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FOI-R--3841--SE
ISSN 1650-1942 February 2014

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Titel	Mätningar av signalstyrka för *signals of opportunity* – en realiserbarhetsstudie av möjligheten att använda RSS för lopslutning vid inomhuspositionering
Title	Received signal strength measurements utilizing signals of opportunity – A feasibility study on the use RSS for loop-closure in multisensor indoor positioning systems
Rapportnr/Report no	FOI-R--3841--SE
Månad/Month	February
Utgivningsår/Year	2014
Antal sidor/Pages	35 p
ISSN	1650-1942
Kund/Customer	Försvarsmakten
Forskningsområde	4. Informationssäkerhet och kommunikation
FoT-område	Ledning och MSI
Projektnr/Project no	E36044
Godkänd av/Approved by	Christian Jönsson
Ansvarig avdelning	Informations- och Aerosystem

Sammanfattning

Denna rapport analyserar möjligheten att använda mätningar av mottagen signalstyrka (RSS) på godtyckliga signaler, s.k. *signals-of-opportunity*, i syfte att förbättra noggrannheten i ett multisensorsystem för soldatpositionering. Radiosignalerna utsätts normalt för kraftig flervägsutbredning och dämpning inuti byggnader. Signalstyrkemätningar som görs på enskilda frekvenser utsätts för kraftig fädning, där flervägsutbredningskomponenter adderas konstruktivt eller destruktivt beroende på position, vilket medför en kraftigt varierande signalstyrka. Genom att istället jämföra signalstyrkemätningar vid multipla frekvenser (där sändarna ofta är placerade på olika positioner) så kan däremot en unik matchning erhållas mellan de uppmätta signalstyrkorna och en position.

I militära tillämpningar finns normalt inte möjligheten att i förväg skapa databaser med RSS-mätningar med tillhörande positionsangivelser. Det är först när en soldat, eller annan plattform, återvänder till en position som den redan har varit på som de har möjlighet att använda denna information. Soldaterna måste därför själva samla in och lagra uppmätta signalstyrkor (på flera samtidiga frekvenser) tillsammans med positionsinformation (och osäkerhetsestimat) från sina egna positioneringssystem. När de signalstyrkor som soldaten senare mäter är tillräckligt lika en uppsättning RSS-värden som tidigare lagrats i databasen så är soldaten nära en position som denne tidigare har varit på. Denna information kan då användas till att förbättra positionsnoggrannheten.

Mätningar har genomförts på signaler från TV och FM radio sändare, samt mobilmaster och TETRA-basstationer. Mätningarna visar att de mottagna signalstyrkorna, när multipla frekvenser mäts och jämförs samtidigt, kan ge ett positionsestimat. Försvårande faktorer är dock att signalstyrkorna varierar med tiden, och att antennens rotation och placeringen av antennen på soldaten kan påverka signalstyrkorna kraftigt. Påverkan skiljer dock kraftigt för de olika frekvenserna så en viktig frågeställning rör valet av frekvenser.

Inomhuspositionering baserat på enbart signalstyrkemätningar bedöms inte vara realiserbart med tillräckligt hög noggrannhet och tillförlitlighet, eftersom det Euklidiska avståndsmåttet kan indikera felaktiga positioner. Dessa felaktiga positionsangivelser kan dock filtreras bort genom att använda information från andra sensorer om mottagarna integreras i ett multisensorsystem. Tekniken med att använda signalstyrkemätningar kan då användas till att förbättra positionsnoggrannheten i ett framtida multisensorsystem för soldatpositionering, exempelvis genom att möjliggöra lopslutning då soldaten återkommer till tidigare besökta platser.

Nyckelord: Multisensorsystem för inomhuspositionering, RSS, signalstyrkemätningar

Summary

The aim of this work is to evaluate the feasibility of using received signal strength (RSS) measurements of existing signals in the environment, so-called signals of opportunity, as a sensor in a multisensor soldier positioning system. Radio signals are typically affected by severe multipath propagation and signal attenuation within buildings. RSS measurements on single frequencies are subject to fading, where multipath components are constructively and destructively combined depending on the location. The signal strength in indoor environments, for single frequencies, will have similar values at multiple positions; however, when combining a set of RSS values measured at different frequencies (often transmitted from different locations) they may provide an unique match between location and RSS vector.

There is typically no possibility in military applications to create a database with geo-referenced RSS values prior to deployment. Only when a soldier, or another platform, is revisiting an old position during the operation they will be able to know that they are close to a previously visited position. Hence, the soldiers must themselves collect and store RSS values while entering a building, together with location information from the soldier positioning system, and then compare the current RSS values with those stored in the database. When these values are sufficiently close to what is stored in the database, this yields information about the current position which can be used to improve the performance of the integrated multisensor system.

Measurements were performed on signals from FM radio, TV, mobile and TETRA base station transmitters. The measurements show how the received RSS is affected by the position. The study also investigates the uncertainties in RSS values that are introduced by the time variation of RSS and also how much shadowing and rotation of the antenna affects the measurements.

Indoor positioning based on RSS measurements alone will not be feasible with high enough accuracy and reliability, since the Euclidean distance metric can point at erroneous positions when a position is revisited. However, the erroneous position estimate may be discarded based on information from other sensors when the RSS positioning technique is integrated with a multisensor indoor positioning system. The RSS positioning technique may then be used to aid e.g. a soldier positioning systems accuracy and reliability, for instance by allowing the system to perform loop-closure.

Keywords: Multisensor indoor positioning, signals-of-opportunity, RSS

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1 Introduction

The main application for the work herein is a soldier positioning system, with a focus on urban operations. Currently, fielded soldier positioning systems are based upon stand-alone GPS receivers. However, systems based on multisensor approaches are under development and these are expected to become available on the market within a few years.

1.1 Project description

Accurate and reliable localization of soldiers in all environments, including urban and indoor operations, is a challenge that has not yet been solved. Existing systems are not able to provide sufficient accuracy (approximately three meters) while simultaneously fulfilling the stringent size, weight and cost requirements.

GPS (Global Positioning System) receivers can provide sufficient position accuracies in many environments. However, the GPS signals are very weak at the surface of the earth and they can easily be jammed. The GPS signal experiences reflection, scattering and attenuation in urban environments, and these effects may cause large position errors. Thus, the position accuracy and availability is often insufficient in urban environments, especially considering indoor operations.

By integrating the GPS receiver with additional positioning sensors, e.g. inertial sensors, magnetometers, barometric and/or imaging sensors, it is believed that the problem with providing an accurate soldier positioning system can be solved. Similar technologies can also be used in future positioning systems for small unmanned aerial/ground vehicles (UAVs/UGVs) and other vehicles operating in urban environments.

The project *Robust positioning for efficient C2* is a R&D project financed by the Swedish Armed Forces. The project started in 2011 and it ends in December 2013. The overall focus of the project has been to address research problems that are considered to be key areas for increasing the robustness and accuracy for military positioning systems. The aim is to demonstrate new technologies and possibilities for localizing soldiers and vehicles, with a particular emphasis on soldier positioning systems in urban environments.

1.2 Background on indoor RSS localization

In indoor operations a GPS receiver can exhibit a very large position error, and even modern high-sensitivity receivers exhibit a poor availability. However, there are strong signals of opportunity available indoors, such as those from FM-radio stations, broadcast TV-stations, mobile phone base stations, Wi-Fi access points etc.

Numerous radio-based techniques have been proposed for use in indoor positioning systems, typically based on Time Of Arrival (TOA), Time Difference Of Arrival (TDOA), Received Signal Strength (RSS) and/or Angle Of Arrival (AOA) information. These techniques have different requirements on either the signal waveform or on the receiver equipment. Some of them require precise time synchronization, which can be difficult to obtain in mobile indoor scenarios. A good survey of the feasibility for the different techniques for signals of opportunity is given in [1]. Low-cost, small and lightweight receivers can be used to measure RSS values, and such receivers are of particular interest for inclusion in future multisensor soldier positioning systems.

1.2.1 Wireless radio channel propagation characteristics

A transmitted radio signal interacts with the environment in an extremely complex manner. First of all, the radio signal experiences distance dependent signal attenuation (path loss). Furthermore, the radio signal is reflected from different objects, diffracted around obstacles, and scattered off various objects.

- Reflection is the result of radio waves impinging on objects with dimensions larger than the wavelength of the radio wave.
- Diffraction occurs when radio waves illuminate edges and corners of large obstacles. They act as secondary sources and re-radiate the radio wave around corners and edges.
- Scattering occurs when the dimensions of the object interacting with the radio wave are in the order of, or less than, the wavelength of the impinging wave.

One important effect of the complex interaction between the radio wave and the environment is that the antenna receives many signal components, which are more or less distorted and delayed. Fading is caused by the constructive or destructive addition of all received multipath components, which causes the rapid fluctuations in the received signal strength that are typical for wireless radio channels. The signal strength, for a narrowband radio system, may therefore vary rapidly in time and in space. Due to the shorter wavelengths, signals with high frequencies experiences fading with shorter spatial movements compared to lower frequencies.

1.2.2 RSS fingerprinting approaches

Bahl et al. uses three Wi-Fi base stations to localize a mobile Wi-Fi-station [2]. The base stations acts as the receiver. Before the mobile node can be localized a reference grid has to be created, where a map of the RSS values from different transmitters at specific positions are collected prior to deployment. This approach is called fingerprinting. With prior knowledge of the signal strength for some positions they use the nearest neighbor method to determine the position of the mobile node. Bahl et al. also utilizes a simple indoor channel model for creating a reference grid, where the parameters in the channel model are based on measurements. They also found out that the orientation of the antenna in relation to the human body affects the results; therefore, they performed measurements with four different orientations (at the same position) to be able to compensate for the attenuation of the human body.

Moghtadaiee et al. have also used the fingerprint technique on FM radio stations together with different kinds of nearest neighbor methods to estimate the position indoors [3]. When measuring the RSS from 17 FM stations the obtained localization error is around three meters. They also show that the position error increases if only one FM channel is used per transmitter antenna. This indicates an increased accuracy of the position when more signals of opportunity are used. Another study on FM based indoor localization by Chen et al. [4] performed a large scale measurement of RSS from 32 different FM broadcast stations and over a hundred Wi-Fi access points over several different rooms, floors and buildings. In the study both a comparison between the two received RSS sets (i.e. FM radio vs. Wi-Fi signals) and a combination of the sets are performed. The results show that the signal sets complement each other well since the lower frequency FM signals exhibits less variations in both space and time compared to the Wi-Fi signals. However, using only FM signal RSS measurements, a large number of radio stations are needed to give a high positioning accuracy (room-level positioning). They also show that the Manhattan distance (the L^1 norm) outperforms the Euclidean distance (the L^2 norm) in their positioning trails.

