SAR results
   5.3.1 First SAR test
   5.3.2 Second SAR test

5.4 Drone results

5.5 Discussion

6 Conclusion

6.1 Conclusions

6.2 Future work
   6.2.1 Extend to cellular
   6.2.2 Frequency scanning
   6.2.3 Additional sensors
   6.2.4 Terrain and weather models
   6.2.5 Loss of communication
   6.2.6 Ad-hoc communication links

Bibliography
## Notation

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2G</td>
<td>Second generation mobile telecommunications technology</td>
</tr>
<tr>
<td>3G</td>
<td>Third generation mobile telecommunications technology</td>
</tr>
<tr>
<td>4G</td>
<td>Fourth generation mobile telecommunications technology</td>
</tr>
<tr>
<td>AOA</td>
<td>Angle of arrival</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code division multiple access (one of the schemes used in 3G)</td>
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<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>GSM</td>
<td>Global system for mobile communications (same as 2G)</td>
</tr>
<tr>
<td>LLS</td>
<td>Linear least square</td>
</tr>
<tr>
<td>NLLS</td>
<td>Non-linear least square</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RSS</td>
<td>Received signal strength</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received signal strength indication</td>
</tr>
<tr>
<td>SAR</td>
<td>Search and rescue</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>SSID</td>
<td>Service set identification (a unique identifier of a wireless network)</td>
</tr>
<tr>
<td>TDOA</td>
<td>Time difference of arrival</td>
</tr>
<tr>
<td>TOA</td>
<td>Time of arrival</td>
</tr>
<tr>
<td>TOF</td>
<td>Time of flight (same as TOA)</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned aerial vehicle</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Background and motivation

There are a variety of existing systems available to aid SAR operations. Such systems include RECCO® reflectors (RECCO [2015]), avalanche receiver/transceivers (Pieps [2015]), airplane flight recorders (archive [2015]), Global positioning system-tracking (GPS) etc. All the previous mentioned techniques require the user to be aware of the risks beforehand to be able to assist the search team. There are only a few techniques that can locate a victim that is unprepared or unaware of the risks, such as infrared cameras (FLIR [2015]), cellular tracking (wikipedia [2015a]), radar (Jet Propulsion Laboratory [2015]), satellite imagery and manual search (Williams [2005]). Out of these techniques, only infrared cameras, cellular triangulation and manual search are used in earnest.

In SAR operations it can be difficult to locate the victims. There are several reasons such as rough weather, terrain, or if the victim is unable to assist the rescue due to injury or other circumstances. According to Nacka-Värmdö Räddningssällskap [2006], rescue personnel in these situations often rely on observations about the victims intentions and possible locations. These observations create large search areas of possible victim locations. Since the rescue teams are resource-constrained, the search has to be carried out in an efficient manner. Therefore, the search areas are prioritized according to information available and previous knowledge of similar scenarios.

With recent advances in unmanned vehicle technologies, it should be possible to aid SAR operations by providing cheap information gathering capabilities. These vehicles could be used to determine if an area is of interest to reduce the search area of the SAR operation.
The last few years explosion in use of smart phones has enabled the use of additional sensors to help locate the victim. There are for example apps at ski resorts that report position data at regular intervals to the local authorities, enabling access to relevant data quickly in SAR scenarios. There is also the possibility of locating mobile phones from its normal usage via Wi-Fi\textsuperscript{1}, Bluetooth or cellular signals. If the phone is out of range of cellular networks, it still sends out requests to connect. These signals could be intercepted and triangulated with the right equipment, enabling cellular triangulation even in areas without cell coverage. Wi-Fi works in a similar way by transmitting probe requests searching for networks. Probe requests can be intercepted and analyzed, even without expensive hardware (Xu et al. [2013]).

By combining multiple agents\textsuperscript{2} the localization process is expected to be more accurate and less time consuming. This would enable SAR operations to use inexpensive and expendable equipment to search large areas and possibly locate the victim faster.

1.2 Goal

The main goal of this thesis is to investigate if Received Signal Strength (RSS) observations done by search agents equipped with smartphones can be used to locate a victim in a SAR scenario. An intermediary goal will be to simulate RSS measurements at different locations, estimating the distance from the origin of the signal to each agent, and deriving the approximate position of the transmitter. The movement of the agents ensures that the measurements are sufficiently independent so that the position of the target can be found with sufficient accuracy. This information can then be used to plan and execute an outdoor field test with Unmanned Aerial Vehicles (UAV).

1.3 Methodology

This thesis focuses on building a system of multiple agents with RSS measurement capabilities, using consumer hardware. This system can then be used to locate a victim by collecting data and providing a position estimate in real time.

This thesis is divided into four phases:

**Phase 1:** Build an understanding of localization algorithms and RF signal properties.

**Phase 2:** Extend the existing Mobile Rescue System with new features to enable automatic victim localization.

\textsuperscript{1}Wireless local area network based on the IEEE 802.11 standards

\textsuperscript{2}Agents is a general term for an entity capable of actions. In this thesis agents will refer to humans, dog patrols, vehicles or unmanned vehicles.
Phase 3: Simulate and fine-tune the localization algorithms in Mobile Rescue System.
Phase 4: Field test the system with UAV’s.

1.3.1 Assumptions and delimitations

To reach the goal within a reasonable amount of time, some simplifications, delimitations and assumptions are made.

