MASTER

Determining the relative position of a device in a wireless network with minimal effort

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Determining the Relative Position of a Device in a Wireless Network with Minimal Effort

Master Thesis

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Abstract

Unlike wired lighting systems, wirelessly controlled luminaires have no fixed connections between lights and switches. The position of a luminaire is an important attribute for either lighting application or other applications requiring position information in a building. Normally during the commissioning process, a commissioning person is required to manually locate the devices and assign their IDs on the floorplan. This master thesis proposes algorithms to perform an almost automatic device localization, in which a relative relationship matrix is generated from Received Signal Strength Indication (RSSI) and the lighting layout with devices’ IDs is determined by matching the relative relationship matrix with floorplan. The automatic device localization will shorten the commissioning time considerably.

The main shortcoming of using RSSI is its instability and the interference susceptibleness noticed in real environments. Experiments are carried out to explore the characteristics of fundamental factors contributing to RSSI variability. Methods and assumptions are introduced to come up with a reliable relative relationship matrix between nodes. Two matching algorithms are introduced to match the devices’ IDs with the positions in the floorplan to formulate the final layout and both of them achieve high accuracy.
Preface

This thesis is a part of my master’s graduation project in System Architecture and Networking group, Eindhoven University of Technology, with Philips Lighting B.V. as host company. First and foremost, I would like to express my gratitude to prof. Johan Lukkien who has provided me with valuable guidance. I would like to express my thanks to Tanir for his scientific support and control the whole project process, especially for helping me check the report despite his busy schedule. I would also thank Richard Verhoeven for providing the TelosB nodes to me for experiments.

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One of the other major influences throughout my graduation project is my parents. I want to thank them for their endless patience to help and encourage me to do better. In the past six months, we skyped every week and every time when I was upset, they cheered me up and always gave me confidence to overcome everything.

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Acronyms

**TDMA** Time Division Multiple Access. 26

**TDOA** Time Difference Of Arrival. 3

**TOA** Time Of Arrival. 3, 10

**WSN** Wireless Sensor Network. 1, 2, 6, 10, 45, 46
Chapter 1

Introduction

In this report, localization algorithms are described to identify and match the ZigBee controlled luminaires inside an office building with floorplan. This chapter firstly introduces the background of localization in a Wireless Sensor Network (WSN) especially a connected lighting system. Then the motivation of doing this graduation project and the problem statement are stated followed by the layout of the report.

1.1 Background

In recent decades, the trend of energy saving and the rapid development of Internet of Things (IoT) have promoted the growth of researches on intelligent office lighting systems. The modern intelligent lighting systems aim to create a more comfortable, productive and sustainable workspace by using proper light conditions [45]. In order to enhance the light conditions for the people working in the building, the light system has integrated sensors that controls the lighting automatically. The data produced by the sensors can also be used for further analysis to improve the lighting system. The Edge [27] is an innovative, multi-tenant office building in Amsterdam. The connected lighting system, constructed by Philips Lighting B.V. together with OVGuide and Deloitte, not only allows employees to personalize the lighting and temperature at their workspaces through a smartphone app, but also provides building managers with real-time data on operations and activities. Nearly 6,500 connected Light Emitting Diode (LED) luminaires and sensors in 3,000 of these luminaires are distributed throughout the building’s 15 floors. The system captures, stores, shares and distributes information throughout the illuminated space [27]. To make use of the collected data, the position of these luminaires and sensors is important and need to be obtained during the commissioning phase, which, unfortunately, is currently still a manual process. The installation of this infrastructures as shown in Fig. 1.1 is a complex and lengthy task.

During the commissioning phase of a lighting system, the control behavior of the lighting system will be configured, according the wishes of the customer, such as grouping of luminaires. In this report, we narrow the concept of commissioning process as the process that provides the position information of individual devices to the control system and the process occurs after the installation phase. Instead of a commissioning process, we simply call it as a localization process. As it is mentioned, the localization process so far involves much manual effort and is time-consuming, labour-intensive and inefficient [44]. For instance, the current available mapping techniques are Trigger→Search→Position method and Go→Position method. The former one includes the methods that the installer has to trigger a luminaire by selecting the luminaire from a list of discovered luminaires and then he has to search for a blinking luminaire in the whole building. This method requires at least two people for walking around the building and in some cases special
tools may be required, such as walkie-talkies or phones for communication between the installers. The latter one includes using electronic devices for identifying the luminaire’s ID. Only two steps are required since the installer can read the ID of the luminaire and then he has to search the device list on the laptop screen to find the specific luminaire and then drag and drop it at the corresponding area. It is estimated that each step takes approximately 30 seconds [45]. Thus, the time for mapping one luminaire for two methods are 2 min and 1.5 min respectively. The cost for these two methods are estimated to be €2.6/luminaire and €1.8/luminaire respectively which will be a non-negligible amount with the increasing number of luminaires [45].

A wireless lighting system that incorporates an automatic localization solution will be significantly easier to install than a system using conventional wired digital control. The electrician only needs to install each device (luminaire or luminaire with sensor) in the appropriate location as it is indicated in the floorplan and connect it to power. The wireless network will be initialized after power up and each device will join the network and identify itself by its unique address. Then the problem is to find out which of these luminaires is in which specific location. The problem will be simple if all the devices are of the same type so that they could be matched directly by the network. Unfortunately, most of the luminaires are in the same type and are identical except for the unique identity allocated to each radio by the chip manufacturer. Using Global Positioning System (GPS) is a way to acquire the absolute position for sensor nodes. Then the luminaires with absolute positions can be matched with the coordinates in the floorplan. Nevertheless, there are many cases where GPS is not practical. For instance, GPS does not work in a building, the GPS signal does not propagate into a building. In addition, there is usually a large number of nodes in a WSN so that it is not cost efficient for every constrained node to be equipped with a GPS [33]. Instead of obtaining absolute position for each luminaire, relative position estimates between each pair of nodes is more practical and receive more attention by most of studies in the area of localization in WSN. Several radio-location methods are proposed for localization in WSNs. According to different wireless standards used, it can be divided into Blue-tooth Low Energy based [13], IEEE 802.11 based [28][11] and IEEE 802.15.4 based technologies. Since luminaires
are equipped with ZigBee chip and there are a number of patents which promise the acceptable accuracy and speed of ZigBee radio based techniques [44], we implement our system in IEEE 802.15.4 which is also designed to support large networks.

Based on the type of knowledge used in localization, localization can be divided into range-based and range-free [17]. Typical range-based algorithms are based on RSSI, Angle Of Arrival (AOA), Time Of Arrival (TOA), Time Difference Of Arrival (TDOA) or Phase Difference Of Arrival (PDOA). The range-free localization algorithms include DV-Hop, fingerprint. Since the location accuracy of range-based approach is relatively higher than of range-free solutions, in this report, we focus on range-based methods [5]. TOA and RSSI are two most popular range-based methods. TOA is proved to be more accurate than RSSI. The main drawback of TOA is that it needs extra hardware for today’s generation of ZigBee chips. Sophisticated techniques are required to measure arrival times to nanosecond accuracy which has additional requirement on ZigBee chip. Compared with other range-based solutions, RSSI is an easier and less expensive one to be implemented as almost all the Radio Frequency (RF) transceiver chips are embedded with Received Signal Strength (RSS) indicators which provide RSSI measurements without any additional cost. However, the positioning accuracy using RSSI is limited due to various factors. Experiments in Chapter 3 are designed to gain insight on the characteristics of radio ranging in wireless sensor nodes.

RSSI based localization can be further categorized into range-based, sequence-based, connectivity-based, fingerprinting-based and mobility-assisted localization. Range-based localization has the assumption that the value of RSSI is a function of distance [9][7][39]. In this way, the RSSI measurements are converted into estimated distance as shown in Fig. 1.2. Sequence-based localization also assumes that RSSI decays over [25][10]. Instead of using a certain function to translate RSSI value into distance, it simply uses the ordered sequence of RSSI measurements. Connectivity-based localization only uses the connectivity information which depends on whether a packet is received or not [53]. In principle, connectivity measurements are a binary quantization of RSSI measurements and this type localization is considered to be less accurate comparing with other types of RSSI-based localization systems. Fingerprinting-based localization systems assume that RSSI is a function of position instead of being a function of distance [9][2][52]. As there are several unknown factors from environment which have big impact on RSSI measurements, there exists some blind area which cannot be measured correctly. In order to overcome the shortcomings of static environment, mobile nodes are introduced to the wireless network in many studies. In mobility-assisted network, mobile nodes will cooperate with static location-aware nodes to output more reliable RSSI measurements.

![Figure 1.2: A wirelessly controlled ceiling light emits a radio signal to determine range](image-url)
CHAPTER 1. INTRODUCTION

After obtaining the relative relationship matrix based on RSSI measurements, various intelligent algorithms are implemented to match the nodes with relative relationship with their true location. Maximum Likelihood (ML) method \([36][35][6]\) is a typical algorithm to estimate the position of location-unaware nodes based on the relative distance between location-aware nodes and location-unaware nodes. Approximate Point In Triangulation (APIT) \([30][18]\) method isolates the environment into triangular regions between beaconing nodes and uses a grid algorithm to calculate the maximum likelihood area in which a node will likely reside. Multidimensional Scaling and Mapping Method (MDS-MAP) \([42][40]\) is proposed to determine the relative positions of nodes based on local distance or connectivity information with only limited number of location-aware nodes. More advanced algorithms such as genetic algorithm \([32]\) and simulated annealing algorithm \([23]\) have been introduced to solve the localization and have acceptable performance.