Commercial systems for indoor positioning based on RSS measurements are available using the fingerprinting approach; the first was Ekahau[1] while Skyhook is another example [5]. Skyhook built maps of the RSS, and service set identification (SSID) from Wi-Fi access points, in shopping malls and other public buildings. These maps are then used in their positioning system, which localizes the users in these buildings. The accuracy of these systems depends on several parameters, such as the number of APs, the quality of

[1] www.ekahau.com

the fingerprinting database and the building layout. Position accuracies of a few meters can however be obtained in many scenarios.

Another example is SenionLab which uses the mobile phone sensors to provide pedestrian indoor navigation capability in large facilities, such as offices, shopping malls and airports. They use WLAN RSS measurements to improve the position accuracy of their pedestrian dead-reckoning algorithms that are implemented in the mobile phone. Small Bluetooth beacons can be installed in the facility to enhance the position accuracy further, using RSS measurements in the mobile phone.

If the positions of the APs are known, but no calibration measurements of the RSS can be performed, it is also possible to estimate the position of a receiver through trilateration if RSS values from three or more APS are available. Each RSS measurement is then used to estimate the distance to the respective AP, often using empirically determined path loss models. However, these models are not particularly accurate and the fingerprinting approach is typically used.

1.2.3 Opportunistic use of RSS-values

In military applications, especially when considering international scenarios, it is not feasible to create databases with RSS measurements on beforehand. Hence, fingerprinting approaches are difficult to implement in practice for this application. However, recently Faragher et al. [6] showed the possibility to use RSS measurements in an opportunistic manner also in previously unvisited areas. They continuously built a database of the RSS values, supplemented with position estimates obtained from a pedestrian dead-reckoning (PDR) positioning system, of the areas they moved through. Later they used these stored RSS values to detect when they approached an area they had previously visited. By using the RSS measurements to perform a “loop-closure” the position accuracy for the PDR-type positioning system could be improved significantly.

1.3 Motivation and description of work

The aim of this work is to evaluate the feasibility of using RSS measurements in a multisensor soldier positioning system. There is typically no possibility in military applications to create a database with geo-referenced RSS values prior to deployment. Only when a soldier, or another platform, is revisiting an old position during the operation they will be able to know that they are close to a previously visited position. Hence, the soldiers must themselves collect and store RSS values while entering a building, together with location information from the soldier positioning system, and then compare the current RSS values with those stored in the database, similarly to the approach adopted in [6]. When these values are *sufficiently close*[2] to what is stored in the database, this yields information about the current position which can be used to improve the performance of the integrated multisensor system.

As discussed above the measured RSS values in an indoor environment will exhibit severe fading. When considering a single frequency in a signal fading scenario, each RSS value will not represent a unique position. However, when using multiple frequencies the set of RSS values may uniquely represent specific positions. The *uniqueness* of the RSS sets depends on many factors, such as the number of transmitters, their positions and the frequency diversity of the set of signals used in the measurements.

[2] The term *sufficiently close* is vague, but it is only when the information is actually integrated into a multisensor system that it becomes possible to determine what level of accuracy is required in order to actually improve the performance of the multisensor positioning system. For instance, even if the RSS values would indicate two different distinct possible positions for a set of measured RSS values, the information about these two positions (with associated uncertainties) could improve the accuracy in the sensor fusion.

Previous work has shown that RSS measurements could provide useful information for indoor positioning systems, also when no prior information on the RSS values are available before the operation [6]. However, it is not possible to directly translate the work presented in [2-4] to our scenario, since the number, type, transmitter powers and locations of the signals differs significantly with location. Furthermore, there is concern that the antenna placement (e.g. when placed on the soldier harness) may significantly affect the RSS values [2]. The aim of this initial study is therefore to evaluate the time and spatial variation of the RSS values for different frequencies that can be expected to occur in, from our perspective, more relevant environments. Also, the effects of human shielding and directivity of the antenna pattern will be evaluated. This is performed in order to provide a first assessment of the feasibility of using multi-frequency RSS measurements as an aid in a future multisensor soldier positioning system. The sensor fusion algorithms for implementing and integrating this technology into the existing experimental soldier positioning system will not be developed in this first phase.

2 Measurements

Received signal strength measurements have been performed at several frequencies in the VHF/UHF band. The measurements were performed indoors in a corridor with several office rooms. The distance between the measurements locations are from 0.5 meters up to 26 meters.

2.1 Measurement system

A Rohde & Schwarz receiver ESVB [7] was used to measure the signal strength. The measurement system can be seen in Figure 1. The receiver was controlled from a PC to automatize the choice of parameters, for example frequency and bandwidth. The frequency range of the receiver is 20 MHz to 2050 MHz and the measurement bandwidth is limited to 10 kHz, 120 kHz, 300 kHz or 1.5 MHz. The antenna connected to the receiver is a standard budget type of omni-directional antenna, mainly constructed for the 2-4 GHz frequency band but the performance in the VHF-bands are acceptable. This type of antenna was selected because of its small form factor, low price and it is likely that a similar type of low-performance antenna could be used in an integrated solider positioning system. The antenna is mounted on a tripod as shown in Figure 1.

2.2 Performed signal strength measurements

A set of frequencies was selected that covers a wide frequency range to get good frequency diversity. The criteria in the selection of the frequencies was that the corresponding transmitter should be stationary and with nearly constant output power over time. However, all stationary transmitters do not have constant output power over time, one example is cellular systems like mobile telephony. Also, the transmitter locations should be geographically separated. With that in mind the frequencies shown in Table 1 was selected manually. The bandwidth was selected with regard to the type of the signal and the possible measurement receiver bandwidths.

Figure 1. Measurement system.

The selected FM radio signals (nr 1-4 in Table 1) are four local radio broadcast stations. Two of the broadcasting stations are located closely in the inner city with a relatively low output power (0.5 kW and 3 kW), see position D and E in the map in Figure 2. The other two broadcasting stations are national publicly funded radio broadcasters with higher output power (20 kW and 60 kW). They are located in nearby cities; see position B and C in the map in Figure 2. A good property of the FM radio signals is that they are located at different positions relative to our location. The FM radio signals normally have a bandwidth of 100-250 kHz. The selected measurement bandwidth was selected to 120 kHz as it matches the measurement receiver's bandwidth and the signals' bandwidth best.

The two selected TV signals (nr 6-7 in Table 1) are both broadcasted from the same location in the inner city, see position F in the map in Figure 2. The TV signals in the UHF band have a bandwidth of 8 MHz that is split over multiple programs, both in frequency and time of the day. Since the TV transmissions were digitalized, the signal is modulated as an OFDM waveform. Therefore a wider bandwidth of 1.5 MHz was chosen here, which is the maximum bandwidth of our measurement receiver.

The location of the TETRA and mobile telephony base stations are not publicly known. The selected frequencies for mobile telephony are spectrally located in the downlink of the GSM-900 and the GSM-1800 bands which both have W-CDMA based waveforms. The GSM-900 downlink has a bandwidth of 25 MHz with 124 channels with 200 kHz channel spacing and the GSM-1800 downlink has a bandwidth of 75 MHz with 374 channels with 200 kHz channel spacing. Here we chose the 1.5 MHz wide bandwidth of the measurement receiver to cover multiple channels.

The selected TETRA frequency is located in the downlink which has a total bandwidth of 10 MHz with 25 kHz channel spacing. When observing the spectrum we could see that only one channel was active at our location and therefore chose to only receive 10 kHz from this frequency.

Note that both the mobile telephony and TETRA systems are Time Division Multiple Access (TDMA) based systems. If the measurement receiver would be able to synchronize with the waveform it could measure the signal strength within the time slots on the control channel where the base station output power is constant. However, this would require more complex measurement equipment compared to what is needed to measure the signal strength from a FM radio station or a TV signal.

During the measurement campaign, the root-mean-square (RMS) value of the received signal power was formed over 10 ms for each frequency sequentially. The signal strength values for all frequencies were collected looping continuously over one minute in every position in the measurement set.

Table 1. Frequencies, bandwidths and signal types for the examined frequency set.

Nr.	Frequency [MHz]	Bandwidth [kHz]	Signal type
1	91.1	120	FM radio
2	94.8	120	FM radio
3	95.5	120	FM radio
4	104.3	120	FM radio
5	391.1	10	TETRA
6	474.0	1500	TV
7	522.0	1500	TV
8	944.0	1500	Mobile telephony
9	1828.4	1500	Mobile telephony

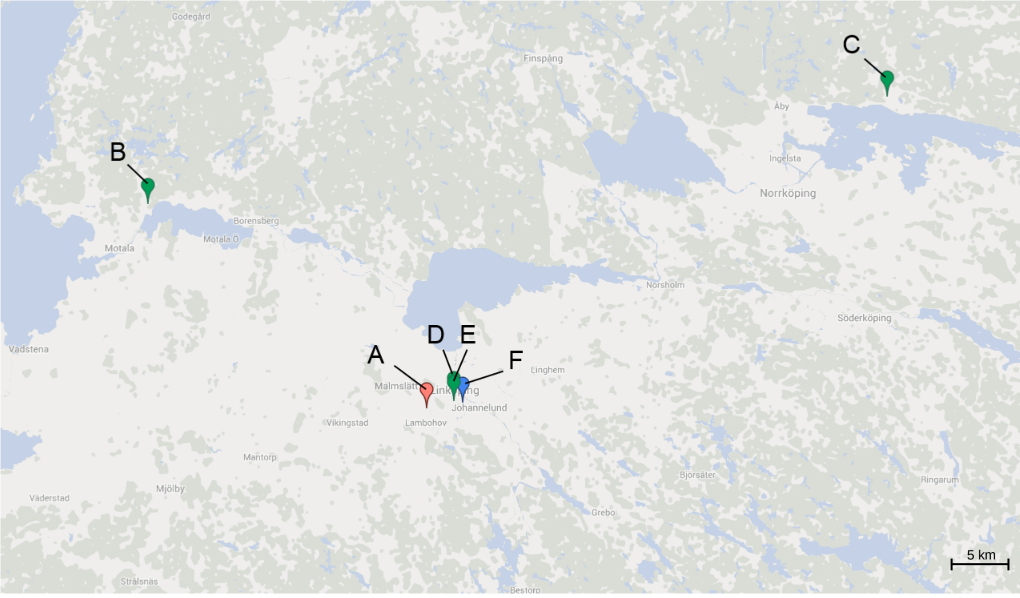


Figure 2. Transmitter positions of (some of) the selected signals. A is the location of the receiver, while B, C, D and E are FM radio broadcast stations on 91.1, 94.8, 95.5 and 104.3 MHz respectively. Position F is where the TV station transmitters on 522 and 474 MHz are located.