Radio technology

Among the different radios in a mobile phone, the GSM radio has the highest probability to be turned on. It also has a long range, which makes it the most desirable to use in a SAR system. There are, however, legal concerns involved in using the GSM frequency band as well as great technical difficulties. For simplicity and ease of testing, we use the Wi-Fi radio instead. Although the range of the signals is shorter, the principles of signal propagation are similar Rappaport et al. [1996].

Target

In Xu et al. [2013] it is shown that most smartphones, with an activated Wi-Fi radio in client mode, can be detected using cheap hardware (20-50$). However, due to time constraints we simplify the system by setting the target phone of the victim in hot spot mode. This enables measurements from all smartphones with a Wi-Fi chip. The radio signals in access point mode and in client mode will have similar RSS. The following assumptions are made:

- The power level of the transmitter is kept constant during the search.
- The target is stationary during the search.

Terrain

The terrain is modelled as a smooth sphere, without vegetation or hills. As such, interference with RF signals is modelled as noise.

Communication

In real SAR scenarios at a mountain or at sea, or at some in other way remote locations, cell coverage is not guaranteed.

Legal issues

In some countries, there are legal implications related to certain RF bands. However, Wi-Fi lies in a public frequency band, and should not pose any legal issues. Laws concerning UAV’s will not be considered in this thesis.
1.4 Related work

1. Gustafsson and Gunnarsson [2008] discusses self calibrating sensor models for various data, including RSS measurements. These models is the core of this thesis and have been used with great success.

2. Gustafsson and Gunnarsson [2007] discusses energy based localization models and its fundamental theory for RSS localization as well as verification of the models.

3. Sichitiu and Ramadurai [2004] suggests using a moving beacon to locate sensor nodes in a wireless sensor network. The moving beacon has to be calibrated beforehand which this thesis avoids by using a self-adaptive approach.

4. Kumar et al. [2014] suggests methods for localizing 4G signals by using data in the physical layer of the 4G network stack. The results suggest that it is possible to distinguish between signals. These result would be an important step for future work.

5. Lui et al. [2011] shows that there are large differences in RSSI measurements between different hardware manufacturers and chipsets. The paper suggests that some chipsets are better than others for RSS based localization. Unfortunately all the chipsets discussed are out of date.

6. Dil et al. [2012] shows that it is possible to have a self-adaptive localization calibration in a dynamic environment. The article also suggested that by surrounding the target with measurements, a better estimate can be found. This assumption is used in the field-test to try and provide a good position estimate.

7. Bitirgan et al. [2011] provides tests for propagation path loss in woodland terrain on different frequency bands. If trees are in direct line of sight of the transmitter the RSSI could potentially be decreased by up to 4 dB per tree.

8. Helhel et al. [2008] suggest methods for calculating propagation path loss due to weather effects. The results show that wet earth and wet trees can significantly reduce signal strength.

9. Xu et al. [2013] discusses methods for a large-scale outdoor mobile tracking system for crowd data collection. A similar system is used in this thesis to gather RSSI measurements.
1.5 Combitech Reality labs

Reality labs is a creative environment initiated to realize projects in an effective and efficient manner. They key to its success is to combine techniques from different business areas to develop new techniques and customer value. The lab regularly make demonstrations, prototypes, products, projects and platforms with usability, security and the environment in mind. It also serves as a central node in Combitech, were ideas can be formed and resources can be acquired to realize them.

The organization provides flexibility by enabling personnel from all over Combitech and Saab to support the projects. This creates a dynamic environment where specialized expertise can be acquired when needed or the opportunity for personnel to further develop their skills.

1.6 Thesis outline

Chapter 2 introduces concepts that have been considered in the thesis. Most of the concepts suggest different techniques for achieving the goal of the thesis, but only a handful of them are present in the actual implementation. Chapter 3 describes the system, its extensions, architecture and implementation details. Chapter 4 describes the variety of tests performed in the field test and their respective parameters. Chapter 5 describes and discusses the results from the field tests and distinguishes between different phones to enable hardware comparisons. Chapter 6 concludes lessons learned from the system, field tests, results and future work.
2.1 Radio signal properties

2.1.1 Signal-to-noise ratio

Signal-to-Noise Ratio (SNR) is the relation between the signal energy and the energy of the noise (Larsson [2012]). The noise is assumed to be white random noise.

\[
SNR_{dB} = 10 \log_{10} \left( \frac{E_x}{E_w} \right) \quad (2.1)
\]

In this expression, \(E_x\) is the signal energy of signal \(x(t)\) and \(E_w\) is the signal energy of white noise \(w(t)\).

2.1.2 Free space propagation

For the idealized case of free space air propagation and no multipath effects, the Friis equation describes the relation between transmitter and receiver powers.

\[
\frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi R} \right)^2 \quad (2.2)
\]

In this expression, the output power of the transmitting antenna is \(P_t\) and the available power of the receiving antenna is \(P_r\), \(G_t\) and \(G_r\) are the gains of the transmitting and receiving antennas, \(\lambda\) is the wavelength and \(R\) is the distance between the antennas.

2.1.3 Multipath propagation

Multipath propagation is the effect of waves reaching the receiving antenna by multiple paths (Larsson [2012]). This can be caused by for example atmospheric
ducting, ionospheric reflection and refractions creating multiple paths of propagation of the original wave. These multiple paths can cause constructive or destructive (fading) interference as well as phase shifts.

\[ y(t) = \sum_{i=1}^{M} \alpha_i x(t - \tau_i) \] (2.3)

In this expression, \( y(t) \) is the received signal, \( x(t) \) is the transmitted signal, \( M \) is the number of paths, \( \tau_i \) is the amount of seconds the path is delayed and scaled in amplitude by a factor of \( \alpha_i \).