1.2 Motivation of Thesis

More and more wireless lighting products are implemented in modern buildings to reduce the complexity for control system by replacing the lighting cabling with ZigBee radio. However, currently, the localization of wireless nodes in commissioning process is still a manual process and it consumes lots of time and labour efforts. In this master project, an almost automatic localization scheme is designed to enhance the efficiency of wireless lighting systems based on RSSI. The main concern for localization algorithms are to achieve acceptable localization accuracy, thus, both reliable adjacency information between nodes and robust graph mapping algorithms are needed. However, the positioning accuracy using RSSI is limited due to various factors such as device characteristics and transmission media properties. In this project, experiments are designed to have an insight of RSSI and investigate the way to obtain reliable adjacency information. With the adjacency information, a localization scheme is proposed and proved to achieve high localization accuracy based on a simple deployment.

1.3 Problem Statement

As it is mentioned in the background, there are going to be more and more intelligent buildings like the Edge in the near future. These intelligent buildings are always equipped with a large number of wirelessly controlled devices such as luminaries, temperature sensors and so on. The problem comes up during the commissioning phase when the installer wants to establish the connection between individual device’ ID and its location for further implementation. In Fig. 1.3, there is a typical layout with 16 luminaires (blue circle) and 1 sink node of (red circle). In order to simplify the problem, in this project, there are some requirements beforehand for the scenarios:

- There is a computer-readable floorplan.
- There is a working IEEE 802.15.4 wireless network among the luminaires and the luminaires can exchange data packets.
- A plurality of luminaires as well as other wireless devices are installed according to the floorplan.
- The luminaires are identical except the ZigBee identity allocated to each radio.
- Each luminaire is embedded with RSSI indicator, which can provide RSSI measurement for the signals received.
- A sink node is supposed to collect the messages from the luminaires and forward to the central base station such as a laptop.
CHAPTER 1. INTRODUCTION

Figure 1.3: A typical layout with 16 luminaires

- All nodes are line of sight.

The problem can be formulated to find a one-to-one assignment \( f : ID \rightarrow L \) that has high localization accuracy:

\[
\sum_{id_i \in ID} f(id_i) \approx f_0(id_i)
\]  

(1.1)

- \( n \) is the total number of positions in floorplan and also the total number of nodes.
- \( ID \) is the set of nodes’ ID. \( ID = \{id_1, id_2, \ldots, id_n\} \).
- \( L \) is the set of coordinates of positions in floorplan. \( L = \{l_1, l_2, \ldots, l_n\} \).
- \( f_0 \) is the true one-to-one assignment from nodes to locations, \( f_0 : ID \rightarrow L \).
- \( X \approx Y = \begin{cases} 1 & \text{when } X = Y \\ 0 & \text{when } X \neq Y \end{cases} \)

The ideal localization accuracy is 100% which means all nodes are localized correctly. The accuracy of localization depends on the quality of relative relationship between nodes and robustness of the localization algorithms.

We design a series of experiments to investigate the fundamental factors contributing to RSSI variability. Several practical factors that are considered to have an impact on the propagation model are given below:

- Device characteristics
- Transmission media properties

Device characteristics contain the node transmitting power and antenna orientation. The transmission media properties include the type of the media, the background noise, and others like temperature, humidity, obstacles within the transmission media. We conduct experiments in a
large space room in which we make sure no node is placed next to wall and the temperature and humidity can be controlled to vary in a small range. We expect that in this way these influences from the transmission media can be minimized.

Based on RSSI, an adjacency matrix is generated which indicates whether two of the luminaires are adjacent or not. Then, the next step is to match the luminaires’ ID with the locations in the floorplan. There are two approaches to do it:

- Point-based matching
- Edge-based matching

Point-based matching first translates the adjacency information between nodes into estimated positions by graph drawing algorithms. Then the problem could be translated match each estimated position to a specific position in floorplan. The best matching could be found by minimizing the sum of the difference distance between each pair of estimated position and the assigned position.

Edge-based matching method match the nodes’ Id with the positions in floorplan directly based on the adjacency information. The best matching could be found by minimizing the sum of the product of adjacency metric between each pair of nodes with the corresponding distance between assigned locations of the nodes.

1.4 Outline of Thesis

The remainder of this thesis is as follows. Chapter 2 describes related work in the field of RSSI-based localization in WSN. Chapter 3 presents the detailed experiments about the influence of the fundamental factors on RSSI. Based on the findings concerning signal strength, Chapter 4 describes the localization scheme and the details of the localization algorithms. The performance of the localization scheme is evaluated in Chapter 5. Finally Chapter 6 presents some conclusions and future work.
Chapter 2

Related Work

2.1 Introduction to Received Signal Strength

The Received Signal Strength Indicator provides a measure of the signal strength at the receiver which is often used as measure for the wireless link quality. The RSSI value is measured in dBm and expresses the signal power. Higher value indicates the received signal is stronger.

2.1.1 Propagation Models

Due to the attenuation of radio signal with distance, RSSI is expected to estimate the distance between wireless devices. The majority of RSSI localization schemes make use of a signal propagation model that indicates the relationship between RSSI values and distance estimates. There are several alternative models which could be found in literature. Egli’s model [8] is one of the well-known models which gives the propagation path loss as

$$L = 20 \log_{10} f + 40 \log_{10}(r) - 20 \log_{10}(h_t) - 10 \log_{10}(h_r) - 43.7$$

(2.1)

Where $f$ is the frequency, $r$ is transmitter-receiver distance, $h_t$ is transmitting antenna height and $h_r$ is receiver antenna height. The Egli’s model can be simplified as log-normal shadowing model as

$$RSSI(d) = P_T - PL(d_0) - 10\eta \log_{10} \frac{d}{d_0} + X_\sigma$$

(2.2)

Where $P_T$ is the transmit power, $PL(d_0)$ is the path loss for a reference distance $d_0$, $\eta$ is the path loss exponent and $X_\sigma$ is a Gaussian random variable with zero mean and $\sigma^2$ variance, which models the random variation of the RSSI value. The log-normal shadowing model is the most widely used signal propagation model.

Dimitrio et al. [56] carry out an empirical characterization of Received Signal Strength variability in 3-D IEEE 802.15.4 networks using monopole antennas. They use the CC2420 radio to verify the log-normal shadowing model in an obstacle-free environment. The research shows that direct distance prediction from raw RSSI data is impossible in the case of 3-D indoor deployments with random antenna orientations.

Heikki et al. [26] find out a more accurate RSS-based location can be obtained with a combination of an unbiased propagation model and the Least Squares (LS) algorithm. Moreover, location error
increases linearly with mean distance from transmitters and with RSS variation caused by shadow fading or varying antenna gain. The increasing frequency decreases the localization accuracy as shadow fading increases with frequency. A satisfactory approximation of localization accuracy in a given network is obtained by the error estimates that are based on linearization however modified when the receiver is close to transmitter. Moreover, this study applies Kalman filtering [19] on estimating coordinates which is shown to be able to remove the largest location errors but cannot improve the median accuracy significantly with the impact from correlated shadowing process.

2.1.2 Sources of RSSI Variability

The results in indoor environment from Dimitrio et al. [56] indicate reflections become the main problem in performing RSSI distance prediction. Only a very small range of RSSI values can be used for extracting distance information for up to 90-120 (cm). Within this range, RSSI changes linearly with distance. In addition, the indoor sensor network deployments suffer from a high degree of link asymmetry due to the multi-path and fading effects as well as due to the random pairwise antenna orientations used during communication.

Zhen Fang et al. [12] conduct an empirical study on RSSI variability characterization and calibration method in wireless sensor network. SKITT sensor nodes are designed for the experiments and these nodes are equipped with a CC2420 communication chip and a monopole antenna. The experiments indicate that RSSI can work well with the localization variability performance for specially instrumented scenarios such as an ideal open, outdoor environment, after strict selection of sensor nodes and calibration. In the experiments, using multiple transmission power levels does not improve the ranging performance.

Torben et al. [49] conduct a practical study on the evolution of RSSI and Link Quality Indication (LQI) over distance measurement based on CC2420 radio. The indoor measurements show a good correlation between path loss model and RSSI values up to 20m. The Path Loss Propagation model has been adapted through curve fitting in order to predict the signal decay in different scenarios using CC2420. RSS values are found out to be useless for direct positioning but may be used to increase the reliability of the RSSI measurements in some way.

Ion et al. [50] explore indoor RSSI-based ranging consistency and error factors in wireless sensor network. NXP’s JN-5148 series (IEEE 802.15.4 compliant transceiver) is used in the experiment and there is an integrated antenna and an external antenna. The results show that the RSSI distance consistency can be achieved if the environment is kept unchanged. However, different devices have different error characteristics which indicates that RSSI measurements can be affected by the hardware inconsistency. Moreover, different antenna angles can have a big impact on distances longer than 3m. A slight location variation for the same scenario also has a big impact. These factors increase the difficulty of using the RSSI in localization.

James et al. [3] connect remotely to large-scale temperature-controlled testbed and show how temperature affects the operation of routing protocol. The results show that the temperature variations has significant effect on the received signal strength which can break IoT applications by affecting the performance of a specific state-of-the-art communication protocol. The study demonstrated that the relationship between temperature and RSS measurements can be parametrized to a first-order model.