The time over which the RMS value is formed will have a larger impact on the TDMA systems than on the none-time multiplexed signals. For example, the timeslots in TETRA are 14.167 ms long and in single carrier mode the control channel will occupy every fourth timeslot. A measure over an entire frame (four timeslots) would always include the control channel which is more likely to have a constant output power. However, we also need to consider that a too long time period would not be feasible in a mobile system since the receiver will move during operation.

A few different types of measurements were performed to find out the feasibility of using RSS measurements as an aid in a multisensor indoor positioning system. The collected sets are:

A. Antenna aspects. The choice of antenna may impact the performance of the RSS-positioning algorithm if the antenna performance is not considered in the algorithm. Two different aspects that could influence the antenna performance were investigated in this work, namely different rotations of the antenna and shadowing the antenna with a human body.

1. Rotations. In the measurements the antenna was mounted on a tripod 1.5 meter above the floor. Four different measurement sets were collected, where the antenna was rotated 90 degrees between each measurement set.
2. Shadowing. In the measurements the antenna was mounted on a tripod 1.5 meter above the floor. To shadow the antenna, a person was standing still approximately 10 cm away from the antenna. The person was shadowing the antenna from four different angles.

B. Time variations. As the RSS may vary over time, due to different propagation conditions and multipath propagation, or varying transmit power, the time variation of the RSS was investigated in two different measurement campaigns. During the measurement phase the antenna was stationary at the same position all the time.

1. Four-day measurement. This measurement was performed during four days over a weekend. During the weekend when the building is empty, the variations of the RSS values could not have been caused by movements from people in close vicinity of the antenna. The reasons for time variations in this case could be propagation conditions, movements outside the building etc.

2. Four-hour measurement. A four hour long measurement set was collected during a normal office day in the building. During the measurement people were moving around in the building. This type of movement can cause extra multipath propagation additionally to what is happening outside the building.

C. Spatial variations. In these measurements the antenna was moved between different positions. During the collection of RSS samples the antenna is stationary at a specific position and it is then moved to the next position when one minute has elapsed. The antenna is mounted on a tripod approximately 1.9 meters above the floor. Three different scenarios were tested with different resolution of the measurement grid.

1. Offices at a floor. In this measurement set the receiver positions are located in different offices or in the connecting corridors. The distance between the measurement positions are between 6.5 and 26 meters. The receiver positions can be seen in Figure 3. RSS values were collected two times at these positions, the second set started half an hour after the first set was completed.
2. 5x4-grid. In this measurement set the receiver positions are ordered in a grid, separated one meter. The receiver positions are marked with blue circles in Figure 4. As can be seen in the figure, the measurement grid is located both inside a room with windows and outside the room in a corridor.
3. 3x3-grid. In this measurement set the receiver positions are ordered in a grid, separated 0.5 meter. The used grid is marked with rectangles in Figure 4. RSS values were collected two times at these positions, where the second measurement started immediately after that the first measurement was completed.

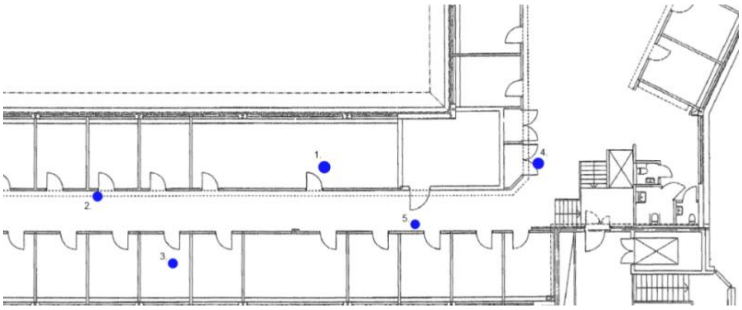


Figure 3. Map of measurement positions (blue circles) in measurement C.1.

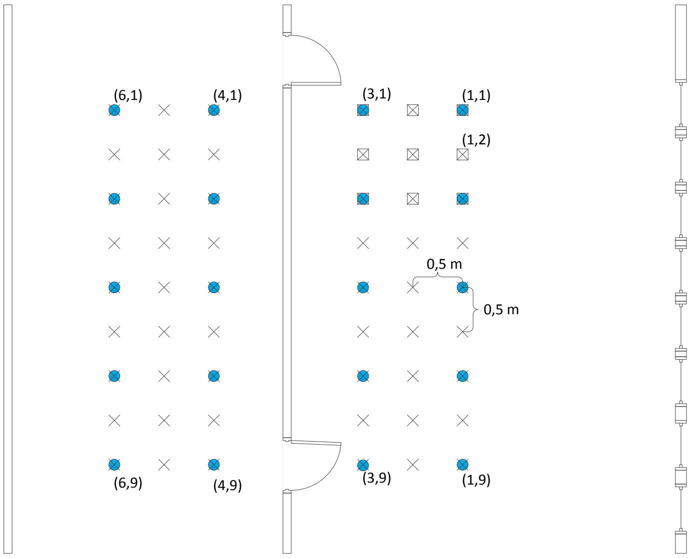


Figure 4. Measurement grid. Positions marked with a blue circle refer to measurement C.2 and positions marked with a rectangle refer to measurement C.3.

3 Results

The collected RSS data from the measurement campaign are analysed in two different ways. First, the variation of the RSS is studied in terms of mean and variance values. The results are shown in table format but also in plots that shows the collected RSS samples over time, for each frequency. The same sort of plot is also used to show how the RSS values differ between receiver positions. In this case the collected RSS values are concatenated in time but the measurement positions are separated with vertical lines. Secondly, the feasibility of using the RSS values for indoor positioning is studied.

Let the measured RSS from frequency number 1 in the measurement set be denoted as $p_{1,x,y}$ where x is the measurement position and y is the sample number. Furthermore, let $\boldsymbol{P}_{x,y}$ in Equation 1 be the vector of the RSS values from all 9 frequencies in the measurement,

$$\boldsymbol{P}_{x,y} = (p_{1,x,y}, p_{2,x,y}, \dots p_{9,x,y}) \qquad (1)$$

Ideally, RSS values obtained at one positions should be the same, independent of when the RSS samples are obtained. The individual RSS values p for each frequency can however be the same at different positions due to fading. When considering the set of RSS values, $\boldsymbol{P}_{x,y}$ should ideally be the same at the same position (i.e. $\boldsymbol{P}_{1,1} = \boldsymbol{P}_{1,2}$) and also differ for different positions ($\boldsymbol{P}_{1,1} \neq \boldsymbol{P}_{2,1}$). However, in reality measurement noise, intersystem interference, fading and multipath propagation will affect the obtained RSS values. Most likely the RSS samples obtained at the same position will not be equal but similar ($\boldsymbol{P}_{1,1} \approx \boldsymbol{P}_{1,2}$) and hopefully the RSS samples at different positions will still differ ($\boldsymbol{P}_{1,1} \neq \boldsymbol{P}_{2,1}$). One type of measure of the distance between two $\boldsymbol{P}$-vectors is the Euclidean distance, which will be studied in this work.

As an example of the Euclidean distance measure; assume five positions (x=[1,5]) with one sample each (y=1) where the RSS is $\boldsymbol{P}_{1,1}$=1, $\boldsymbol{P}_{2,1}$=2, $\boldsymbol{P}_{3,1}$=3, $\boldsymbol{P}_{4,1}$=4, $\boldsymbol{P}_{5,1}$=5 for one frequency. The Euclidean distance in this example is visualized in Figure 5, where the diagonal values are zero. The diagonal corresponds to the Euclidean distance between the RSS samples compared to themself. The distance between all of the other combinations can also be seen in the figure. This type of plot will be frequently used in the following sections where results of the measurements are presented.

3.1 Time variation

It is important that the RSS values obtained at one position do not change significantly over time. To obtain ideal results from a RSS-based positioning method there should be no time variations or fluctuations of the RSS at a specific position. In the following section we analyze the time variations of the obtained RSS measurement data set from one position indoors (position 1 in Figure 3).

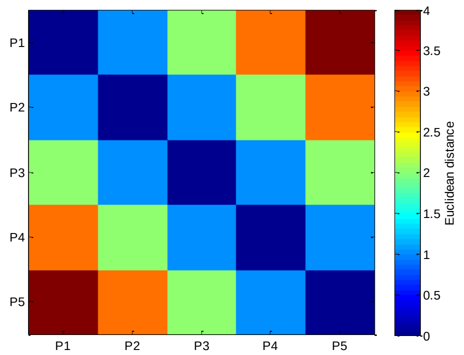


Figure 5. An example plot of the Euclidean distance between RSS values from five different positions.

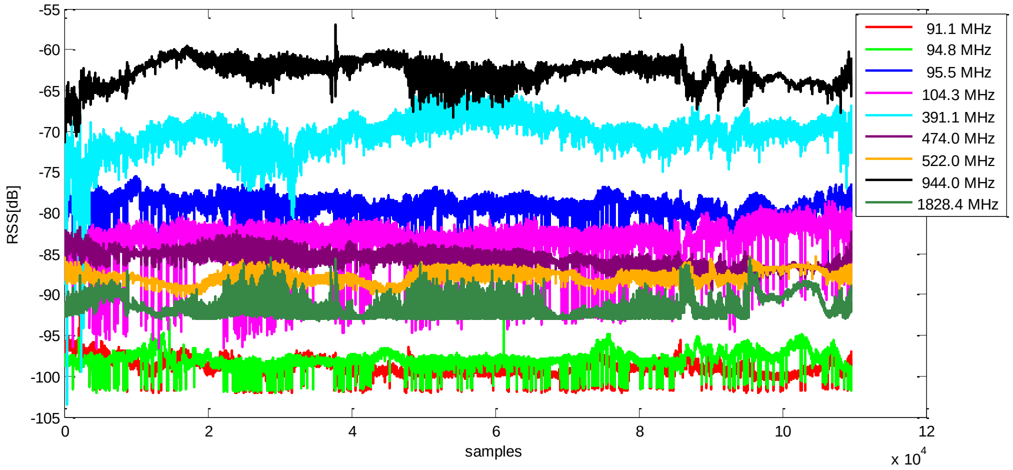


Figure 6. Signal strength for selected frequencies over a weekend, measured at position 1 in the office measurement (see Figure 3).