## 2.2 Radio propagation models

Radio wave propagation is a function of frequency and the distance between transmitter node and receiver node Rappaport et al. [1996]. Different radio propagation models are used to model signal propagation in various environments.

### 2.2.1 Log-distance path loss model

The log-distance path loss model as described by Andersen et al. [1995] states that if the received power at distance \( d_0 \) is \( P_0 \), then the power lost at distance \( d \) is logarithmically proportional to the ratio \( \frac{d}{d_0} \). Thus, the received power at distance
2.3 Sensor measurements

d can be expressed as follows:

\[ P(d) = P_0 - 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + e \]  \hspace{1cm} (2.4)

In this expression \( \gamma \) is the path loss exponent and \( e \) is a Gaussian distributed error component. The path loss exponent is dependent on the environment, and in infinite vacuum it has a value of 2.

2.2.2 Forest propagation model

Bitirgan et al. [2011] introduces a forest propagation model that suggests that trees in the direct signal path have a large effect on signal strength. Depending on technology the propagation path loss measured is 1dB at CDMA 2100MHz, 2dB at GSM 900MHz and 4dB at GSM 1800MHz per tree in line of sight.

2.2.3 Wet earth propagation model

Helhel et al. [2008] discusses signal propagation path loss depending on weather conditions. The article suggests that wet trees provides a far larger path loss effect than the increased earth conductivity associated with heavy rain. Combined with the concepts introduced in section 2.2.2 the weather effects, especially heavy rain has a large effect on signal propagation in woodland areas.

2.3 Sensor measurements

There are several measures from a signal that could be used to localize a transmitter. Either by signal energy, SNR, Time Difference Of Arrival (TDOA), Angle Of Arrival (AOA) or information inside the signal such as timestamps. These measures are described in detail below. The basic sensor model used in this thesis (Gustafsson [2010]).

\[ y = h(x; p) + e \]  \hspace{1cm} (2.5)

In this expression, \( x = (x_1, x_2, x_3)^T \) is the position of a target and \( p = (p_1^T, p_2^T, ..., p_N^T)^T \) contains the locations \( p_k = (p_{k,1}, p_{k,2}, p_{k,3})^T \) of each sensor. The distance between the target and each sensor \( r_i \) can be calculated by:

\[ r_i = \|x - p_i\| \]  \hspace{1cm} (2.6)

2.3.1 Received signal strength

RSS is a measure of how strong the signal is at the receiver location, this is usually taken from the Received Signal Strength Indication (RSSI) of the device. Note that there is no exact definition of how to achieve this measure. Lui et al. [2011] showed that different chip manufacturers use different techniques and parameters to calculate the RSSI result and the results can vary greatly by chip sets of the same manufacturer. The most common techniques are measures of signal energy
or SNR, see wikipedia [2015b].

### 2.3.2 Time of arrival

Time Of Arrival (TOA) is a measurement of time differences between receiver and transmitter. This scheme is sometimes called Time Of Flight (TOF) and it requires highly accurate clocks as well as synchronization between nodes. TOA is commonly used in GPS and cellular localization systems. The message is timestamped in the transmitter before the message is sent over RF and then timestamped again when the message is received. The time difference of these timestamps is then used together with known facts about the RF propagation effects, such as the propagation velocity through a certain material, to calculate the distance (Gustafsson [2010]).

\[
t_i = \frac{r_i}{v}
\]  

(2.7)

In this expression, \( t_i \) is the time of arrival at sensor \( i \), \( r_i \) is the distance between the target and sensor (eq. 2.6) and \( v \) is the velocity of the RF.

### 2.3.3 Time difference of arrival

TDOA is a measurement of the time differences between a transmitter and multiple receivers. As in TOA, highly accurate clocks and synchronization between nodes is required. TDOA can be used to calculate the relative position between each of the receivers to the transmitter. By using each received measurement a more accurate estimate can be calculated (Gustafsson [2010]).

\[
t_{i,j} = \frac{(r_i - r_j)}{v}
\]  

(2.8)

In this expression, \( t_{i,j} \) is the time difference of arrival between sensor \( i \) and \( j \), \( r_i \) and \( r_j \) is the distance between the target and sensor \( i/j \) (eq 2.6) and \( v \) is the velocity of the waveform.

### 2.3.4 Angle of arrival

AOA can be determined by measuring TDOA at several antennas in array configuration. Depending of the antenna array configuration angles in different planes can be detected \( x, y \) and \( z \). AOA provides a measure of direction of the transmitter and can be used with other measures to provide a more accurate estimate of the location (Gustafsson [2010]). AOA in two-dimensions can be calculated by:

\[
\phi_i = \arctan(x_1 - p_{i,1}, x_2 - p_{i,2})
\]  

(2.9)

In this expression, \( \phi_i \) is the angle of arrival from the target at position \( x \) to the sensor \( i \) at position \( p_i \).
2.4 Positioning techniques

Various positioning techniques exist to localize a transmitter, the most common techniques uses a variety of stationary receivers to estimate a position. This thesis focuses on localizing a stationary transmitter using multiple mobile receivers with known positions instead, however the principles are similar and are described below.