2.2 Localization Algorithms Based on RSSI

The existing localization schemes can be characterized by various criteria [17]. For instance, localization algorithms can be divided into anchor-based or anchor-free. Anchor-based algorithms
assume that all reference nodes are nodes whose real positions are known in advance. Anchor-free localization algorithms only require a few anchor nodes. Also localization can be range-based or range-free depending on whether distance measurement is needed. Moreover, static or mobile sensor nodes, indoor or outdoor deployment, two or three dimensional space could be criteria as well. Here, we lists some localization algorithms in three groups: distributed algorithm, centralized algorithm, mobility-assisted approach.

2.2.1 Distributed algorithm

In distributed localization algorithms, each sensor node localizes itself through messages exchanged with a number of neighboring anchor nodes [34][41][15][54][48][43][16]. All relevant computations are done on the sensor nodes themselves. The anchor nodes can be more than one hop away from unknown nodes when the density of the anchors is low. The densities of the anchors and unknown sensor nodes are needed to be decided carefully according to the size and topology of the partial network. An unknown node need to receive enough location information from anchors to calculate its own position. So as to obtaining the accurate locations, unknown sensor nodes densities and the way of determining the spatial relation are the key points in design of distributed localization algorithms.

Nirupama et al. [4] propose a range-free, distributed localization algorithm called centroid localization algorithm. This method needs location-aware nodes to broadcast their position information. Location-unaware nodes record the RSS measurements from the reference nodes. Each location-unaware node calculates its position by using a centroid determination based on the positions of the anchors. The location information from anchor nodes can be used to estimate position and RSSI can be used to improve the accuracy of localization.

Tian et al. [18] proposes Approximate Point In Triangulation (APIT), another range-free and distributed algorithm. APIT divides the environment into triangles according to the connectivity of a few anchor nodes. A node’s position can be narrowed down to estimated area based on its presence inside or outside of these triangular regions. The diameter of the estimated area can be improved to a certain accuracy level by combining of anchor positions. The accuracy of unknown nodes’ estimated position can be determined by calculating the center of the intersection of all triangles in which the unknown node resides.

2.2.2 Centralized algorithm

Centralized localization algorithms are basically migration of inter-node ranging and connectivity data to a sufficiently powerful central base station such as a laptop and then the migration of resulting locations back to nodes respectively [41][23][34][16]. The advantage of the centralized schemes is that they can acheive higher accuracy by implementing more complicated algorithms and process a large amount of data. Moreover, these methods require less anchor nodes than nodes in distributed algorithms.

Shang et al. [42] propose Multidimensional Scaling and Mapping Method (MDS-MAP) which is a centralized algorithm and it is based on connectivity information and a few anchor nodes. This method can be range-free or range-based. The connectivity information will be converted into absolute coordinates by a mathematical technique called MDS. The algorithm contains three steps as follows:

1. The first step is to generate a node distance matrix D based on calculating shortest paths between all pairs of nodes in the network.

2. Second step is to calculate the relative node positions based on the distance matrix D using
classical metric MDS. In two dimensional map the two largest eigenvalues and eigenvectors will be retained to be the coordinates of nodes.

3. The last step is to transform the relative node coordinates into absolute coordinates using a few anchor nodes at least three for two dimensional map.

The accuracy of relative position estimation is affected by several factors, including the network connectivity, the errors of local distance measures, the length of the path, and the number of common nodes of two adjacent relative maps.

Guo-Fang et al. [32] propose a genetic algorithm together with the corresponding fitness function and genetic operators to implement the localization. The algorithm is validated with 100 nodes randomly distributed in a square region of $10 \times 10$. The distance measurements are blurred by introducing a Gaussian noise. The results show that the proposed localization scheme is able to achieve rather high accurate location of 100 nodes with 8 anchor nodes and 5% Gaussian noise.

Derks et al. [9] implement Gridded RADAR [1], Area Based Probability (ABP) as well as Single Point Matching (SPM) matching algorithm to test fingerprinting RSSI-based technique in scalable localization problem. By comparing the result, SPM outperforms RADAR while ABP fails to meet the requirements. However, SPM might not give the output in a finite number of iterations and the running time is significantly larger than RADAR’s running time. In this study, it also finds out that the performance of RSSI measurements can be improved from 3m to 2m with an additional ZigBee radio.

Natasa et al. [22] present a heuristic algorithm based on an iterative approach that is designed for the specific problem of matching nodes of two weighted graphs of equal size, using monotonic relation between the weights of the corresponding edges. The algorithm assumes a set of reference nodes first. For each iteration, a location from the set of non-assigned locations is assigned to exactly one non-localized node. The assignment is determined by the so-called voting procedure involving all reference nodes. Every unknown node will be assessed by all reference node using the RSSI measurements between the pairs of nodes and the distance between the pairs of locations. Once a location is assigned to a certain node, this node will be added to reference nodes set. It turns out that the mapping algorithm can achieve relatively low error rate (less than 7.5% for 50% of the cases) when the number of reference nodes is at least 10% of the total number of nodes.

2.2.3 Mobility-assisted approach

In conventional methods, RSSI has been widely used as a distance measure mainly in the context of static WSNs. However, a number of parameters from the environment cause the inaccuracy of RSSI values. Several studies make efforts to improve localization performance by introducing the mobility into WSNs. In general cases, a group of mobile anchor nodes send out a signal and unknown sensor nodes will record certain properties by technologies like TOA, RSSI, etc. Then unknown sensor nodes positions are determined by transforming signal measurements into position estimated via some localization algorithms.

Xing et al. [55] study target detection for mobility-assisted WSNs. In this project, they propose a data fusion model which enables static and mobile sensors to effectively collaborate in target detection. Mobile sensors collaborate with static sensors and move reactively to achieve the required detection performance. Wang et al. [51] detect the coverage holes using Voronoi diagrams and devise three movement-assisted sensors from densely deployed areas to sparsely deployed areas.

Hongyang et al. [5] evaluates the performance of RSSI method when applied to mobility-assisted sensor networks. It demonstrates the collaboration between mobile and static nodes could reduce the anchor densities on demand comparing to all-static network deployments. Moreover, mobile
sensors can cooperate with the static sensors to fix the limitation of node localization in the static sensor networks.

Nevertheless, there are some limitations for mobility-assisted network [16]. The first one is that the uncertainty of anchor movements will increase the difficulty of localization. The second one is that additional measurements are required from mobile anchors in mobility-assisted localization schemes.
Chapter 3

Experiments of RSSI Variability

3.1 Experiment Preliminary

In the experiment part, we used TelosB motes (as shown in Fig. 3.1) as sensor nodes and carried out the implementation in Contiki OS [37].

Each TelosB mote is equipped with a CC2420 radio and an embedded antenna [29]. CC2420 radio works in 2.4 GHz band, a wideband radio with Offset Quadrature Phase Shift Keying (O-QPSK) modulation with Direct Sequence Spread Spectrum (DSSS) at 250kbps [21]. It is specifically designed for low power wireless applications and supports 8 discrete power levels: 0dBm, -1dBm, -3dBm, -5dBm, -7dBm, -10dBm, -15dBm and -25dBm at which its power consumption varies from 29mW to 52mW. A built-in RSSI gives a digital value that can be read from an 8 bits, signed 2s complement $RSSI_{VAL}$ register. The RSSI value is calculated over 8 symbol periods (128 $\mu$s). The power $P$ at the RF pins can be derived from $RSSI_{VAL}$ directly using the following equation:

$$P = RSSI_{VAL} + RSSI_{OFFSET}[dBm]$$

where the $RSSI_{OFFSET}$ is found empirically during system development from the front end.
gain, which is approximately -45dBm.

The platform used for programming TelosB is Contiki using C language. Data analysis is done through Python and Matlab.

This chapter contains four different scenarios. Details on RSSI versus distance will be provided and discussed. All the experiments are carried out at a large meeting room 144 in High Tech Campus building 48 in Eindhoven and all the nodes are placed on the table to simulate the condition in which the luminaires are attached to the ceiling. In this setup there is a clear line of sight between each pair of nodes. For a ZigBee network, there are 16 channels to be chosen from 11 to 26 in 2.4 GHz range. Since channel 26 (2.480 GHz) does not overlap with WiFi channels, channel 26 is used in the experiments. Otherwise it will be indicated.

A simple deployment is shown in Fig. 3.2 which contains a sender, a receiver and a sink. Senders in this report refer to nodes in sender mode while receivers are the nodes in receiver mode. Sender will send out broadcast message with a counter which is used to calculate the package loss rate. Receiver will record the information with the following format: \( \langle \text{nodeID}, \text{RSSI} \rangle \) to its memory as a list. Note that the nodeID is the ID of sender. A sink node will send unicast to receivers and the receiver will respond the sink with the list. In this way, the information is collected for further processing.