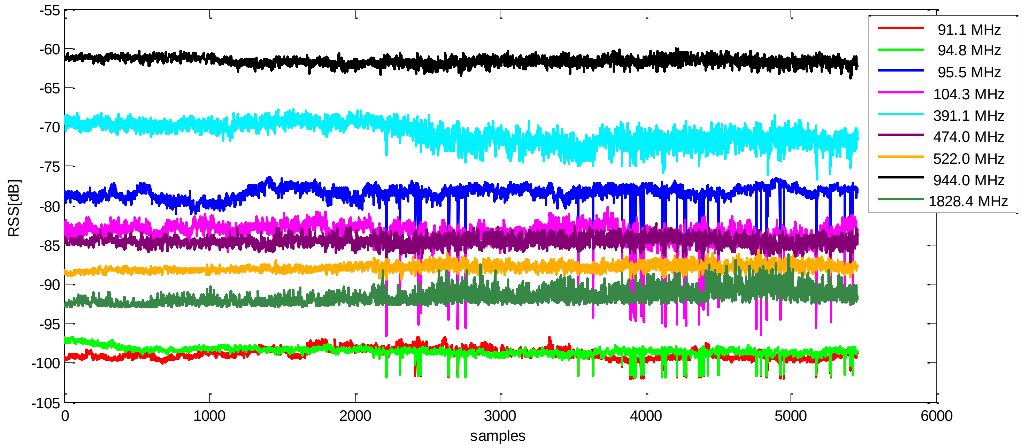


Figure 7. RSS measurements over 4 hours from the weekend measurement set.

Figure 6 shows the RSS over time, during a measurement over a weekend. The measurement was started in the afternoon day 1 (20th of June), was running day 2-4 (which was during midsummer holidays) and stopped around lunchtime day 5 (24th of June). During the holidays the building was quiet and empty, which means that there were no people moving around in close vicinity of the receiving antenna. From the figure it can be seen that the received power for some of the frequencies varies around 10 dB, especially the mobile telephony and TV signals (474.0 MHz, 522.0 MHz, 944.0 MHz and 1828.4 MHz), while other frequencies vary around 5 dB. There are also some “glitches” in the same figure. These glitches are large variations in RSS with short time duration that occur at several frequencies during a short time interval. They originate from some sort of peculiarity of the measurement receiver[3].

In Figure 7 we can see four hours of RSS values during the afternoon (10:04 – 14:35 UTC) of day 2 (21st of June) in the weekend measurement. In this short time perspective the variations of the RSS is smaller compared to the (longer-term) variation that is seen over the period of several days. Hence, the variance will be larger over a longer measurement time, due to the slow variations in the average RSS value.

[3] The peculiarity has been repeated in a controlled measurement. A signal generator with constant output power connected to the measurement receiver gave the same behavior as observed in the RSS measurements.

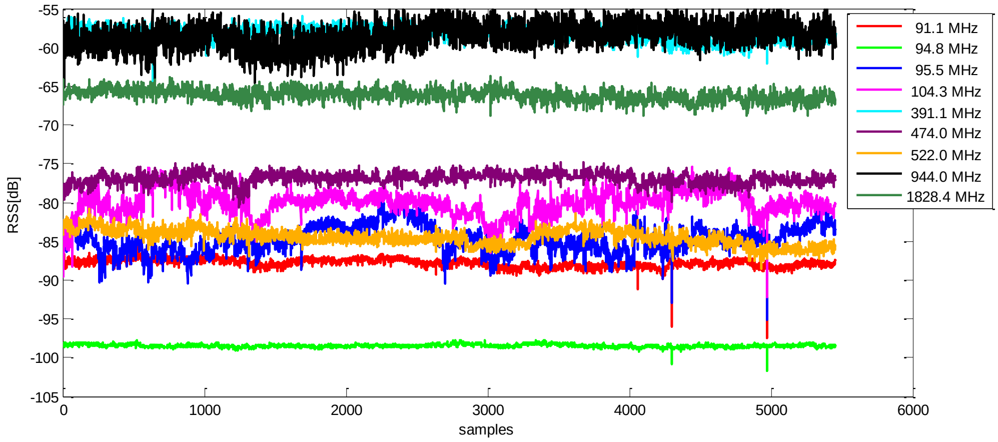


Figure 8. RSS measurement for the four-hour (B.2) measurement set, measured at position 1 in the office measurement (see Figure 3).

Apart from the glitches mentioned earlier, the frequency that varies the most over these four hours is 391.1 MHz, where the average RSS value varies almost 5 dB during this time perspective. The other frequencies have variations of around 2-3 dB.

Another set of RSS values was collected during approximately four hours (10:04 – 14:35 UTC) during a day (7th of June) with normal movement in the building, see Figure 8. A comparison of the RSS values from this measurement with the previous measurement shows that the overall average RSS value for some of the frequencies has changed, especially for 91.1 MHz, 391.1 MHz, 944,0 MHz and 1828.4 MHz. Another observation in the comparison is that the variation over time is larger in Figure 8 compared to Figure 7, for almost all of the frequencies. It is hard to give a thorough explanation to these observations from the limited measurements conducted in this work; however, one reason is that the second measurement was conducted during a normal office day with a lot of people moving around and hence creating additional multipath components. The average RSS values between the measurement sets could also have changed due to different propagation conditions. For the TDMA-signals the alignment to the control timeslot could have been different between the two conducted measurements. Further studies are needed in order to fully determine the cause for the large differences in the average RSS values.

Table 2 shows the mean signal strength and variance for the four-hour measurement data sets and the weekend measurement set. A larger variance indicates a large time-variability of the RSS, which makes it difficult to recognize the position when it is revisited. The table shows that three of the frequencies (95.5 MHz, 104.3 MHz, and 944 MHz) seem to have larger variance compared to the others in the 4 hour measurement set. The measurement set over the weekend on the other hand shows that only two of them (391.1 MHz and 944 MHz) have a large variance.

The observed variance of the RSS values over time will create an uncertainty if this data was used in a positioning algorithm. Figure 9 shows the Euclidean distance for the 1000 first samples for the two different four-hour data sets above. Ideally, the Euclidean distance should have been zero for both of these two data sets if there were no time variations, but this is not the case as can be seen in Figure 9. This is due to the time variance of the obtained RSS values. If we compare Figure 9a and Figure 9b, it can be seen that the latter exhibits larger Euclidean distances. The reason for this could be that the variance (see Table 2) is larger for several of the frequencies in the four-hours measurement seen in Figure 9b compared to the weekend (four-hours) measurement in Figure 9a.

Table 2. Average and variance of RSS.

Nr.	Frequency [MHz]	Average signal strength [dBm]			Variance [dB]		
		4 hours	Weekend	Weekend (4 hours)	4 hours	Weekend	Weekend (4 hours)
1	91.1	-88	-99	-99	0.3	0.8	0.4
2	94.8	-98	-98	-99	0.0	0.7	0.3
3	95.5	-85	-79	-78	3.0	1.1	1.5
4	104.3	-80	-83	-83	2.7	1.67	1.8
5	391.1	-58	-70	-71	0.7	4.3	1.8
6	474.0	-77	-86	-85	0.5	1.0	0.4
7	522.0	-84	-88	-88	1.1	0.5	0.2
8	944.0	-59	-63	-62	2.4	2.1	0.2
9	1828.4	-66	-92	-92	0.5	1.3	0.9

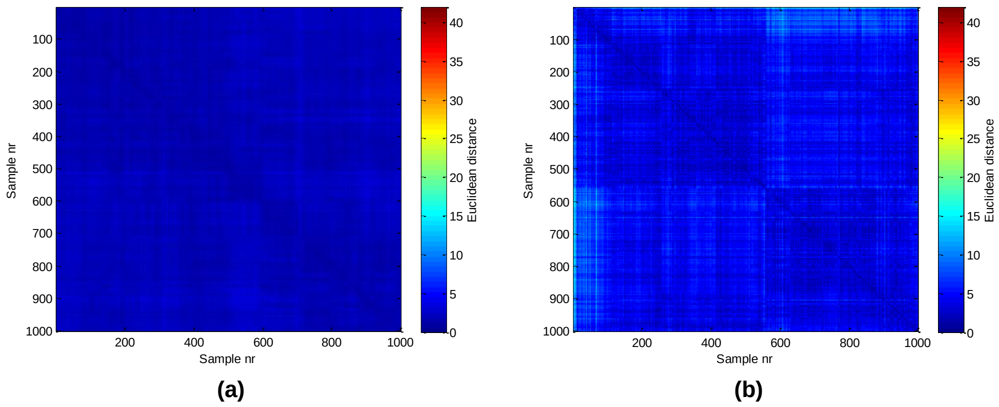


Figure 9. Euclidean distance for the set of nine measured RSS values obtained at the same position, (a) is over the first 1000 sample of the four-hours period of the weekend measurement set and (b) is over the 1000 first samples in the four-hours measurement set.

In summary, the RSS time-variability will negatively affect the possibilities of performing loop-closure based on the RSS measurements. However, the time-variability will in most cases be smaller if the time period decreases. A comparison of the variances in Table 2 of the entire weekend measurement and the four-hours snapshot of the same measurement shows this phenomenon.

3.2 Antenna aspects

The antenna used in this work is a low budget omni-directional antenna. Its performance is not specified in any datasheet, so the performance is unknown, especially when it is mounted on the tripod. In the following sections, the effects of different antenna rotations and shadowing of the antenna from different angles will be discussed.