2.4.1 Trilateration

Trilateration is a technique used to compute a position using several measures of distance (Gustafsson [2010]). It is commonly used in GPS and navigational systems. The main advantage of trilateration is that it does not depend on measured angles. Trilateration can be used with different geometries such as circles, spheres or triangles depending on the applications needs. Usually three different measurements are needed to compute the relative location, but increasing the amount of measurements should in theory yield a more accurate result (Gustafsson [2010]).

By measuring the distance to the target, circles are formed around the measurement point. The intersection between the circles are computed as points of interest, if three or more circles intersects, an area of interest can be calculated and the relative position can be determined.

![Trilateration diagram](image_url)

*Figure 2.2: Trilateration in two dimensions.*
\[
\begin{align*}
\begin{cases}
    r_1^2 &= x^2 + y^2 \\
r_2^2 &= (x - d)^2 + y^2 \\
r_3^2 &= (x - i)^2 + (y - j)^2
\end{cases}
\end{align*}
\] (2.10)

In this expression, \( r_1, r_2, r_3 \) is the radius of the circles, \( x \) and \( y \) are positions and \( i, d \) and \( j \) are offsets in position.

In three-dimensional trilateration, spheres are most commonly used. This enables the trilateration to compute a volume of interest (relative position in three dimensions) creating zero, one or two possible locations. Further assumptions are required to find the correct location, this is usually done by exploiting problem specifics such as non-zero values.

\[
\begin{align*}
\begin{cases}
    r_1^2 &= x^2 + y^2 + z^2 \\
r_2^2 &= (x - d)^2 + y^2 + z^2 \\
r_3^2 &= (x - i)^2 + (y - j)^2 + z^2
\end{cases}
\end{align*}
\] (2.11)

In this expression, \( r_1, r_2, r_3 \) is the radius of the circles, \( x, y \) and \( z \) are positions and \( i, d \) and \( j \) are offsets in position.

### 2.5 Regression techniques

Due to imperfection in the distance measurements, the data collected will be ambiguous. To overcome this problem, different curve fitting techniques are required. These approximations can be used in algorithms to predict the victim’s location.

#### 2.5.1 Linear least squares

Linear Least Squares (LLS) is the basic approach to fit measured data into a linear function (Gustafsson [2010]). It minimizes the sum of squared differences between the estimated and measured data to provide a linear fit. To accomplish this, we consider the observed data an overdetermined linear system with \( n \) variables and \( m \) equations:

\[
y_i = \sum_{j=1}^{n} X_{i,j} \beta_j, (i = 1 \ldots m)
\] (2.12)

Here the unknown vector \( \beta \) contains the coefficients, or partial derivatives, for each of the variables. Solving the problem involves finding the coefficients that minimize \( S(\beta) \) which is defined as the sum of squares of the residual function:

\[
S(\beta) = \sum_{i=1}^{m} \left| y_i - \sum_{j=1}^{n} X_{i,j} \beta_j \right|^2
\] (2.13)
2.5.2 Non-linear least squares

Non-Linear Least Squares (NLLS) tries to fit measured data to a non-linear function (Gustafsson [2010]). The function is first approximated using a linear model, then the function will be iteratively refined.

\[
V_{NLS}(x) = \frac{1}{2} \sum_{k=1}^{N} \varepsilon_k^2(x)
\]  

(2.14)

In LLS the solution is unique but in NLLS there are usually multiple solutions. There are several methods that provide a local optimal solution to the problem such as gradient-, steepest descent- and direct search-methods.

2.6 Numerical techniques

There are numerous numerical optimization techniques to solve the system of equations created by the radio localization system. Patwari et al. [2003] uses a conjugate gradient method. In this thesis however, we use the Gauss-Newton method to solve NLLS problem associated with our radio localization system.

2.6.1 Gauss-Newton

The Gauss-Newton method is a numerical technique to solve NLLS problems (Gustafsson [2010]). It is an improved version of Newton’s method for finding the minimum of a function. The algorithm requires a good initial guess to converge properly and find the global minimum of function \( S \). As can be seen in equation 2.15, the NLLS to be solved has \( m \) equations and \( n \) variables. The function \( S \) expresses the squared sum of residuals from the current estimate.

\[
S(\beta) = \sum_{i=1}^{m} r_i(\beta)^2
\]  

(2.15)

\( r = (r_1, \ldots, r_m), \beta = (\beta_1, \ldots, \beta_n) \)

To get to the next estimate \( \beta^{(s+1)} \), the partial derivatives of the residual function \( J_r \) is used to calculate a direction and range of a step to be taken from the current estimate \( \beta^{(s)} \), as shown in equations 2.16 and 2.17.

\[
(J_r)_{ij} = \frac{\partial r_i(\beta^{(s)})}{\partial \beta_j}
\]  

(2.16)

\[
\beta^{(s+1)} = \beta^{(s)} - (J_r^T J_r)^{-1} J_r^T r(\beta^{(s)})
\]  

(2.17)

The iteration is stopped when one of two conditions is met:

1. the length of the step is so small that the estimate can be considered to have converged
2. the number of iterations has reached a specified limit without the estimate converging

When the iteration stops from the first condition, the algorithm has found a minimum of the function $S$, but it is impossible to know if it is local or global. When it stops from the second condition, the estimate did not converge at a solution at all.
The purpose of the system that is constructed in this thesis project is to collect measurement data over large areas and predict the origin of the radio signal measured. To reduce implementation time, the already existing Mobile rescue system was used as a base, since it provided data synchronization, map and visualization services (see section 3.1 for details). These services were extended and divided into modules that communicate via the Internet.