![Figure 3.2: Simply deployment with one sender and one receiver](image_url)

### 3.2 Transmitter Variability

Generally speaking, a WSN node contains modules including power management, sensors, controller and radio. The radio module is the most relevant one in RSSI localization system. It is important to ensure that each sensor node has consistent transmitting power because different transmitting powers can alter RSSI value which will lead to wrong relative relationship between nodes. The default transmitting power is level 31(0dBm) and it can be changed between 1 to 31. The relationship between transmitting power level and output power is shown in Tab. 3.1 [21]. The RSSI values received at the same receiver from different senders can be different, even when all the other parameters that affect the RSSI such as transmitting power are kept constant. The differences may be due to the deficiency of strict consistency in the process of sensor manufacturing and element device selecting.
CHAPTER 3. EXPERIMENTS OF RSSI VARIABILITY

<table>
<thead>
<tr>
<th>PA_LEVEL</th>
<th>OUTPUT POWER [dBm]</th>
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</tr>
<tr>
<td>27</td>
<td>-1</td>
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<tr>
<td>23</td>
<td>-3</td>
</tr>
<tr>
<td>19</td>
<td>-5</td>
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<td>15</td>
<td>-7</td>
</tr>
<tr>
<td>11</td>
<td>-10</td>
</tr>
<tr>
<td>7</td>
<td>-15</td>
</tr>
<tr>
<td>3</td>
<td>-25</td>
</tr>
</tbody>
</table>

Table 3.1: Output power settings at 2.45 GHz

3.2.1 Scenario

To characterize transmitter variations, we measure the received signal power of different TelosB nodes with the same transmitting power level. The transmitting power of each node is set to from level 3 to level 31 with a step size of 4 and the receiver is kept still. As shown in Fig.3.2, sender will broadcast the message with increasing transmitting power. The receiver receives the message and records the sender ID, counter, transmitting power level, RSSI and LQI and forwards the data to a sink node through unicast. A sink node is attached of the laptop and forwards the data to the laptop via the USB interface. The distance between the sender and the receiver is 1 meter.

3.2.2 Results

For each node and each transmitting level, 50 measurements are collected. Mean values of RSSI measurements are shown in Fig. 3.3. For different node at the same transmitting power level, the mean RSSI values received in the same receiver are different. For example, in case of transmitting power level is 31, the highest RSSI is about -41dBm from node 1 while the lowest RSSI is about -50dBm from node 2. The variation between nodes at the same position does not change with the increasing transmitting power. For instance, in each transmitting power level, the average RSSI value from node 1 is always the highest one.
CHAPTER 3. EXPERIMENTS OF RSSI VARIABILITY

3.3 Antenna Orientation

In characterize the variations in antenna orientations for each node, we design an experiment to study the antenna radiation patterns in the TelosB motes.

3.3.1 Scenario

As is shown in Fig. 3.4, each TelosB node is tested in eight directions (0, 45, 90, 135, 180, 225, 270, 315 degrees). The transmitting power of each node is set to be level 15 (-7 dBm) and the receiver keeps still. The distance between sender and receiver is 1 meter.

Figure 3.4: Collect RSSI measurements in eight directions
3.3.2 Results

For each sender and each direction, 50 measurements are collected. Fig. 3.5 shows the RSSI values recorded at the same receiver for all the senders and for all 8 orientations. For each orientation the average RSSI value is computed. A coarse radiation pattern is obtained for each node in Fig. 3.6.

- In Fig. 3.5, different nodes have different performance in the same position with the same orientation. The variation in direction of 270 degrees is the smallest which is less than 5 dBm compared to the variation in other directions. The biggest variation is more than 10 dBm.

- From Fig. 3.6, we can see that for individual node, it performs better in vertical direction which means 90 and 270 degrees. Especially in the direction of 270 degrees, all the nodes come to their peak values. The radiation patterns for nodes are similar. For instance, all nodes have higher RSSI in vertical directions and lower RSSI in horizontal directions.

In the following experiments, the RSSI measurements between two nodes are collected while strongest direction of their antenna (for instance, 270 degrees) points to each other as shown in Fig. 3.7. To simplification, we refer direction of antenna to the direction of antenna which sends out the message with the strongest signal strength.
CHAPTER 3. EXPERIMENTS OF RSSI VARIABILITY

Figure 3.6: Radiation patterns for each node

Figure 3.7: Two nodes face each other with directions of their antennas

3.4 Variations Across Different Radio Frequency Channels

IEEE 802.15.4 and ZigBee divide the 2.4 GHz band into 16 channels as shown in Appendix A. For different radio frequency, the wavelength of the radio is also different which might have an impact on RSSI.

3.4.1 Scenario

In this experiment, three different nodes are used as senders and four different frequency channels (Channel 11, Channel 15, Channel 19 and Channel 26) are picked as test frequency bands. As mentioned before, each measurement is recorded while sender and receiver are facing each other with the direction of their antennas. The distance between the sender and the receiver is increasing from 1 meter to 10 meters with a step size of 1 meter.
3.4.2 Results

For each node and each frequency channel, mean values based on 50 measurements are shown in Fig. 3.8 and Fig. 3.9.

- For each node using the same frequency channel, the RSSI value decreases as the distance between nodes increases. The obvious outliers happen without regularity within a frequency channel.

- Altering the radio frequency channel will change the influence from indoor environment. For example, in Node 3, obvious outliers in channel 11 are at distance of 2 meters, 5 meters, while outliers in channel 15 are at distance of 2 meters, 4 meters, 6 meters and 9 meters. Moreover, different frequency channels have more similar behavior within 4 meters and have more variations after that. The reason is that shorter distance will have less influence due to multipath fading.

- For the same frequency channel, the influence from environment is similar for different nodes. For instance, in frequency channel 26, all the nodes have outliers at the distance 2 meters and 5 meters.

![Figure 3.8: RSSI measurements for each nodes in different frequency channels](image-url)
CHAPTER 3. EXPERIMENTS OF RSSI VARIABILITY

Figure 3.9: RSSI measurements for each frequency channel with different nodes: a: Channel 11; b: Channel 15; c: Channel 19; d: Channel 26;

3.5 Variations From Static Environment

As it is shown in the last experiment, RSSI values are not able to reflect the distance between two nodes even when two nodes point the direction of their antenna to each other. This is because of the influence from indoor environment. The environment factors are various and not clear yet, it is difficult to find out the evidence where the outliers will happen. Nevertheless, it is clear that the change of the environment will impact on the RSSI which improve the performance of RSSI. Therefore, mobility of the receiver is introduced in this experiment to change the environment.

As the experiments are done in the Channel 26 and the wavelength of the radio can be calculated which is about 6 centimeters. To gain a larger impact on the signal path with minimal mobility range, the receiver is moved within the range of a circle with diameter of 6 centimeters.

3.5.1 Scenario

In this experiment, two nodes are used to test the performance with and without the mobility. As the measurements with static receiver are already collected in the last experiment, in this experiment, the measurements with mobile receiver will be recorded. During data collecting, receiver is moved within a small range. Since the mobility will increase the variability of the
measurements, mean value is no longer valid to indicate the true value of the measurements. In this case, maximum value is recorded to reflect the relationship between nodes. Similar with the last experiment, the distance between two nodes increases from 1 meters to 10 meters with step size of 1 meter.

3.5.2 Results

For each distance, 150 measurements are collected. The distribution of top 30% measurements is shown in Fig. 3.10. At distance of 1m, 2m, 3m, 4m and 6m, the measurements are more concentrated while at distance 5m, 7m, 8m, 9m and 10m, the measurements distribute in a wider range.

The maximum measurements are recorded to be compared with the maximum measurements with static receiver and it is shown in Fig. 3.11. We can find that the RSSI values with mobile receiver can overcome most of outliers which happen with still receiver.

In addition, the RSSI values with mobile receiver show a trend of log-normal distribution which...
CHAPTER 3. EXPERIMENTS OF RSSI VARIABILITY

matches the signal propagation model. The reason why mobility could improve the performance of RSSI is that RSSI measurements are easy to be crippled by multipath fading or reflection from environment. With mobility, the probability that the receiver can record the true RSSI from the sender increases.

Also, according to the log-normal signal propagation model, the difference of the same length decreases with the distance between nodes. For example, the RSSI difference between the node at 1 meter and the node at 2 meters is about 10dBm. And RSSI from the node at 2 meters is just about 6dBm higher than RSSI from the node at 3 meters. The difference after about three meters is too small to be distinguished by nodes. That is to say, it is difficult for a receiver to distinguish whether its sender is in 4 meters away or 6 meters away. Fortunately, finding out the nearest neighbors of a node is sufficient for us to go into the localization phase.

3.6 Conclusions

In this chapter, four experiments are carried to evaluate the performance of RSSI with different influence factors.

- The RSSI values received from different senders at the same receiver can be different even when all the other parameters that affect the RSSI are kept constant. To minimize the influence caused by transmitter variability, a standardized sensor node manufacture, strict selection of nodes are required. In this project, TelosB nodes with similar performance are selected for the localization phase.

- The result from the experiment of antenna orientation indicates that the integrated antennas in TelosB nodes are directional antennas. It is to say that the TelosB nodes only act as good transceivers in the certain direction which is not desirable for localization application. Omnidirectional antennas are required for nodes used in localization. Due to the lack of omnidirectional antennas, the RSSI measurements are recorded while the pair of nodes are both faced with the strongest antenna direction to simulate the omnidirectional antennas’ behaviors.

- The variability of frequency channels can improve the performance of RSSI by picking the highest RSSI value across all the frequency channels. Nevertheless, the comparison between still receiver and mobile receiver indicates that the variability of frequency channels does not bring large improvements. The reason might be the change induced by different frequency channels is not large enough since all of the frequency channels works under the 2.4GHz. Moreover, while collecting messages from other frequency channels except for channel 26 (WiFi free), there exists large packet loss rate due to the WiFi interference.