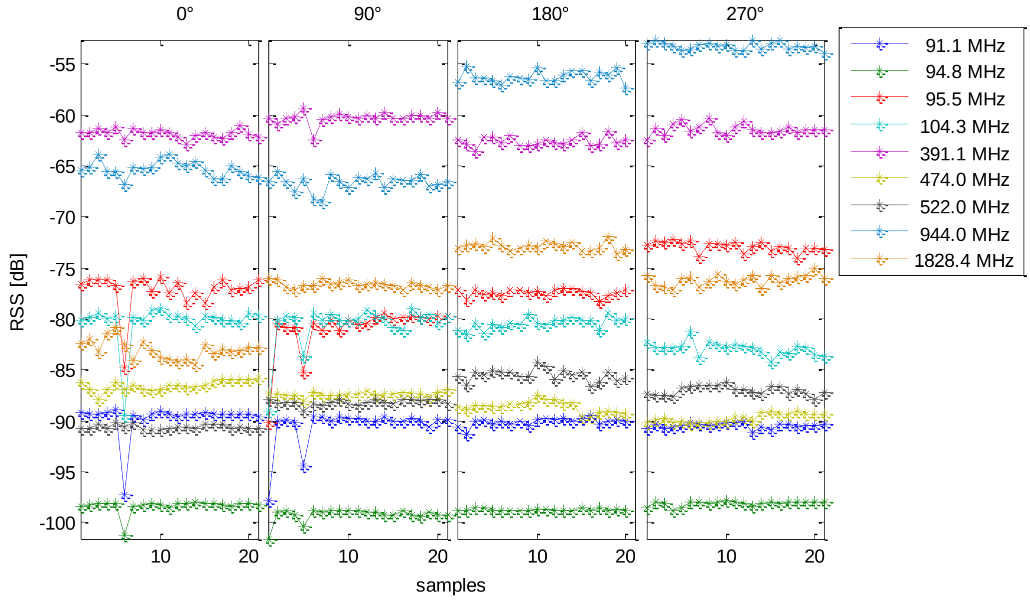


Figure 10. RSS for different antenna rotations for the selected frequencies. The RSS variation in rotation can be seen between the four “windows”. Inside each window, the time variation during the one-minute measurement for the current rotation can be seen.

3.2.1 Antenna rotation

In Figure 10 we can see the signal strength measured with four different antenna rotation angles. As can be seen in the figure, different antenna rotations will affect the RSS values for some of the frequencies, especially the higher frequencies (944.0 MHz and 1828.4 MHz). The glitches that were observed in the time variation measurement previously discussed are also visible in 0° and 90° direction measurements.

Table 3 shows the average of the RSS samples from Figure 10. For most of the frequencies the difference of the average RSS between different rotations is only a few decibels. However, there are some frequencies were the variance is large, especially for 944 MHz and 1828.4 MHz, as can be seen in the table.

The RSS variation caused by the rotation of the antenna will affect the possibilities to perform loop-closure if the orientation of the antenna is different between different measurement samples collected at the same position (e.g. between the first and second time a person visits the same location). Figure 11 shows the effects of different antenna rotations in a plot of the Euclidean distance where all (nine) frequencies are used. Here it is clear that the first two and later two rotation angles have a smaller Euclidean distance to each other than the other two rotation angles. The observed glitches in Figure 10 are clearly visible in Figure 11 as horizontal and vertical lines.

The variation of the RSS shown here might also be partially due to variations in time rather than only the effect of the antenna rotation angle; the measurement duration over each angle is 1 minute and the rotation procedure between the measurements took less than a minute. However, since the variations are typically smaller within each measurement for the different rotations, compared to the changes that occur after changing the antenna rotation, it is likely that the effects here are mainly caused by the antenna rotation.

In conclusion, the type and quality of the antenna has a substantial impact on the measurements. In the end, in an application where the receiver/user moves over the same position but in different directions/rotations, these effects could result in a data set which exhibits higher variations due to other factors than due to the changes in position.

Table 3. Average RSS for different antenna rotations.

Frequency [MHz]	Average RSS [dB]				Variance [dB]
	0°	90°	180°	270°	
91.1	-90	-91	-90	-91	0.1
94.8	-98	-99	-99	-98	0.1
95.5	-77	-81	-77	-73	8.2
104.3	-80	-81	-80	-83	1.1
391.1	-62	-60	-63	-61	0.7
474.0	-87	-87	-89	-90	1.4
522.0	-91	-88	-86	-87	3.5
944.0	-65	-67	-56	-53	32.7
1828.4	-83	-77	-73	-76	13.4

3.2.2 Shadowing from different directions

In Figure 12 we can see the measured signal strength from a stationary measurement with the antenna shadowed from different angles. Here we can see that locating the antenna close to the body (in level with the chest) will affect the RSS depending on the position of the body in relation to the antenna. The variation is higher for those frequencies that already have showed tendencies of a high time variability, namely 95.5 MHz, 104.3MHz, 944.0 MHz and 1828.4 MHz. Also, the variances of the RSS values, see Table 4, further indicates that these frequencies are more sensitive to shadowing.

Figure 13 shows the Euclidean distance between the collected data points in this measurement set. Compared with the results in Figure 11, it seems that for the set of nine frequencies the different shadowing directions have a smaller impact on the Euclidean distance than the rotation angle of the antenna. Also, the variances are smaller in Table 4 compared to Table 3, which indicates that the shadowing directions have less impact on the RSS compared to the antenna directions.

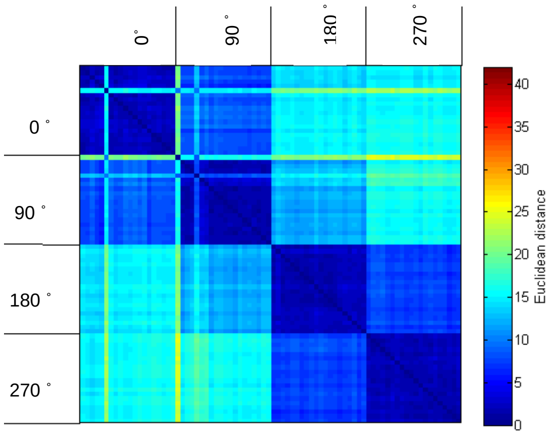


Figure 11. Euclidean distance, based on the RSS of all nine measured frequencies, between the different rotation angles of the antenna.

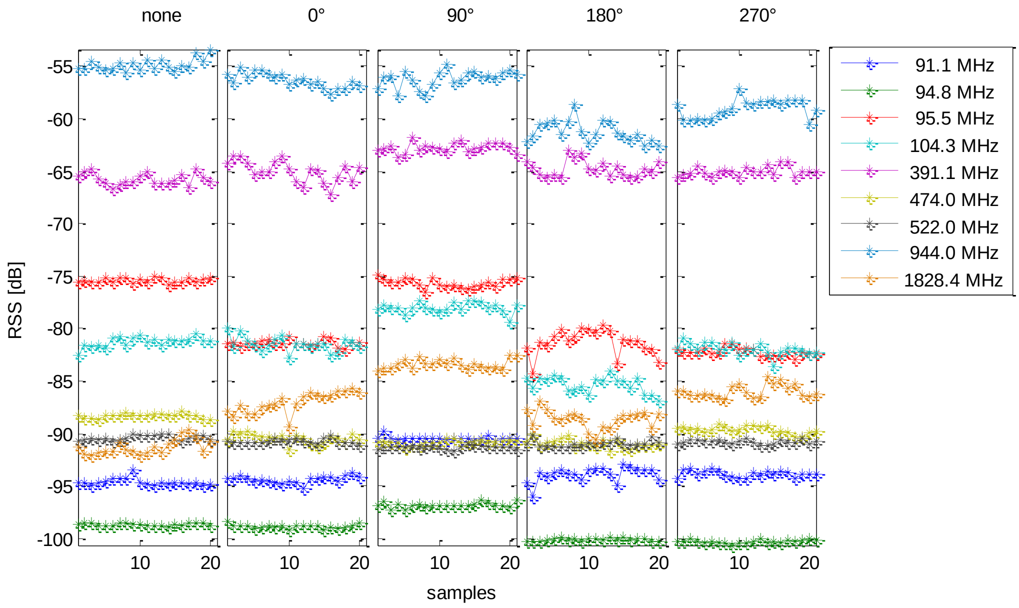


Figure 12. RSS for different shadowing directions of the antenna for the selected frequencies. The first set is without shadowing. The RSS variation in shadowing direction can be seen between the four “windows”. Inside each window, the time variation during the one-minute measurement for the current direction of shadowing can be seen.

Table 4. Average RSS for shadowing of the antenna from different directions.

Frequency [MHz]	Average RSS [dB]					Variance [dB]
	None	0°	90°	180°	270°	
91.1	-95	-94	-91	-94	-94	2.2
94.8	-99	-99	-97	-100	-100	1.6
95.5	-75	-81	-76	-81	-82	9.0
104.3	-81	-82	-78	-85	-82	5.4
391.1	-66	-65	-63	-65	-65	1.0
474.0	-88	-90	-91	-91	-90	0.9
522.0	-90	-91	-91	-91	-91	0.1
944.0	-55	-56	-56	-61	-59	5.1
1828.4	-91	-87	-83	-89	-86	6.9

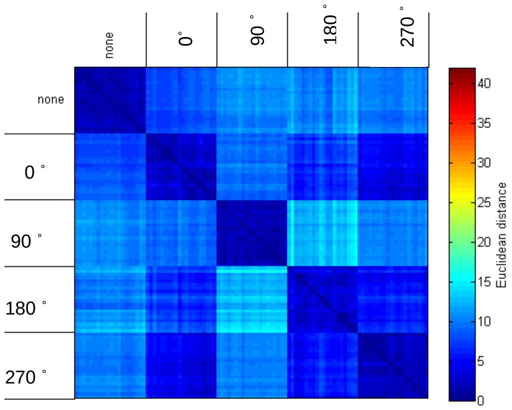


Figure 13. Euclidean distance, based on the RSS of all nine measured frequencies, between the different directions of the shadowing of the antenna. ”None” is when nothing is shadowing the antenna.

As mentioned before, although the variations are smaller, they need to be taken into consideration. All these factors that contribute to an undesired variation in RSS will need to be smaller than the variations observed over different positions.