The mobile application component handles the collection of the measurement points, the analysis component processes the data to produce a position estimate, the agent simulator moves virtual agents through the search area and the search planning module issues movement orders. In this implementation the analysis, simulation and planning modules are run in sequence in the same process on the backend. Note that these processes can run on different machines. To communicate between modules, a cloud service is used, which also acts as backup storage. This chapter presents a description of the different modules.

3.1 Mobile application module

Mobile Rescue System is an android app originally developed by Combitech AB. It is used to coordinate SAR operations, providing a unified overview of the operation, as well as member to member communication.

3.1.1 Existing system

The existing application is a prototype system that provides near real-time positions of its participants in a map interface. This enables a unified overview
Figure 3.1: The modules of the system.

Figure 3.2: Screenshot of the mobile application in use.

of the entire operation, which in turn enables easier cooperation and coordination between search participants. The idea behind the system is that each search participant brings a smart phone with the app installed to receive continuous information during the operation. Known facts about the target are shared in the app, together with a picture of the missing person. The users can create POI’s\(^1\) on the map to bring attention to

\(^1\)Point Of Interest
3.1 Mobile application module

relevant findings that could aid in the search effort. The app also enables direct communication with other users and the possibility to post public messages via a bulletin board interface.

![Figure 3.3: The previous architecture for the mobile application.](image)

### 3.1.2 Extensions

The purpose of extending the existing mobile application is to enable the agents to collect RSS measurements, but also to visualize the data from the simulation, analysis and planning modules and to specify a common communication interface that connects the different parts of the system. To enable these features, some changes to the architecture and communication interfaces are necessary, as can be seen in figure 3.4.

The primary extensions of the Mobile rescue system application are described below.

**RSS observations**

The mobile application collects RSS measurements from different positions by continuously performing Wi-Fi scans, which results in a list of heard Wi-Fi access points and associated RSS measurements. This is done in a background service that iterates over the list of discovered SSID:s, finds the one associated with the target phone, and pushes the RSS value to the cloud.
Multiple sessions

In the old application, all data ends up in the same bucket in the cloud service. It is impossible to separate new data from old, and there is no possibility to delete data without wiping the entire database. The new implementation supports multiple sessions. The idea is that a new session is started for every new search operation. This is a great help during development but also when the system is deployed, since multiple sessions can run simultaneously against the cloud storage without interference.

Agent classification

In a search operation, different agents typically have different needs and capabilities. Therefore a classification of agent type is introduced. Some suggested agent types include Human, Dog (patrol), UAV and Helicopter.

Map objects

In order to visualize the new information introduced in the system (heat maps, target estimates and search grids), new map objects are implemented. This enables real-time visualization of the analyzed data, which can guide the searchers.

Playback feature

The data is stored in the cloud service in such a way that the chain of events is traceable afterwards, and no information is destroyed. This could enable a playback feature that reanimates the search operation in the application (or some other viewer) as if it was running live. Searchers could use this feature to assess the operation to improve their routines. The implementation of such a playback viewer, however, is left for future work.
3.2 Admin module

The admin interface is a web application that is able to start and stop the backend node. It can also visualize data in real time, start simulations, set simulation parameters, purge data records and generate test sessions. These features greatly support the field testing capabilities of the system.

![Figure 3.5: The admin interface for one of the test sessions.]

3.3 Simulation module

The main objective of the simulator is to generate measurement points to test the analysis module of the system. It can also be used for training scenarios in which searchers practice using the system. The simulation runs on the backend node in the system and has several features:

1. Simulate multiple virtual agents moving through the search area according to the planner’s decisions.

2. Inject simulated RSS measurements according to different sensor models into existing agents (virtual or physical). The sensor simulation uses the widely used log-distance path loss model (see section 2.2.1). For this feature, the simulator is required to be aware of the location of the (virtual or physical) target transmitter.

3. Introduce errors to the measurements, such as signal noise and location errors.

3.3.1 Agent movement

The movement of virtual agents is simulated just like in a computer game. Upon entering the routine, the time elapsed since the last iteration is estimated, and multiplied with the speed of the agent. This provides the distance the agent travels towards its goal in this iteration.
3.3.2 RSS observations

Simulating measured signal strength for an agent is a matter of measuring the actual distance between the agent and the transmitter, and using this value as input to the log-distance path loss model. Using only this setup would generate a perfect monotonically decreasing curve, but in reality some random noise is expected. For this purpose a Gaussian distributed error with a standard deviation of 8 dB is added to the RSS, creating a more realistic noise on the measurements.

3.4 Analysis module

The backend node includes an implementation of the Gauss-Newton algorithm that estimates the position of the transmitter given the RSS observations collected by the agents. Every observation consists of a GPS coordinate and the measured RSS value in that point. After combining the information from all the measurements and creating the position estimate of the transmitter, the estimate is pushed through the cloud service to the other smartphones.