- The mobility of receiver within a small range provides reliable RSSI measurements. However, it is not practical to move the devices like luminaires since they are fixed on the ceiling. The practical scenario of the mobility will be discussed in the future work.
Chapter 4

Localization Scheme

This chapter introduces the whole localization process from the data gathering to final matching results. First, we describe the adjacency matrix generation based on a deployment with 16 nodes. Then, two localization algorithms are proposed. The first one is point-based matching algorithm which translates the adjacency matrix into estimated positions and matches it with the positions in floorplan. The second one is edge-based matching algorithms which compares the adjacency matrix with distance matrix generated from floor plan.

An overview of the localization process is shown in Fig. 4.1. An adjacency matrix is generated based on RSSI measurements and the floorplan. Then, a matching engine works with the adjacency matrix, floorplan and anchor nodes. In case the matching engine cannot figure out a reliable matching result, the matching engine might ask for more anchor nodes which is shown in flow a from Matching Engine to Anchor Nodes. If the number of required anchor nodes exceeds a certain level, the matching engine will ask to perform RSSI collection again which is indicated in flow b. The criteria to judge if the matching engine needs more anchor nodes or if RSSI collection is required again will be discussed in the next chapter.

Figure 4.1: Overview of localization process
4.1 Model Formulation and Data Collection

Localization scenario of 4×4 deployment in a large meeting room is considered in this chapter. The deployment of the positions is shown in Fig. 4.2. The distance between two neighbor locations in horizontal & vertical direction is 2 meters. The true locations of nodes are shown in Fig. 4.3. An extra sink node (SN) is needed to collect the information from other nodes and forward to the laptop for analysis.

Figure 4.2: 4×4 deployment in a large meeting room

Figure 4.3: 4×4 deployment of luminaires
Each node except SN contains `receiver_mode` and `sender_mode`. The node in `receiver_mode` will record the sender ID, RSSI and counter of the message received into its memory and send to SN. The node in `sender_mode` will keep sending out broadcast with a counter periodically.

Assuming antennas are omnidirectional and all the nodes are within the transmitting range of SN, so there is no need for special routing schemes. SN will send out four types of messages: broadcast messages of `TYPE_A` and `TYPE_B` and unicast messages of `TYPE_C` and `TYPE_D`. The data collection can be divided into three steps:

1. Initializing:
   - SN sends out broadcast messages of `TYPE_A` (see Fig.4.4.a);
   - Upon receiving message of `TYPE_A`, nodes reply to SN and record SN’s ID in local memory;
   - SN records the nodes’ ID in a list in its local memory;

2. Communicating:
   - SN picks up one of the nodes in the list and send unicast message of `TYPE_C` to the node (see Fig.4.4.b);
   - Upon receiving the `TYPE_C` message, it invokes its `sender_mode`;
   - Other nodes still work in `receiver_mode`;
   - SN sends unicast message of `TYPE_D` to the node in `receiver_mode` and marks it (see Fig.4.4.c);
   - Upon receiving the `TYPE_D` message from SN, the node in `sender_mode` will invoke the `receiver_mode`;
   - Repeat Step 2 until all the nodes have been marked in the list(see Fig.4.4.d);

3. Data gathering:
   - SN sends out broadcast messages of `TYPE_B` (see Fig.4.4.d);
   - Upon receiving the message of `TYPE_B`, nodes reply to SN with its nearest neighbor list;
   - SN sends the nearest neighbor lists to laptop over USB;

A simple example with six luminaires and one sink node is illustrated in Fig. 4.4. Note that only when the RSSI is larger than a threshold, the receiver will accept the message. The threshold is set to be -47dBm based on the result Fig.3.11. The receiver will only record the maximum RSSI for each neighbor. The process for node of `receiver_mode` is shown in Fig. 4.5.

Nevertheless, due to the limitation of node condition and the need of data processing, process of collecting the neighbor list of the 4×4 deployment is different from the description above.(explain better)

- In order to simplify the data collecting process, instead of assigning `sender_mode` and `receiver_mode` for each node, there is only one sink node, one receiver node and other nodes are all sender nodes.
- As there is only eight nodes available for experiments, the nodes will be shuffled to different position each round;
- In order to obtain all the signal strength received in one position, the receiver node will record all the signal received from sender nodes and send to sink node;
Figure 4.4: Data collecting process a. SN gets the list of nodes by broadcasting; b. Node 1 is invoked as send_mode and other nodes record the maximum RSSI received from node 1; c. Node 1 turns back to receiver_mode and SN marks its state; d. SN collects the neighbor list form each node by broadcasting;

- As the antenna in TelosB is not omnidirectional, during the data collection, all sender nodes will turn their strongest direction to receiver node’s position. And the receiver node will be turned around so that it has the chance to face each sender node with its strongest direction.

- During the data collection, the receiver node will be moved in a small range.

An example to collect data in one position is depicted in Fig. 4.6, the arrows represent nodes and the direction of arrows indicate the strongest radio direction of nodes. Green arrow represents receiver node and the yellow arrows are sender nodes. The red circle is sink node and it will forward the data to the laptop through USB.

In Fig. 4.6.a, the receiver node is placed in the position 1 and sender nodes are in the positions 2,3,5,6,7,8 respectively. Time Division Multiple Access (TDMA) is implemented to avoid the collision between sender nodes. More than 150 measurements are recorded from each sender. During the data collection, the receiver is rotated and moved in a small range at the same time. Fig. 4.7 explains the local memory inside the receiver in this case. There is a list in local memory to record the message temporarily and two pointers List_Head and List_End which points to the first element and the last element in the list respectively. Upon receiving a new broadcast
message, the receiver will save the message into the end of the list and the List_End will point to next Entry. As long as the list is not empty, the receiver will send the head of the list to
CHAPTER 4. LOCALIZATION SCHEME

<table>
<thead>
<tr>
<th>Receiver_Position</th>
<th>Sender</th>
<th>Send_Position</th>
<th>Counter</th>
<th>RSSI</th>
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Table 4.1: A part of the neighbor list (1)

<table>
<thead>
<tr>
<th>Receiver_Position</th>
<th>Sender</th>
<th>Send_Position</th>
<th>Counter</th>
<th>RSSI</th>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 4.2: A part of the neighbor list (2)

sink node by unicast periodically and the \textit{List\_Head} will point to next entry. The partial result is shown in Table. 4.1. Then, the send nodes are moved to new positions which have not been occupied as shown in Fig. 4.6.b. The partial result can be found in Table. 4.2. Similarly, more than 150 measurements are recorded from each sender. Until all the positions have been occupied, the receiver will be moved to next position and collect the messages from senders again.

![Figure 4.7: Local memory in Receiver](image)

4.2 Adjacency matrix generation

From above, a table with neighbor lists for different positions is gathered from each node and a part of the table can be found in Table. 4.3. The RSSI in the table is the maximum RSSI value between each pair of nodes. If the maximum RSSI value is smaller than threshold (-47dBm), the block will be left empty. Then, the neighbor list is transformed into an adjacency matrix by Alg.1. Let \( NL_i \) be the neighbor list for Node \( i \), and the elements in \( NL_i \) are of the form \( \{id, RSSI\} \). Let \( NNL_i \) be the nearest neighbor list for Node \( i \). For each node, a nearest neighbor list is generated from its neighbor list. Based on the observation of the floor map in Fig. 4.2, the maximum number of neighbors is 4, i.e., location F and the minimum number of neighbors is 2, i.e., location A. A gap with 5dBm is set according to the empirical experiment which allows the 5dBm variation among
nodes with the same distance. The algorithm below shows the process to generate the nearest neighbor list for Node \( i \). Moreover, there are some special cases to be considered.

1. After determining the first element \( E_{first} \) from \( NL_i \), there are more than one element having the same max RSSI values. In this case, a random element will be picked from them.

2. After determining the next element \( E_{next} \) from \( NL_i \), there are more than one element having the same max RSSI values. In this case, all the elements will be picked.

3. In case 2, the total number of \( NNL_i \) might exceed \( N_{max} \) if all the elements are picked up. In this case, we continue to pick up all the elements since there is no evidence which element is closer.

4. After the first element is determined, the RSSI value of next element is not valid since \( E_{next}.RSSI < E_{first}.RSSI - Gap \). In order to make sure that each node has at least \( N_{min} \) nodes in its \( NNL_i \), the next element is still picked.

\[\text{Algorithm 1} \quad \text{Algorithm to generate nearest neighbor list for each node}\]

1. \( NNL_i \leftarrow \emptyset \) \quad \( NNL_i \) is the nearest neighbor list for Node \( i \).
2. \( Gap \leftarrow 5 \text{dBm} \)
3. \( N_{max} \leftarrow 4 \) \quad \( N_{max} \) is maximum number of nearest neighbors.
4. \( N_{min} \leftarrow 2 \) \quad \( N_{min} \) is minimum number of nearest neighbors.
5. Pick up the element \( E_{first} \) from \( NL_i \), such that \( E_{first}.RSSI \) is the max RSSI in \( NL_i \).
6. \( NNL_i = NNL_i \cup E_{first} \)
7. remove \( E_{first} \) from \( NL_i \)
8. while size(\( NNL_i \)) < \( N_{max} \) do
9. \quad Pick up the element \( E_{next} \) from \( NL_i \), such that \( E_{first}.RSSI \) is the max RSSI in \( NL_i \).
10. \quad if size(\( NNL_i \)) \geq N_{min} \cap E_{next}.RSSI < E_{first}.RSSI - Gap then
11. \quad \quad break
12. \quad else
13. \quad \quad NNL_i = NNL_i \cup E_{first}
14. \quad \quad remove \( E_{next} \) from \( NL_i \)
15. \quad end if
16. end while
17. return \( NNL_i \)

| RSSI/dBm | 1 | 2 | 3 | 4 | 5 | 6 | ...
|---------|---|---|---|---|---|---|---|
| 1       | - | -40| -43| - | -39| -45| ...
| 2       | -39| - | -40| -45| -42| -39| ...
| 3       | -44| -37| - | -43| -45| -41| ...
| ...     | ...| ...| ...| ...| ...| ...| ...