3.3 Spatial variations

To be able to use the RSS values to enhance the accuracy of a multisensor positioning system some requirements have to be fulfilled. The set of RSS values at a position should have a small variation over time, so that the RSS values are similar when a position is revisited. The combined set of RSS values should also be unique at different positions, so that different positions could be distinguished. Though, it is not necessary that the RSS values for all of the frequencies need to differ between different positions. The time variations of the RSS at one position have previously been discussed and in the following section we are going to study the spatial variations of the RSS values and what type of spatial resolution can be expected.

Figure 14 shows the RSS values, for the five measurement positions shown in Figure 3. The set of RSS values changes between different positions, but there are also time variations between multiple measurements at the same position. As can be seen in Figure 14, the frequency 94.8 MHz is very stable during the one minute measurement period at every position but it differs between positions. A frequency that is not that stable is 944.0 MHz, which varies almost 10 dB between consecutive measurement samples at the same position. However, the RSS make an even more drastic change between different positions, which can be seen as distinct steps between the measurement positions. It can also be seen that the time variation at position *5* is larger for many of the frequencies compared to the time variations at the other measurement positions. Therefore, it may be more difficult to make use of the RSS measurements there.

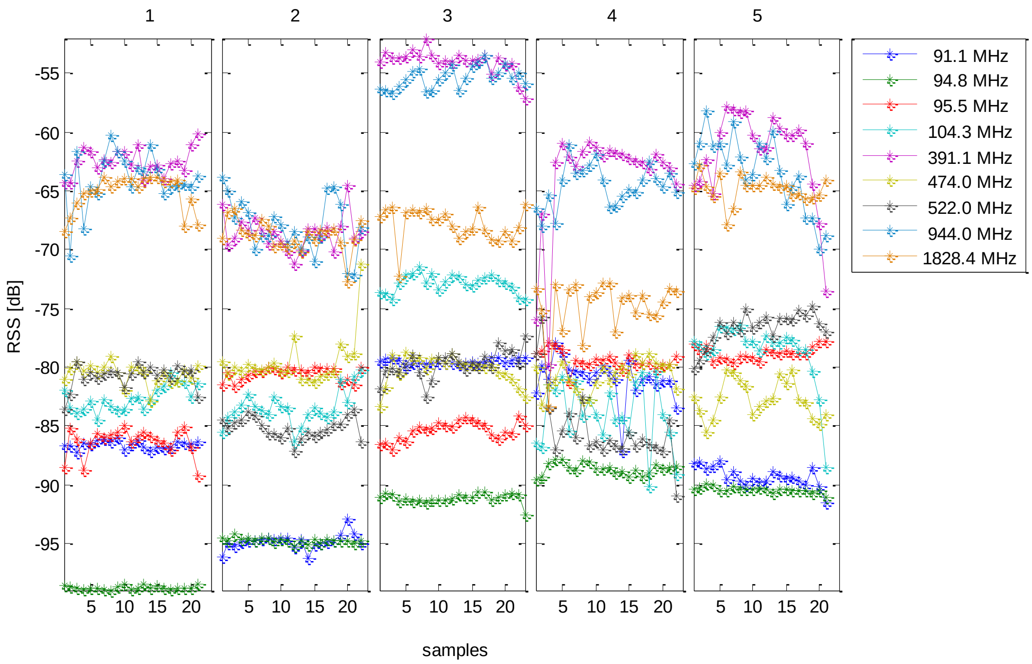


Figure 14. RSS at different positions for the selected frequencies. The RSS variation in position can be seen between the four “windows”. Inside each window, the time variation during the one-minute measurement for the current position is shown.

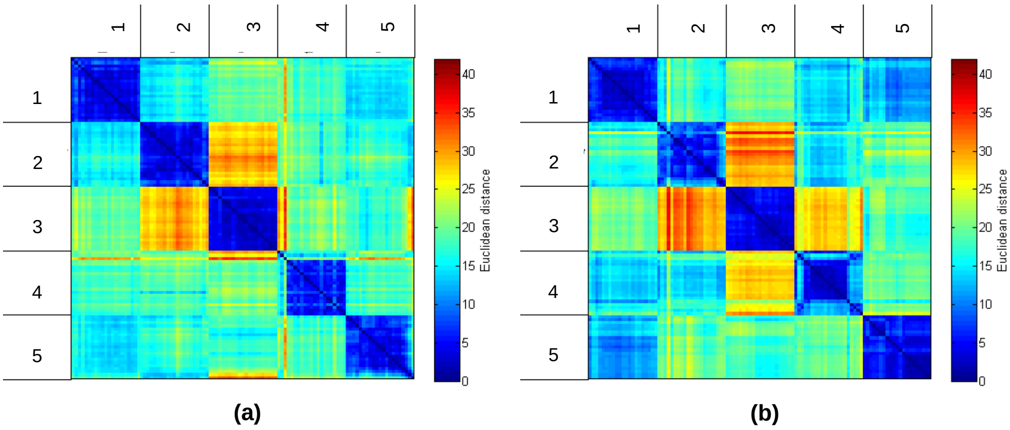


Figure 15. Euclidean distance between the five positions. Two sets were collected; (a) is the first set and (b) is collected at the same positions half an hour after the first set.

In Figure 15 the Euclidean distance between the vectors, consisting of all nine frequencies, is shown. A distinct diagonal of dark blue squares can be seen, which shows the Euclidean distances of the vectors for the same position. This means that the Euclidean distance for the vectors that represents the same position is almost the same during the one minute measurement time. As there are no more dark blue squares, besides those in the diagonal, it is possible to distinguish between different positions. If the blue square in the upper left corner is studied we can see some small light blue pixels, which is due to time variations at the position *1* (compare with the RSS values in Figure 14). If we look at Figure 15b in the upper right corner, which shows the Euclidean distance between position *1* and position *5*, we can see some dark blue pixels. These dark blue pixels indicate an increasing risk for falsely deciding that the position *1* and position *5* is the same position. The Euclidean distance between position *2* and position *3* are well above 25, which is the largest values in these figures. In reality these two offices are not that far away, see Figure 3. Hence, the Euclidean distance of the RSS vector cannot be directly related to the spatial distance.

The results shown in Figure 15 look promising. However, the distance between the measuring positions are quite far, tens of meters. What will happen if we move the measuring positions closer to each other? Can we still distinguish different positions from each other, with the Euclidean distance? In the following section we will look at what happens with the Euclidean distance when we are decreasing the distance between the measurement positions.

Figure 16 shows the Euclidean distance for receiver positions on a one meter grid, which is shown in Figure 4. As can be seen in Figure 16 the diagonal is still very distinct, which means that it is possible to distinguish between different positions even in this case. However, the Euclidean distance between some of the positions are quite small, especially for those in the bottom right corner of Figure 16 and position (4,5) and (4,7) in the same figure. This means that it will be more difficult to distinguish between these positions compared to the other positions. However, the positions in the bottom right corner are geographically close to each other, so the positioning error will not be that large in this case.

As we previously have seen, it is possible to distinguish between different positions that are in a 1 meter grid or further apart of each other. In the following section we will show what will happen if we make the grid even denser than we previously have studied.

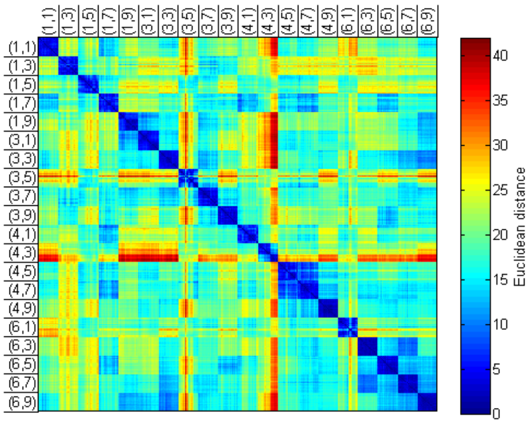
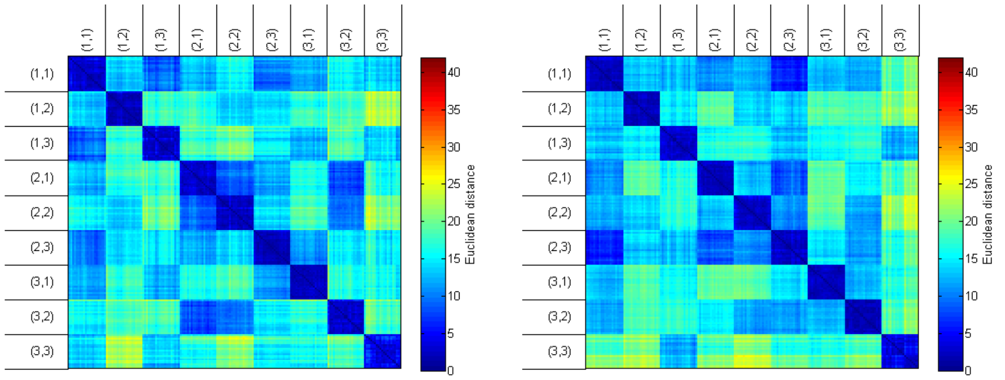


Figure 16. Euclidean distance between the grid positions in measurement set C.2.



(a) **(b)**

Figure 17. Euclidean distance between the grid-positions, distanced 0.5 meters. (a) shows the first measurement set and (b) shows the second measurement set obtained immediately after the first set.

In Figure 17 the Euclidean distance for measuring positions in a 0.5 meter grid, see Figure 4, is shown. If Figure 17 is compared with Figure 16 we can see that the former is much more overall blue than the latter figure. This is an indication that the overall Euclidean distance is smaller, which yields a higher probability of making an erroneous loop-closure decision. However, we can still see a dark blue diagonal, which shows that the Euclidean distance is smaller for the same position compared to the other positions.

Despite the fact that there are time variations in the obtained RSS values for the different frequencies at the same position, see Figure 14, we are able to distinguish between different positions with the Euclidean distance. In general we can say that the Euclidean distance will decrease if the geographical distance between different positions decreases, but there are exceptions, see for example Figure 15b in the upper right corner.

3.3.1 Revisiting positions

The soldier may, sooner or later, come back to almost the same position that previously was visited. If we assume that there is no time variation of the RSS values, the Euclidean distance between the previously obtained RSS and the current RSS, when revisiting the same position, should be close to zero. In reality we can expect some time variations of the RSS, as we have seen earlier. Figure 18 shows the Euclidean distance when the same positions are revisited after half an hour, for the five office measurement positions (shown in Figure 3). Compare the results with those shown in Figure 15 for the two separate cases.