3.4.1 Implementation of Gauss-Newton algorithm

In order to use the RSS measurements for estimating the position of the transmitter, the coordinates are converted from spherical to Cartesian (XYZ) so that the origin lies in the center of the earth, the xy-plane intersects with the surface at the equator, and the z-axis goes through the poles. The Gauss-Newton algorithm needs an initial guess to work, and in this implementation the position of the strongest RSS reading is used. Using the log-distance path loss model normally requires the knowledge of the transmitted power in order to deduce the distance of travel from the received power. The transmitted power is estimated as the fourth variable in addition to the x-, y- and z-coordinate of the transmitter. This way, we do not need a prior knowledge about transmission power. The function that is minimized by the Gauss-Newton algorithm equals:

\[
S(\beta) = \sum_{i=1}^{m} r_i(\beta)^2
\]  

(3.1)

This equation describes the sum of squared residuals (NLLS), where \(m\) is the number of observations and \(\beta\) is a vector that consists of the 4 unknown variables. As in all equation systems, \(m\) is required to be greater than the number of unknowns, four, in order to find any solution at all. The residual function is chosen as follows:

\[
r_i(\beta) = |b_i - (\beta_4 - 10\gamma \log_{10}(|\hat{p} - p_i|))|
\]  

(3.2)

The function expresses the difference between the measured RSS in point \(i\) and the value given by the log-distance model based on the distance to the estimated position to position \(i\). In the expression, \(b_i\) is the actual measured RSS reading, \(\hat{p}\) is the estimated position of the transmitter and \(p_i\) is the actual position of the measurement point.
3.5 Planning

The planning part of the system includes algorithms for automated planning of the agent movements and runs on the backend. Based on the situation analysis provided by the analysing module, the planning module issues orders to each idle agent and communicates them via the cloud service. This part of the system is mostly used when simulating agents, but can optionally be used by physical agents as well. The planning module issues orders in two phases:

1. Scan the search area for a signal (Scanning phase)
2. Locate the transmitter (Locating phase)

3.5.1 Scanning phase

The purpose of this phase is to quickly cover as much of the search area as possible to get a rough sense of where to concentrate the search effort. The implementation for this phase is very simple (fig. 3.6): every idle agent is directed to the nearest unexplored grid cell. The phase is over when the estimated position has iterated a certain number of times, or if the entire grid has been explored.

3.5.2 Locating phase

In the locating phase, the agents are guided to ensure fast information gathering so that the victim can be found in a timely manner (fig. 3.7). This is done by surrounding the transmitter with measurements, effectively reducing the localization error of the transmitter in an efficient manner.

3.6 Cloud service

All cloud communication is done through a cloud service called Firebase\(^2\) which propagates the data automatically to all connected clients. While this relies on a healthy Internet connection at all times, this solution also provides modularity which enables easier changes of cloud service provider or other parts of the system. By using the Internet, additional modules can easily be attached to the system without being physically at the site of the search operation.

---

\(^2\)Firebase is a cloud service, that provides real time updates of data to all clients within 200ms.
Figure 3.6: The simple exploration algorithm used in the scanning phase. Blue cells represent already explored cells, green cells are the agent's current position and white cells are unexplored cells.
Figure 3.7: Surrounding the target with measurements during the localization phase. The red cell represents the position estimate, blue cells are already explored cells, green cells are the agents current position and white cells are unexplored cells.
The field tests were conducted on a large open grass field (Figure 4.1) and a forest (Figure 4.2) in the outskirts of Linköping. The tests used a smartphone as target, which was configured to act as a Wi-Fi access point\(^1\). It was placed on a camera tripod at approximately one meter above ground for all tests, unless otherwise specified. This was done to ensure ideal signal conditions, such as RSS, range and line of sight. The GPS position of the target phone was assumed to be its true position.

Four different types of tests were conducted; *Localization*, *Coverage*, *SAR* and *Drone*. These tests were designed to validate the system as well as to test possible scenarios. The data collected can be useful in future work. This chapter presents a detailed description of aforementioned test types.

### 4.1 Localization tests

Localization tests were designed to provide measurements that improves the effectiveness of the localization algorithm. Surrounding the target with measurements ensures optimal localization results (Dil et al. [2012]). The agents travel at the edge of the field to provide measurements surrounding the target from all directions.

### 4.2 Coverage tests

Coverage tests were designed to cover the field with as many measurements as possible. This data could be used in future research.

\(^1\) Also known as "hotspot mode"
Figure 4.1: The grass area used for the localization, coverage, drone and the first SAR test. The size of the rectangle is roughly 133 x 218 meters.

4.3 SAR tests

SAR tests were designed to verify the system, by hiding a smartphone and letting the search crew find it using only the system and the information it provides. The placement of the target equipment made it unlikely for a search crew member to accidentally find it by just walking past it. Two SAR tests were conducted during the field test and the target smartphone was hidden instead of being on the camera stand. In the first test the target transmitter was hidden at the edge of the field under some leaves. The second test was conducted in a thick forest and the target smartphone was hidden under some branches in the underbrush at the edge of the search area.
4.4 Drone tests

Drone tests were designed to analyse the possibility of using unmanned aerial vehicles with the system. The test was conducted using a quadcopter\(^2\) with Ardupilot\(^3\) and a Samsung Galaxy S II Plus to provide measurements. The test mimics the localization tests but with a drone moving at a higher velocity. These tests are intended to test how well the system works with a low density of RSS measurements and relatively infrequent GPS position updates.

---

\(^2\)A quadcopter is a radio-controlled UAV helicopter with four rotors.

\(^3\)Ardupilot is an open-source software that was used to control the quadcopter.
Figure 4.3: The quadcopter used for the drone tests.

4.5 Hardware

During the test, five phones were used to capture RSS and GPS measurements. We use these measurements to analyze the influence of hardware differences on the localization performance (Lui et al. [2011]).