Table 4.3: A part of the neighbor table

Thus far, every node has a \( NNL_i \) that contains its nearest neighbors. It is not difficult to come up with an adjacency matrix by combining all the \( NNL_i \). Let \( A \) be the adjacency matrix.

\[A[i][j] = \begin{cases} 1 & \text{Node } j \in NNL_i \\ 0 & \text{otherwise} \end{cases}\]
At this point it should be highlighted that the adjacency matrix might be asymmetric. For instance, Node \( i \) is in the NNL of Node \( j \) while Node \( j \) is not in the NNL of Node \( i \). In this case, the Node \( j \) will be considered as one of the nearest neighbors of the Node \( i \). Thus,

\[
A[i][j] = A[j][i] \begin{cases} 1 & A[i][j] = 1 \land A[j][i] = 1 \\ 0 & A[i][j] = 0 \land A[j][i] = 0 \end{cases}
\]

A part of final adjacency matrix is shown in Table 4.4.

| RSSI/dBm | 1  | 2  | 3  | 4  | 5  | 6  | ...
|----------|----|----|----|----|----|----|-----|
| 1        |    | 1  | 1  | 0  | 1  | 0  | ...
| 2        | 1  |    | 1  | 0  | 1  | 1  | ...
| 3        | 0  | 1  |    | 0  | 0  | 0  | ...
| ...      | ...| ...| ...| ...| ...| ...| ...|

Table 4.4: A part of the Adjacency Matrix

4.3 Point-based Matching Algorithm

In order to assign the nodes to locations in the floorplan, the point-based matching algorithm first calculates the estimated locations for each node based on the adjacency matrix. Then, it computes the best matching between locations in the floorplan and estimated locations.

4.3.1 Problem formulation

As it is shown in Fig. 4.8, the point-based matching algorithm first translates the adjacency matrix into estimated coordinates by graph drawing algorithms and compares them with the coordinates of locations in the floorplan.

1. Translate adjacency matrix into estimated coordinates;
2. Match the estimated coordinates with the location coordinates of the floorplan;

The localization problem is formulated as an assignment problem to find out the bijective assignment \( f : ID \rightarrow L \) that minimizes the sum of the squared distances between nodes’ estimated coordinates and their assigned coordinates in the floorplan:

\[
\sum_{id_i \in ID} d^2(e_i, f(id_i)) \tag{4.1}
\]

- \( ID \) and \( L \) are defined in Chap.1.3.
- \( E \) is the set of estimated coordinates of nodes. \( E = \{e_1, e_2, \ldots, e_n\} \).
- Given \( p_i = (x_i, y_i) \) and \( p_j = (x_j, y_j) \) represent coordinates of two positions, \( d \) is a distance function specified by Euclidean distance metric, i.e., \( d(p_i, p_j) = \sqrt{(x_i - y_i)^2 + (x_j - y_j)^2} \).

Two graph drawing algorithms are implemented to come up with estimated coordinates in following sections.
4.3.2 Multi-dimensional Scaling

Multidimensional Scaling (MDS)\cite{42} is a graph drawing algorithm which makes use of the fact that the coordinate matrix can be derived from eigenvalue decomposition from matrix $B$. The matrix $B$ is computed from proximity matrix $P$ using double centering. The proximity matrix can be generated from the adjacency matrix $A$. In adjacency matrix $A$, only the nearest neighbors are labeled as 1 while the proximity matrix needs a relationship for all pair of nodes. In this report, the shortest path between two nodes is calculated as the value in $P$ with Alg.2.

Algorithm 2 Algorithm to generate proximity matrix from adjacency matrix

\begin{verbatim}
ProximityMatrixGenerate
1: $P \leftarrow A$
2: $P(i, j) = \infty \quad \forall$ unadjacent pair $(i, j)$
3: for $k = 1 : n$ do
4:     for $i = 1 : n$ do
5:         for $j = 1 : n$ do
6:             if $P(i, k) + P(k, j) < P(i, j)$ then $P(i, j) = P(i, k) + P(k, j)$;
7:     end if
8: end for
9: end for
\end{verbatim}

Then, the steps of classical MDS algorithm are as following:

1. “Apply double centering: $B = -\frac{1}{2} J P^{(2)} J$ using the centering matrix $J = I - \frac{1}{n} 11'$, where $n$ is the number of objects, $11'$ is $n$-by-$n$ matrix of all 1’s.
2. Determine 2 largest eigenvalues $\lambda_1, \lambda_2$ and corresponding eigenvectors $v_1, v_2$ of $B$.
3. Then, compute $E = VG^{1/2}$ where $V$ is the matrix of 2 eigenvectors and $G$ is the diagonal
matrix of 2 eigenvalues of $B$.

$E \in \mathbb{R}(n \times 2)$ is a set of estimated coordinates for $n$ nodes. Note that in order to generate $m$ dimension coordinates, instead of 2, $m$ eigenvalues and corresponding eigenvectors are needed.

So far, the $E$ is a set of relative coordinates and it is arbitrarily rotated and flipped compared to floorplan. In order to do point matching, the estimated coordinates and location coordinates in floorplan should be placed in the same coordinate system. Therefore, at least three anchor nodes are needed to transform the relative estimated coordinates into absolute estimated coordinates. The transformation includes scaling, rotation and reflection. In practice, it is better to choose the corner nodes. The relative map and the absolute map after MDS are shown in Fig. 4.9.

Figure 4.9: a. Relative map generated by MDS; b. Absolute map generated by MDS with three anchors (node 1, node 4 and node 13)

The complexity of the MDS algorithm is $O(n^3)$, where $n$ is the number of nodes. MDS is good at finding the right topology of the network, but not the precise locations of nodes since MDS uses proximity matrix to estimated the distance. The proximity matrix is calculated based on the shortest path which cannot reflect the real distance precisely.

### 4.3.3 Force-directed Graph Drawing

Force-directed algorithms [20] model the graph layout problem by assigning attractive and repulsive forces between nodes and finding the balance states for all nodes.

The steps of basic force-directed graph drawing is as following:

1. Generate a set of random coordinates for each nodes.
2. For each node, compute the repulsive force $Fr$ from other $n-1$ nodes and attractive force $Fa$ from its adjacent nodes. ($Fr$ and $Fa$ are defined in Alg.3.)
3. Coordinates for next step are calculated for each node by its combined force $F$ and current coordinates.
4. $Energy = \sum F^2$
5. Continue from step 2 until the difference of current $Energy$ and $Energy$ in last iteration is smaller than a threshold. (The threshold is an empirical value.)

The repulsive force between each pair of nodes ensures that any pair of nodes will not come too close to each other while the attractive force between two adjacent nodes ensures they will not be too far away from each other. The algorithm will stop until the variation of $Energy$ is smaller than a threshold. Under this condition, all the nodes are in a relative balance state. In order to obtain a more grid layout after force-directed graph drawing, in this report, we define our own repulsive force $Fr$ and attractive force $Fa$ based on the adjacency matrix $A \in \mathbb{R}^{(n \times n)}$. Some scenarios need to be mentioned to explain the forces implementation (see Fig. 4.10).

- If $A(i,j) = 1$, the node $i$ and node $j$ are adjacent. There are two scenarios in Fig. 4.10.a and Fig. 4.10.c. In scenario a, there will be no attractive force between node $i$ and node $j$. Otherwise, an attractive force $Fa$ will drive them move towards each other.

- If $A(i,j) = 0$, the node $i$ and node $j$ are not adjacent. There are also two scenarios in Fig. 4.10.b and Fig. 4.10.d. In scenario d, there will be no repulsive force between node $i$ and node $j$. Otherwise, a repulsive force $Fr$ will drive them to move apart.

Similar to MDS, to transform the relative coordinates into absolute coordinates, at least three anchor nodes are needed. Anchor nodes can also be set while initiating the coordinates for each node and it will come out with a better layout.

The algorithm to compute repulsive force and attractive force is illustrated in Alg.3.
CHAPTER 4. LOCALIZATION SCHEME

Algorithm 3 Algorithm to calculate force in Force-direction graph drawing

\begin{algorithm}
\begin{algorithmic}[1]
\Procedure{ForceCalculateForNode}{i}
\ForAll{node $j \in P_i$, $P_i$ contains all adjacent nodes of Node $i$}
\If{$d_{ij} = 0$}
\State $fa \leftarrow \text{random}$
\State $Fa(i) \leftarrow Fa(i) + fa$
\Else
\If{$d_{ij} \geq \text{radius}$}
\State $fa = d_{ij}^2/K$
\State $Fa(i) \leftarrow Fa(i) + fa$
\EndIf
\EndIf
\EndFor
\ForAll{node $j \in N$, $N$ contains all the nodes}
\If{$i \neq j$}
\If{$d_{ij} < \text{radius}$}
\State $fr \leftarrow -C \times K^2/d_{ij}$
\State $Fr(i) \leftarrow Fr(i) + fr$
\EndIf
\EndIf
\EndFor
\EndProcedure
\end{algorithmic}
\end{algorithm}

Note that the \textit{radius} of node is set as $1.2K$ based on empirical tests, and $K$ is the distance between two nearest location in floorplan and is set as 1 here. $C$ is the parameter used to regulate the relative strength of the repulsive and attractive force. The relative map and absolute map after Force-directed graph drawing is shown in Fig. 4.11.