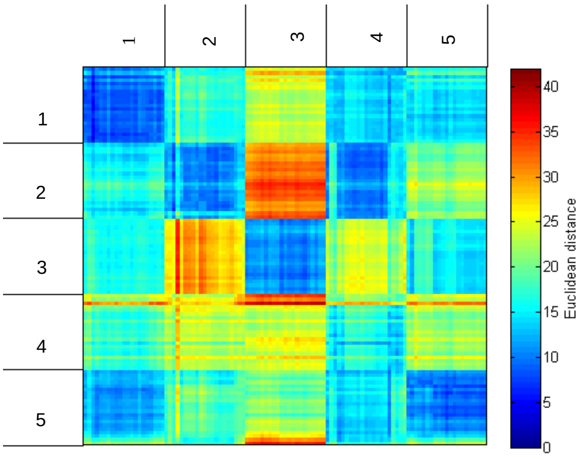


Figure 18. Euclidean distance between the first and second run (half an hour apart) of the five positions in measurement C.1.

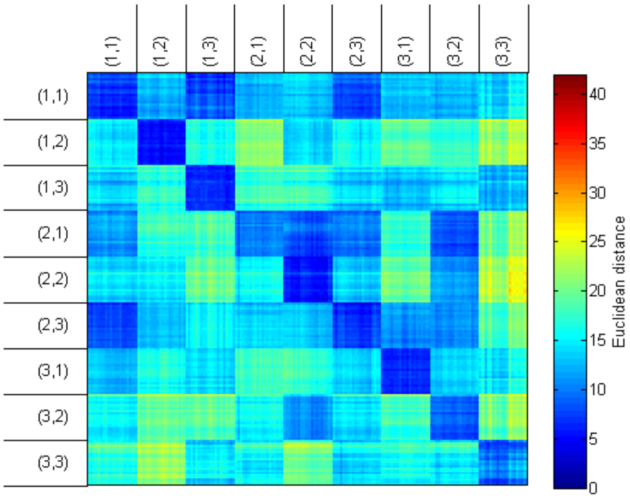


Figure 19. Euclidean distance between the first and second measurement of the 3x3-grid positions.

Some of the differences are that the Euclidean distances for the revisited positions are larger here compared to the Euclidean distances in Figure 15 and also the distinct diagonal of dark blue squares are no longer visible in Figure 18. Hence the vector containing the nine RSS values for the same positions will become less similar over the time. Although for most of the positions, the vectors will still be more similar to those collected at the same position than to the set of RSS values measured at other positions.

In Figure 19, which shows the Euclidean distance between the first and the second set of measurement on the small 3x3-grid, it is possible to see that even a small amount of time (a few minutes) will increase the Euclidean distance between the data points from the same position (compare with Figure 17).

One conclusion of the revisiting trails is that there is an ageing factor of the obtained RSS values. If the RSS measurements are to be integrated in a multisensor indoor positing system, this ageing factor has to be considered so that more newly obtained RSS values are rated higher than old ones. Too old RSS values could introduce large position errors.

Table 5. Average Euclidean distance between positions in measurement set C.1 using a different number of frequencies.

	Average Euclidean distance

Nr. of freq.	min	mean	max
9	13.2	14.4	28.0
8	12.1	13.6	26.4
7	10.9	12.7	24.6
6	9.6	11.7	22.7
5	8.2	10.6	20.8
4	6.5	9.4	18.7
3	4.5	8.0	16.5
2	2.3	6.3	14.0
1	0.6	4.0	10.4

3.4 Choice of frequency set

The number of frequencies and the choice of frequencies will affect the Euclidean distance. When using fewer frequencies, the minimum, maximum and mean Euclidean distance between RSS at different positions will typically decrease. This can be seen in Table 5 where the Euclidean distance between the positions in measurement set C.1 is calculated using different number of frequencies. The values presented in the table represent the average over all the combinations of frequency sets.

The choice of signals to include in the frequency set also matters. Here a "bad" frequency choice could for example be a signal with a large time variance or a noisy signal with a small spatial variance. A "good" frequency choice will contribute to an increased Euclidean distance at different positions more than a "bad" frequency choice. Also, a bad frequency choice could have a larger Euclidean distance to the same (revisited) position, for example due to a large time variance.

The choice of frequencies is a balance act. Multiple frequencies give a good diversity but could also make the receiver more complex. When selecting a subset from the nine observed frequencies in our measurements, the variance of the RSS in the four-hour long measurement gives a quite good hint on which frequencies that are closer to a constant RSS over time at a single position. This indicates that it is possible to sort out some frequencies during an initialization on a system while standing still. However, it does not give any information on the spatial variations. The minimum and maximum Euclidean distance in measurement set C.1 (five different positions) for the nine frequencies individually, presented in Table 6, give more information on the spatial variability of the RSS for individual frequencies.

To be able to evaluate the maximum and minimum Euclidean distance between measurements in this and following tables, a mean over the one minute measurements have been taken, so that only one Euclidean distance value is obtained for each pair of measurements. This also prevents outliers and "glitches" in the data to have a too large impact when searching for minimum and maximum values. In Table 6 we can see that the largest minimum Euclidean distance between different positions is obtained using frequencies 1, 2 and 5. Frequency number 3, 4 and 8 are also better choices than 6, 7 or 9 but the variance over time is larger for these frequencies (see Table 2).

Table 6. Average Euclidean distance between different positions in measurement set C.1 using only one frequency.

	Average Euclidean distance

Freq. nr.	min	mean	max
1	1.4	6.2	15.3
2	0.7	3.9	10.1
3	0.6	3.4	7.6
4	0.6	4.3	11.2
5	0.7	5.0	14.6
6	0.2	1.1	3.1
7	0.2	3.7	8.7
8	0.6	4.2	12.7
9	0.3	3.8	10.0

Table 7. Average Euclidean distance between different positions in the measurement sets with antenna rotation (A.1) and shadowing (A.2).

	Average Euclidean distance Measurement set A.1			**Average Euclidean distance Measurement set A.2**		
Freq. nr.	**min**	**mean**	**max**	**min**	**mean**	**Max**
all 9	7.2	9.2	16.1	3.5	6.9	12.8
1, 2, 5	0.9	1.1	2.4	0.3	2.3	5.4
3, 4, 8	4.0	7.4	15.8	2.8	5.3	10.5

Table 8. Average Euclidean distance between different positions in the measurement sets for positions 0.5 m apart (C.3) and further apart (C.1).

	Average Euclidean distance Measurement set C.1			**Average Euclidean distance Measurement set C.3**		
Freq. nr.	**min**	**mean**	**max**	**min**	**mean**	**Max**
all 9	13.2	1.4	28.0	7.6	13.0	22.4
1, 2, 5	8.8	9.9	21.4	1.8	6.6	14.8
3, 4, 8	3.7	7.7	17.2	3.0	8.4	17.2

Ideally the minimum Euclidean distance between two measurements at different positions would be larger than the maximum Euclidean distance between two measurements from the same position but where the antenna rotation, shadowing or the time of the measurement differ. When the minimum distance between measurements at different positions is smaller than the maximum distance from measurements at the same position, we have an uncertainty in the results and can therefore not unambiguously draw a conclusion on the position that can be used to directly and robustly perform loop-closure.

In table 7 the minimum, mean and maximum Euclidean distance for the measurement sets on antenna rotation and shadowing are presented for different sets of frequencies based on the selection of “good” frequency sets discussed above.

Measurement A.1 on antenna rotation has a maximum distance value of 16.1 when using all nine frequencies. If only frequencies 1, 2 and 5 are used, the maximum distance is reduced to 2.4. In the same way, measurement A.2 (shadowing of the antenna) reduces the maximum distance from 12.8 to 5.4 when reducing the frequency set from all nine to only using frequency 1, 2 and 5.

In Table 8, the minimum, mean and maximum Euclidean distance for the measurement sets with positions on different distances are presented for different sets of frequencies. In measurement C.1 with five different positions, the minimum Euclidean distance between two different positions is 13.2 when using all nine frequencies. This value is smaller than the maximum distance from the antenna rotation. When only using the selected “good” frequencies 1, 2 and 5 the minimum distance in measurement set C.1 is 8.7, which is larger than the maximum distance for antenna rotation and shadowing when using these frequencies. This indicates that a well-chosen subset of frequencies can improve the results.

When we are looking at measurement set C.3 with a 3x3 grid of positions 0.5 m apart, the closest positions should ideally have a smaller distance than between larger areas (as in measurement set C.1). In measurement set C.3, the antenna rotation is constant and the room is quite empty so there is no object close to the antenna; hence, antenna rotation and shadowing would not affect the results. The minimum Euclidean distance in measurement set C.3 for frequencies 1, 2 and 5 is 1.8, which is smaller than the maximum distance for both antenna rotation and shadowing. Hence, here we can see that we would have an uncertainty in the position determination.

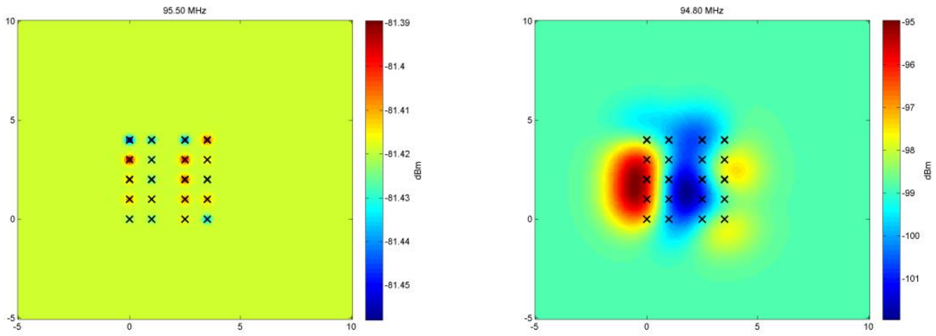
This might not be considered as a bad result since 0.5 m apart is quite close and we might want to consider the two positions as approximately the same place. However, at the same time the maximum Euclidean distance is 14.8, which is larger than the minimum distance for measurement set C.1.

From this we can conclude that it is possible to improve the results by carefully choosing the frequencies that are used, but there will still be an uncertainty in the position decision. By determining how large this uncertainty is by calculating the probability of an erroneous result, and the absolute distance to the erroneously picked locations, the severity of the uncertainties can be determined.