<table>
<thead>
<tr>
<th>Phone</th>
<th>Role</th>
<th>ID</th>
<th>Wi-Fi chipset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samsung Galaxy S II Plus</td>
<td>Agent</td>
<td>RL02-S2+</td>
<td>Broadcom BCM4334</td>
</tr>
<tr>
<td>Samsung Galaxy S II Plus</td>
<td>Agent</td>
<td>RL03-S2+</td>
<td>Broadcom BCM4334</td>
</tr>
<tr>
<td>Galaxy S III</td>
<td>Agent</td>
<td>JE-S3</td>
<td>Broadcom BCM4334</td>
</tr>
<tr>
<td>Samsung Galaxy S4 Mini</td>
<td>Agent</td>
<td>MP-S4 mini</td>
<td>Qualcomm Snapdragon 400</td>
</tr>
<tr>
<td>LG G3</td>
<td>RSS-Target</td>
<td>JS-LG G3</td>
<td>Broadcom BCM4339</td>
</tr>
</tbody>
</table>

Table 4.1: Phone type, their roles, id and chipsets that were used during the field test.
The session data from all the tests was stored in the cloud and analyzed offline. The data was spliced into data sets only containing data from a single agent, as if that agent had been alone in the session. Then position estimates were produced at the same points in time as in the original session. This data was used to produce two kinds of result sets; a time-lapse of map objects, and the error in the target estimates plotted over time.

The map time-lapse enables comparison in performance between the different phones. The time-lapse graphs consist of multiple maps, each row representing a specific moment in time and each column corresponding to a subset of the agents. The legend of the maps is found in Table 5.1.

We also analyze the localization accuracy as a function of time, because the position estimate changes over time when more RSS measurements become available. This analysis allows us to analyze the influence of hardware differences and individual agents on the localization performance. Each line in the graph corresponds to a subset of the agents as found in the legends of each plot.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green triangle</td>
<td>True target position</td>
</tr>
<tr>
<td>Red X</td>
<td>Most recent target estimate</td>
</tr>
<tr>
<td>Red line</td>
<td>Path of target estimates</td>
</tr>
<tr>
<td>Black ring</td>
<td>RSS measurement point</td>
</tr>
<tr>
<td>Magenta line</td>
<td>Path taken by agent</td>
</tr>
<tr>
<td>Dashed black line</td>
<td>Reference search grid</td>
</tr>
</tbody>
</table>
5.1 Localization results

Four localization tests were conducted during the field test and time-lapses of the resulting sessions can be seen in Figure 5.1, 5.3, 5.5 and 5.7. The localization performance graphs can be seen in Figure 5.2, 5.4, 5.6 and 5.8. In all of the tests the error stabilizes at different times. Points of interest are marked at times $t_1$, $t_2$ and $t_3$.

Time $t_1$ represents the time where a large decrease in the estimation error has occurred as can be seen in the localization performance graphs. The corresponding movements of the agents can be seen in the time-laps graphs.

Time $t_2$ represents the time where a small decrease in localization error has occurred and the position estimate starts to stabilize. The stabilization usually happens when the agents have started to surround the target with measurements.

Time $t_3$ represents the time where the target is completely surrounded with measurements.
Figure 5.1: Time-lapse of first localization test

Figure 5.2: Estimation error divided on different phones over time for the first localization test

Error in target estimation
Figure 5.3: Time-lapse of second localization test

Figure 5.4: Estimation error divided on different phones over time for the second localization test
**Figure 5.5:** Time-lapse of third localization test

**Figure 5.6:** Estimation error divided on different phones over time for the third localization test
Figure 5.7: Time-lapse of fourth localization test

Figure 5.8: Estimation error divided on different phones over time for the fourth localization test
5.2 Coverage results

One coverage test was conducted during the field test. The time-lapse of the session can be seen in Figure 5.9. The localization performance graph can be seen in Figure 5.10. In the localization performance graph different hardware are shown to stand out from each other.
Figure 5.9: Time-lapse of the coverage test

Figure 5.10: Hardware comparison between different phones over time during the coverage test
5.3 SAR results

Two SAR tests were conducted during the field test. The time-lapses of the resulting sessions can be seen in Figure 5.11 and 5.13. The localization performance graphs can be seen in Figure 5.12 and 5.14.

5.3.1 First SAR test

The first SAR test was conducted in an open area with line of sight and provided excellent RSS readings throughout the test. This can be seen in Figure 5.14, where the position estimate error decreases with time for all hardware before stabilizing.

5.3.2 Second SAR test

The second SAR test was conducted in a thick forest with poor line of sight. This created noise and loss of measurements, which reduced the effectiveness of the system. This is clearly shown in Figure 5.13 where some of the phones are unable to decrease the position estimate error. But the position estimate using all the phones were able to stay within 20-30 meters.
Figure 5.11: Time-lapse of first SAR test

Figure 5.12: Hardware comparison between different phones over time for the first SAR test
Figure 5.13: Time-lapse of second SAR test

Figure 5.14: Hardware comparison between different phones over time for the second SAR test
5.4 Drone results

Five drone tests were conducted during the field test. The resulting time-lapse graphs can be seen in Figure 5.15. The localization performance graphs can be seen in Figure 5.16. In all drone tests the position estimate error is greatly reduced. Because the drone is able to surround the target with measurements in a timely manner. It should also be said that the first few measurements are from when the drone is still stationary on the ground. This can provide large errors in the position estimate since the RSS measurements can differ by up to 10dBm but the measured position remains the same.
Figure 5.15: Time-lapse of the drone tests

Figure 5.16: Error in estimated position over time for the drone tests
5.5 Discussion

The data from the localization tests shows that after a certain amount of measurements the localization error stabilizes in the range of 5-20m. This usually happens when measurement points are spread out sufficiently in space, which is an expected result (Dil et al. [2012]). However the time it took to get the localization error within reasonable limits seems very promising, especially when all phones work together to provide an estimate. We expect that the time required for the localization performance to stabilize decreases further by spreading out the search crew sufficiently.