![Figure 4.11: a. Relative map generated by force-directed graph drawing; b. Absolute map generated by force-directed graph drawing with three anchors (node 1, node 4 and node 13)](image)

The complexity of Force-directed Graph drawing algorithm is $O(kn^2)$ where $n$ is the number of nodes and $k$ is the iteration counter which is related to the number of nodes and termination condition. In general, $k$ increases as the number of nodes growing and the \textit{threshold} decreasing.
4.3.4 Point matching

After the graph drawing, a set of estimated coordinates for each node is generated. The problem for point matching is to match the coordinates of \( n \) nodes in \( E \in \mathbb{R}^{(n \times 2)} \) with the coordinates of \( n \) locations in \( L \in \mathbb{R}^{(n \times 2)} \). As it can be seen in Fig. 4.12, the blue circles are nodes waiting to be matched with a specific red circles (locations).

![Image](image.png)

**Figure 4.12: An example of point matching**

The Hungarian method\[^24\] is a combinatorial optimization algorithm that solves the assignment problem in polynomial time. In \[^31\], Munkres reviewed the algorithm in 1957 and proved that it is strongly polynomial. The time complexity of the original algorithm is \( O(n^4) \).

The matching result can be seen in Fig. 4.13 that both estimated maps by graph drawing algorithms can be matched correctly using the Hungarian algorithm.
4.4 Edge-based Matching Algorithm

4.4.1 Problem formulation

Instead of translating the adjacency matrix into a set of point coordinates in point-based matching algorithm, edge-based matching algorithm uses adjacency matrix directly.

The localization problem in edge-based matching algorithm is to find the bijective assignment \( f : ID \rightarrow L \) that minimizes the objective function:

\[
\sum_{id_i, id_j \in ID} A_{i,j} d^2(f(id_i), f(id_j))
\]

- \( ID, L \) are defined in Chap.1.3.
- \( d \) is defined in Chap.4.3.1.
- \( A \) is the \( n \times n \) adjacency matrix, i.e., \( A_{i,j} = 1 \) indicates node \( id_i \) is adjacent to node \( id_j \) and \( A_{i,j} = 0 \) indicates node \( id_i \) is not adjacent to node \( id_j \).

The reason why the bijective assignment \( f \) is able to be solved by minimizing the objective function Eq.4.2 is that the objective will be minimized when the adjacent edges are matched with the shortest distance between two locations. That is to say, this method is trying to minimize the distance between two adjacent nodes.

Take a simple example with four nodes as it is shown in Fig. 4.15. Let the distance between two neighbor positions be 1 so we can have the distance matrix in Table. 4.5 for the positions in the floorplan. The adjacency matrix of nodes is displayed in Table. 4.6. It is obvious that only when nodes are located in the right places (using one anchor node to eliminate the symmetric solution), the objective function has the minimal value:

\[
\sum_{id_i, id_j \in ID} A_{i,j} d^2(f(id_i), f(id_j)) = 6
\]
where the minimal value is the sum of squared distance between all adjacency edges and the bijective assignment $f$ is shown in Fig.4.14:

Figure 4.14: Bijective assignment $f$

Table 4.5: Distance matrix for the deployment with four nodes

<table>
<thead>
<tr>
<th>Distance</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
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<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
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<tr>
<td>D</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.6: Adjacency matrix for the deployment with four nodes

<table>
<thead>
<tr>
<th>Distance</th>
<th>Node 1</th>
<th>Node 2</th>
<th>Node 3</th>
<th>Node 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Node 2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Node 3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Node 4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

4.4.2 Fast Ant System

The localization problem in edge-based matching algorithm is actually an Quadratic Assignment Problem (QAP) [14]. The QAP is one of the most difficult problems in the NP-hard class and there is no known algorithm for solving this problem in polynomial time [38]. There are still several exact and heuristic algorithms try to resolve the Quadratic Assignment Problem and Ant System-based heuristics method is a well-designed method for solving QAP. In this report, Fast ANT System (FANT) [46][47] is implemented to solve the localization problem.

The main process in FANT is to manipulate the weight matrix $W \in \mathbb{R}^{n \times n}$ where $w_{ij}$ is the weight of matching node $i$ with location $l$. On the one hand, FANT enhances the value of the weight matrix corresponding to the current best matching solution. One the other hand, when
the process appears to be stagnating, FANT will reinitialize the memory and give less weight to the best solution [46].

“FANT contains two main process as following:

- **Ant process**
  The Ant process constructs a new assignment \( f \) by randomly choosing the location \( l \) of nodes \( i \) with a probability proportional to \( w_{il} \). Then the solution is improved with a local search and sent to the Queen process

- **Queen process**
  A parameter \( R \) is required for Queen process. Queen process mainly responsible for managing the weight matrix \( W \), a variable \( v \) and the best matching solution \( f^* \) found by the system so far. Initially \( v = 1 \) and \( m_{il} = v, \forall i, l \). Then repeats the following steps:
  1. Activate an Ant process,
  2. Wait for a solution \( f \) from an Ant process,
  3. IF \( f = f^* \) then set \( v ← v + 1 \) and \( w_{il} ← v, \forall i, l \),
  4. IF \( f \) is better than \( f^* \) then set \( f^* ← f, v ← 1 \) and \( w_{il} ← v, \forall i, l \),
  5. Set \( w_{if_i} ← w_{if_i} + v, \forall i, \)
  6. Set \( w_{if_i^*} ← w_{if_i^*} + R, \forall i \)” [46]

As is the case in graph drawing, due to the symmetric deployment, the assignment solution \( f \) after FANT is arbitrarily rotated. In order to come up with the specific assignment solution which can be used directly to match the node with its location, at least two anchor nodes are required in the case of grid deployment with 16 nodes. Since above methods require at least three anchor nodes, we also set three anchor nodes for FANT to be able to compared with other methods. In addition, FANT does not always come up with unique result. That is to say, in some cases, minimal value of the objective function can be obtained by more than one bijective assignment. Thus, to finalize the unique result, manually checking is required which is one of the cases for feedback line a in Fig. 4.1.

The complexity of FANT is \( O(k \times n^2) \), where \( n \) is the number of nodes, \( k \) is the iteration number of ant process. Since QAP is NP-hard problem and there is no known algorithm for solving this problem in polynomial time. There is no certain limitation for \( k \). Nevertheless, we can estimate the value of \( k \) by testing some adjacency matrices generated in some ways.
Chapter 5

Performance Analysis

In this Chapter, 26 adjacency matrices are generated to evaluate the performance of proposed localization scheme. A criterion is proposed to evaluate the quality of adjacency matrices. Then the mapping results of localization schemes are discussed.

5.1 26 Adjacency Matrices Generating

In Chapter 4, a neighbor list in Table. A.1 is generated by selecting the maximum RSSI value between each pair of nodes. In order to obtain more adjacency matrices, a random RSSI value is picked up from the top 30% sorted RSSI values for each pair of nodes. There are two reasons for selecting the RSSI value from top 30%. The first one is that the random selection simulates the case when the highest RSSI cannot be recorded due to the insufficient mobility. Narrowing the range of selection within top 30% promises a certain correctness level of the RSSI value. The mobility will result in more impractical measurements and usually these measurements are lower than normal. Based on empirical test result, top 30% of the measurements can indicate the distance difference to some extent. It has been discussed in the Chapter 4, scenario 5.

Together with the adjacency matrix we obtained by maximum RSSI value, now there are total 26 adjacency matrices to be tested. The graphs generated based on the 26 adjacency matrices using force directed graph drawing are listed in the Appendix B.

5.2 Evaluation of Adjacency Matrices

First we define the correctness of an adjacency matrix $A$ with $n$ nodes as Degree of Correctness (DoC) and it is defined as follows:

$$DoC(A) = \sum_{id_i, id_j \in ID} A_{i,j} \approx \frac{R_{f_0(id_i), f_0(id_j)}}{n \times (n - 1)}$$

- $ID$, $n$ are defined in Chap.1.3.
- $A$ is defined in Chap.4.4.1.
- $R$ is the adjacency matrix based on the ground truth.
• Bijection assignment $f_0 : ID \rightarrow L$ is the true localization between nodes and localizations.

The DoC for the 26 adjacency matrices are shown in the Fig. 5.1. The data set is arranged in the increasing order by DoC.

![Figure 5.1: DoC for 26 datasets](image)

## 5.3 Evaluation of Localization Schemes

Based on the 26 data sets, the average accuracy of three matching schemes is presented in Fig. 5.2. M1 is point-based matching with MDS graph drawing; M2 is point-based matching with force-directed graph drawing; M3 is edge-based matching based on FANT. The accuracy of each of these methods is determined by the percentage of correctly localized nodes (see Eq.1.1). For instance, if there are 8 correctly localized nodes in the set of 10 initially non-localized nodes, the accuracy is 80.0%. Three anchors are used during the localization and they are node 1, node 4 and node 16.