4 Gaussian process RSS estimation

Gaussian Process (GP) is a multidimensional regression method that is used in many different areas for example in robotics. Given some training inputs, the GP model tries to predict the outcome for new inputs based on the training set. The GP model is proposed for modeling the RSS for localization in [6] and [8].

To obtain signal strength maps for all frequencies used in this work the Gaussian Process modeling for Matlab from Rasmussen et al. [9] have been used. The GP with a squared exponential kernel model is trained with the mean RSS values for each position in measurement set C.2. The hyper parameters are optimized for each frequency with the minimize-function from Rasmussen's toolbox. Figure 20 shows the estimated mean signal strength over the area shown in Figure 4. The black crosses in the figures show the position of the training positions which corresponds to the blue circles in Figure 4.



(a) **(b)**

Figure 20. GP modeled mean signal strength maps for measurement set C.2. The signal strength estimate is plotted for frequency 95.5 MHz in (a) and 94.8 MHz in (b).

For some specific frequencies, the GP model fails to model the distribution of the signal strength over the selected area, see for example Figure 20a. However, for these particular cases the measured RSS value in every position is very close to the overall mean RSS value which could be the reason why the modeling fails.

A GP is a zero mean process, which means that the process tends to zero. However, the RSS value does not tend to zero. In the figures above the assumption is made that the RSS tends to the mean RSS over all training points for each frequency. This is not the case in reality, where the signal strength decreases with the distance to the transmitter. There are several ways to model the distance dependency. For outdoor scenarios these types of models are a quite good approximation but in indoor environments the radio wave propagation is more complex and available channel models (which do not take the building floor-plans into account) do not provide sufficiently accurate results.

The minimize-function from Rasmussen's toolbox optimizes the hyper parameters σ_f and l that represent the signal variance and a length scale factor that determines how fast the correlation between two points drops off. It is of high importance that these hyper parameters are adequately selected, otherwise the model will not be able to predict the RSS values successfully. In [8] a description of the GP model and the selection of its hyper parameters are given.

5 Discussion

In a mobile indoor positioning system based on RSS techniques, the receiver has to sample the complete set of RSS values fast enough. Fast enough is a very vague definition, but for a soldier positioning application it depends on how fast the soldier is moving. A fully equipped dismounted soldier will seldom move more than 2-3 dm during a 50 ms time period, which then could be considered as an upper limit in time. The sampling of the RSS values can be done sequentially or in parallel to ensure that the samples are collected during a time period where the soldier movement can be considered negligible. Both ways have their pros and cons. In this work we have sequentially sampled the signals.

With sequential sampling the receiver cannot stay too long at each frequency. The receiver has to sample the RSS from the first frequency and then switch to the next frequency to sample that RSS and so on until all frequencies have been covered. All this has to be done during the time that the person using the system is considered to be stationary. This means that if we double the number of frequencies the sampling time for each frequency will be reduced to half, if we assume that the switching time for changing frequency is negligible. To achieve RSS values with a low variance the sampling time should be as long as possible at each frequency. This is contrary to the fact that an increased number of frequencies achieve better results. So there is a trade-off between the number of frequencies and the sampling period at each frequency.

In the case of parallel sampling of the RSS values, where all the RSS values from the different frequencies are obtained in parallel, the sampling time for each frequency can be as long as the time the person using the system is considered stationary. The drawback with parallel sampling is that the frequencies used in the positioning system cannot be separated too much in frequency. Hence, the frequency diversity will be limited. In a not too expensive high-end receiver, a realistic maximum bandwidth is approximately 50 MHz. This means that public FM radio signals cannot be measured in parallel with broadcasting TV signals with such a receiver. Instead, we have to choose either FM radio or TV signals, if using a single receiver. If we can afford to have multiple receivers, several frequency bands can be measured in parallel.

If the RSS-based positioning should be integrated with a foot-mounted inertial navigation system, the receiver must have a small form factor and be cheap. In an early prototype, that kind of receiver could for example be something similar to the FunCube dongle [10], which has the size of an USB-dongle and a bandwidth of 96 kHz. In a commercial product several different receiver chips, covering multiple frequency bands, has to be used to reduce the size and cost even further.

The antenna must have a small size so it can be easily integrated into the system. It is realistic to anticipate that the antenna will be placed very close to the human body. Therefore, the antenna is most likely going to affect the positioning accuracy that can be obtained, as we have seen in measurements where the shadowing and rotation of the antenna affects the RSS values.

In this work the signals of opportunity was manually selected, but in an integrated soldier positioning system the signals has to be selected automatically at start-up (or prior to deployment to the area of operations). The selection of signals and the number of signals to use can be crucial for the resulting positioning performance. In this work we have not studied how to automatically select suitable signals. An idea is to scan several frequency bands during the initialization of the system. If the average RSS value is above a pre-defined threshold, and the signal do not exhibit an excessive time variation, we can conclude that there is a signal at that frequency that could be of use. As we also have mentioned, some of the signals are TDMA based, so to obtain more accurate RSS values the receiver could be time synchronized to the transmitter. Another important aspect in the selection of suitable signals is the transmitters' positions. To increase the accuracy, of the loop-closure decision, it is desirable that the transmitters are selected so that the angles of arrival are distributed around the area of interest.

5.1 Further work

Ideas of work tasks that we have, in this initial feasibility study, identified to be of interest to study further are summarized below:

- Measurements in other types of buildings which may have other propagation and multipath characteristics. In different areas the available number and types of transmitters will also differ, which will change the set of possible signals to measure. Hence, this examination is necessary in order to reliably evaluate the possibility of using RSS measurements in a soldier positioning system. This could include mobile measurements, using for example a small platform like the Fun Cube dongle where we are able to collect data continuously over larger areas.
- Test different types of antennas and their placement relative to the human body. As we have seen, the rotation and shadowing of the antenna affects the measured RSS. Form factor and antenna placement will be important factors in the development of a military system.
- Investigate different types of measures other than the Euclidean distance, for example the Manhattan distance (L^1 norm). In [4], the Manhattan distance provided an improved positioning accuracy.
- Prediction of RSS values for not yet visited positions. In this work Gaussian processes are proposed as an example. The Gaussian process model has to be further trained with example measurements and its parameters have to be optimized to achieve higher accuracy. A reliable prediction of the RSS values even one or two meters from the visited trails would significantly improve the chances of visiting areas which have RSS values in the data base.
- Integration with our existing experimental multisensor soldier positioning system, which is based upon foot-mounted INS, GPS-receivers and also can incorporate visual sensors for improved localization and automatic mapping capability.
- Investigate methods for cooperative creation of RSS database maps for loop-closure decisions. For instance, a team of soldiers could build and share the same database, thereby substantially increasing the likelihood of visiting positions that already has been mapped during the operation. However, considering low-cost receivers the measured RSS values may differ considerably between units even at the same place[4].
- Investigate the use of deployable transmitters outside of buildings, resembling a scenario with transmitters placed on vehicles. This could be useful in operations where there is a limited number of suitable signals of opportunity to be used.
- Increase the number of used signals. In metropolitan areas the number of available signals, e.g. FM radio transmitters, is significantly higher. With a larger set of signals we could further analyze the amount or types of signals that is desirable in an integrated positioning system. Chen et al. [4] has shown an increased positioning accuracy when the number of used signals are increased.
- Develop a method to automatically choose which signals to use. When deployed in completely new areas, a selection of feasible signals has to be made automatically during system initialization (or prior to deployment).

[4] As an example, indoor positioning using mobile phones and RSS measurements is challenging since different mobile phones may exhibit variations in the RSS values exceeding 10 dB.

6 Conclusions

Radio-frequency signals interact with the environment. First of all, the radio signal experiences distance dependent signal attenuation (path loss). Furthermore, the radio signal is reflected from different objects (multipath propagation), diffracted around obstacles, and scattered off various objects. As a consequence, the antenna receives many signal components that are more or less distorted and delayed. Fading is caused by the constructive or destructive addition of all received multipath components, which causes the rapid fluctuations in the received signal strength that are typical for wireless radio channels. The signal strength, for a narrowband radio system, may therefore vary rapidly in time and space.

The results of the measurements performed in this work shows that there is a difference in the obtained RSS values for different indoor positions. Using the Euclidean distance between the set of measured RSS values for different positions it is often possible to distinguish between different indoor positions. In general we can say that the Euclidean distance will decrease if the geographical distance between different positions decreases, but there are exceptions caused by the combination of choice of signals and the indoor radio propagation conditions.

The number and types of signal that are used in the evaluation with the Euclidean distance has a crucial role. If the number of signals are increased, the observed Euclidean distance will also increase. Some signals will increase both the minimum and the maximum Euclidean distance and some will increase only the maximum Euclidean distance, which is desirable. Hence, by carefully selecting a sub-set of the available signals, the positioning results can be improved.

A strong time variation is observed in the RSS measurements. The time variations will negatively affect the accuracy of any RSS-based positioning algorithm, also when using the set of RSS values to perform loop-closure. Therefore, an ageing factor is proposed. The ageing factor should weight newer RSS-samples higher than older samples, as too old samples may introduce large errors in the positioning estimate.

Another factor that might negatively affect the performance of the indoor positioning is the antenna and its placement. In the results of the antenna measurements we can see that shadowing the antenna from different directions, and also rotating the antenna in different directions, will affect the obtained RSS values. However, the variations of the RSS values due to the antenna effects are mostly smaller than the variations between locations.

The main aspects that will affect the performance of RSS based positioning are:

- **Transmitters:** The selection of suitable transmitters depends on their position, output power, waveform, and frequency band. The number of selected signals is crucial.
- **Receiver system:** The antenna type and its placement and rotation relative the room will affect the positioning accuracy. The measurement receivers' bandwidth and measuring time must be adjusted to the waveform of interest.
- **Propagation conditions:** The time variations caused by the radio wave propagation will affect the positioning accuracy. Also, different types of buildings may affect the attenuation of the RSS value.

In conclusion, indoor positioning based on RSS measurements alone will not be feasible with high enough accuracy and reliability, since the Euclidean distance metric can point at erroneous positions when a position is revisited. However, the erroneous position estimate may be discarded based on information from other sensors when the RSS positioning technique is integrated with a multisensor indoor positioning system. The RSS positioning technique may then be used to aid e.g. a soldier positioning systems accuracy and reliability, for instance by allowing the system to perform loop-closure.

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