In our small scale testing, there seems to be a correlation between the chipset and the corresponding localization performance. Our tests were resource constrained, which meant that we had to use the phones available. With further testing, one could determine which chip manufacturers would be the most suitable for these kind of measurements. Lui et al. [2011] did such a study, however with hardware that is currently outdated. It would be interesting to review and update the study with current hardware.

The SAR tests were mainly successful, since the search crew were able to find the target phone in both tests. In the first test, the position estimates were off by up to 20m. This was not a problem since the position estimate was sufficiently stable, so that the search crew could perform a manual search in the area of the position estimate until the phone was found. The manual search could also have been performed in a more timely manner, if the search crew would have had more experience with manual search patterns. In the second test, the estimates were worse than in the first. The error in the position estimate stabilized between 20 and 30 meters. This decreased performance was probably due to two reasons:

1. The test was performed in forest terrain, which influences the RSS measurements and thus localization performance.

2. The target was placed at the very edge of the search grid. This is a problem due to the way the estimation algorithm works, discarding estimates that lie outside the search grid. It is possible that a position estimate less than 20 meters from the true position was found north or east of the target. This would place the position estimate outside of the search grid, and cause the system to discard it.

The drone tests showed flaws with the current system, mainly because of the limited sampling frequency of RSS measurements and GPS updates. The speed of the quadcopter created large errors in positioning because the frequency of GPS updates is close to $\frac{1}{5}$ Hz, which is low in relation to the quadcopter’s speed. We had some problems polling the GPS with a higher frequency on the smartphones, related to CPU load. This is not considered a large problem, since the drones are
equipped with their own GPS and RSS hardware. However, we did not have time to integrate it to this system directly. There exist several off-the-shelf GPS systems that update their position at 10Hz and these could easily be integrated with the system either via micro controllers on the drone or with a USB connection to the phones. There exists off-the-shelf hardware that could be used to collect RSS measurements from all sources via monitoring capabilities (TP-Link [2015]).
6

Conclusion

6.1 Conclusions

The prototype system implemented in this thesis has shown that it is possible to build a system with consumer hardware that is able to aid in SAR operations by providing an additional tool to discover RF-signals that belong to the victim. This greatly reduces the search area and provides the resource constrained search crews with a more accurate position estimate. Since the hardware used in the prototype is inexpensive and lightweight, it could be mounted to several already existing platforms such as helicopters, snowmobiles and boats. This would increase the already existing vehicle capabilities. By introducing UAV’s equipped with a similar system, fast sweeps of large areas could be made semi-automatically to enable a fast response time in SAR operations such as sea- and mountain-rescue. There are also situations were it could be used to localize lost equipment such as flight data recorders\(^1\) or other RF equipment.

With that said, there are still several limitations that have to be addressed until the system is ready for commercial use. The largest limitation is the use of Wi-Fi technology because of its limited range and the fact that it might not be activated on the victim’s phone. The extension to GSM should be considered for further research. In addition, we assumed a single stationary victim, which is often not the case. If the system could provide off-grid communication, it would be especially potent in conditions with no cellular coverage since it still would be able to localize without the need of a base station.

\(^{1}\)Flight data recorder used in investigations of aviation accidents.
6.2 Future work

There are several extensions that could be made to the thesis. The following sections describe the most promising in our estimate. Most of the extensions require more expensive hardware and possibly custom made hardware.

6.2.1 Extend to cellular

If the system could be extended with 2G, 3G or 4G hardware there would be numerous improvements in performance. The localization would work on passive phones, the range would increase and the signal would propagate better through materials. The main problem with this approach is to distinguish different signals in a correct manner. There have been some research into the area such as Kumar et al. [2014], which proves that depending on implementation in the base stations, one can successfully distinguish between signals in the physical layer. Further investigation would be required, but it should be possible to create a prototype system.

6.2.2 Frequency scanning

If the system could scan multiple frequencies, it would be able to detect more signals and provide more versatility. This could be done using a software defined radio, that could listen to several frequency bands, process the information in hardware and then pass it on for further analysis.

6.2.3 Additional sensors

By adding additional sensors the information could be fused to create new data. This could be done by adding antenna arrays to provide angle of arrival measurements, which would greatly decrease the localization error. It could be possible to fuse with camera- and radar-technology to provide additional capabilities for the system.

6.2.4 Terrain and weather models

As suggested in section 2.2.2 and section 2.2.3 the radio propagation models could include terrain and weather effects. The overall localization algorithm could also use statistical knowledge about the terrain and weather to weight particular areas as more likely. For example areas of shelter in storm conditions or areas with water supply in barren terrain.

6.2.5 Loss of communication

It could be of interest to study what would happen to the system during loss in communication or measurements. Losses could occur due to line of sight issues with the victim radio signals, inability to connect to the Internet or a weak GPS signal.
6.2.6 Ad-hoc communication links

An interesting idea is to use the agents themselves to create an ad-hoc communication network\(^2\) between participants, creating a chain that can send messages between nodes in the system. This would be especially useful in remote locations where GSM coverage is an issue.

\(^2\)Ad-hoc networks is a general term for networks independent of pre-existing infrastructures.


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