![Figure 5.2: Average accuracy for three matching schemes over 26 datasets](image)

As it can be seen from Fig. 5.2, M3 has the highest accuracy while M1 is worst scheme. Both M2 and M3 achieve high accuracy over 95% if the quality of adjacency matrix is higher than 85%. The accuracy of the localization results with M1 are in Fig. 5.3. First, it can be found that there is no strong relations between the DoC of adjacency matrix and its result with M1. For
example, dataset 20 and 26 have high DoC (94.2% and 95.8% respectively) while the accuracy of the localization are rather low (50% and 25% respectively). However, dataset 1 and 6 have lower DoC (85% and 89.2% respectively) while the accuracy of the localization are all 100%. We can still find that with the DoC increasing, there are more datasets which can be matched with 100% accuracy. Thus, to some extent, the DoC can indicate the quality of the adjacency matrix.

Figure 5.3: The localization accuracy of 26 adjacency matrices using M1

M2 has received high accuracy over the datasets. However we still want to know what is the confidence level for each localization result. That is to say, we want to know if the localization result is presented with 100% certainty. In order to do that, we introduce a Degree of Dissimilarity (DoD) to evaluate the confidence level for each node and it is defined as follows:

\[
\text{DoD}(A_i) = \frac{\sum_{i \neq j, i_d, j_d \in ID} (A_{i,j} \simeq R_{f(i_d), f(j_d)}) \times d(f(i_d), f(j_d))}{n}
\]

- ID, n and \(A_{i,j} \simeq R_{f(i_d), f(j_d)}\) are defined in Chap.1.3.
- \(A\) is defined in Chap.4.4.1.
- \(R\) is defined in Chap.5.2.
- \(d\) is defined in Chap.4.3.1.
- Bijection assignment \(f : ID \rightarrow L\) is the localization result.

The node with higher DoD has higher probability to be incorrectly located. Let the nodes with top 3 DoD values be the ‘suspicious’ ones. The ‘suspicious’ nodes will be check manually. Thus if the ‘suspicious’ nodes turn out to be located correctly, it means that we could have higher certainty of the localization result. If one of the three DoD is found to be located to a incorrect place, the new manually checked node will be added into the anchor set and new result will be produced based on new anchor set. If all of the suspicious nodes are incorrectly located, there must be something wrong with the initial measurement. The data collection process will be done again with new anchor set. The feedback line a and b in Fig. 4.1. In this way, we can further improve the confidence level of the localization result.
CHAPTER 5. PERFORMANCE ANALYSIS

Take one of the dataset as an example, the accuracy of the localization result by M2 is 87.5%. The DoD for each node is shown in Table 5.1. The ‘suspicious’ nodes are Node 13, Node 9 and Node 10. In Fig. 5.4, these three ‘suspicious’ nodes do have more incorrect connections which is highlight be red color. The incorrect located nodes are Node 13 and Node 14. By manually checking the node in location N, Node 14 is found instead of Node 13. And other two nodes are located in the correct locations. Then these ‘suspicious’ nodes become anchor nodes. With the additional anchor nodes, M2 is able to come up with the correct localization result.

Similarly, by checking nodes with top 3 DoD can further improve the confidence level of the result of M3.

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<td>5.5</td>
<td>1.3</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.1: DoD for each node, the blue cells are the nodes with top 3 DoD, the red elements are the incorrectly located nodes

Figure 5.4: Layout after M2 with DoD for each node

So far, the initial anchor nodes are Node 1, Node 4 and Node 16. As it is mentioned in force-directed graph drawing, different selections of anchor nodes will impact the quality of generated layout. The layout will be closer to floorplan with more anchor nodes in corner positions. Fig. 5.5 shows two layout generated by force-directed graph drawing with different anchor nodes. In Fig. 5.5.a all anchor nodes are in corner locations while none of the anchor nodes in Fig. 5.5.b are in corner locations. It is obvious that layout in Fig. 5.5.a is better than Fig. 5.5.b. Thus, the selection of anchor nodes might have impact in localization result. In order to find out the relationship between the number of corner nodes in anchor sets and the localization results, all different pair of three anchor nodes are tested. Average accuracy are presented in Fig. 5.6. It can be seen that more corner nodes in anchor set will improve the accuracy of results.

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Figure 5.5: Layout after force-directed graph drawing with different anchor nodes. a. Node 1, Node 4, Node16; b. Node 6, Node 7, Node 10

Figure 5.6: Localization accuracy of three methods with different anchor sets
Chapter 6

Conclusions

6.1 Conclusions

The primary goal of the graduation project is to propose an automatic localization schemes based on the RSSI in WSN in indoor environment.

The accuracy of RSSI is limited due to several factors. In experiment part, we carried several experiments to explore the characteristics of RSSI. Based on the observation during the experiments, we found that both the hardware of the nodes and the properties in transmission media have significant influence on performance of RSSI. In hardware, node variability and antenna orientation are two main factors. The performance of RSSI can be improved after strict selection of sensor nodes with omnidirectional antennas. In transmission media, we found that by introducing mobility to the network, the RSSI will be more reliable. Based on the signal propagation model, RSSI can be used to find the nearest neighbors for specific scenarios and come up with a reliable adjacency matrix.

In localization part, we propose two different localization schemes based on different matching algorithms. In point-based matching scheme, adjacency matrices will be translated into points first. Two graph drawing algorithms are implemented: MDS and force directed graph drawing. In edge-based matching scheme, FANT is introduced and implemented.

To analyze the localization schemes, a grid 4 × 4 deployment in a line of sight scenario is built up. And 26 adjacency matrices based on that deployment are generated and both the quality of adjacency matrices and the accuracy of matching algorithms are evaluated. First, DoC is defined to analyze the performance of adjacency matrices. Generally speaking, the adjacency matrix with higher DoC is considered as a good one. According to the results, all of the 26 adjacency matrices are in good quality (DoC higher than 85%).

For matching algorithms, point-based matching with force directed graph drawing and edge-based matching with FANT achieve high accuracy over 26 datasets. The average accuracy of M2 is 96.6% while the average accuracy of M3 is 100%. Also, the different selection of the anchor nodes will have influence of the results. Selecting more nodes in corner position can achieve higher accuracy. Moreover, in order to have higher confidence level of the result, a feedback mechanism is proposed. Three ‘suspicious’ nodes are provided with the localization result. After checking the ‘suspicious’ nodes manually, the results can be decided to acceptable or not.
6.2 Future Works

Due to the limitation of nodes in experiment, we have to use 7 nodes to obtain the RSSI values from 16 positions. In addition, we rotate the nodes to simulate omnidirectional antennas. These methods cannot reflect the reality. Thus, 16 nodes with omnidirectional antennas are required to redo the data collection. Moreover, we just verified the feasibility of a grid deployment with 16 nodes. As it is mentioned in introduction, there are more than a thousand luminaires waiting for localization. For a single router, it can control at most 250 nodes. Thus, a larger deployment should be tested to verify the scalability of our localization scheme. In addition, in a real implementation, wireless sensor networks have various deployment other than grid deployment. The algorithm to generate adjacency matrix has to be smarter by considering more features in floorplan.

In this thesis, we introduce the mobility of nodes to eliminate the influence from the environment. Nevertheless, moving a luminaire is not practical. Using an additional mobile node to collect measurements under each nodes could be a feasible way. Another possible solution is to design a calibration system to replace the mobility.

In evaluation part, we use DoC to evaluate the adjacency matrices. Nevertheless, there is no guarantee that an adjacency matrix with high DoC must be easier to be correctly matched. More criteria for the quality of adjacency matrices are needed.

Moreover, we propose a feedback mechanism to improve the confidence level of our localization result. However, the confidence level is not quantified since we only have 26 datasets to be tested. Also, the feedback mechanism need to be improved with a large WSN. Thus, there might be an algorithm to detect ‘suspicious’ areas instead of ‘suspicious’ nodes. In addition, in this thesis, our localization schemes are valid over the surface in a line of sight indoor environment. We do not address the localization problem within an environment with static sources of error like walls.
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Appendix A

ZigBee Channels

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Hex</th>
<th>Frequency</th>
<th>SC mark</th>
<th>WiFi Conflict</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0x0B</td>
<td>2.405GHz</td>
<td>0x0001</td>
<td>Overlaps Ch 1</td>
</tr>
<tr>
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<td>0x0C</td>
<td>2.410GHz</td>
<td>0x0002</td>
<td>Overlaps Ch 1</td>
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<tr>
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<td>2.415GHz</td>
<td>0x0004</td>
<td>Overlaps Ch 1</td>
</tr>
<tr>
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<td>0x0E</td>
<td>2.420GHz</td>
<td>0x0008</td>
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</tr>
<tr>
<td>15</td>
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<td>Overlaps Ch 6</td>
</tr>
<tr>
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<tr>
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<tr>
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<td>0x0080</td>
<td>Overlaps Ch 6</td>
</tr>
<tr>
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<td>No Conflict</td>
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Table A.1: ZigBee Channels
Appendix B

26 adjacency graphs

Figure B.1: Case 1 by force-directed graph drawing with anchor 1,4,16

Figure B.2: Case 2 by force-directed graph drawing with anchor 1,4,16
APPENDIX B. 26 ADJACENCY GRAPHS

Figure B.3: Case 3 by force-directed graph drawing with anchor 1,4,16

Figure B.4: Case 4 by force-directed graph drawing with anchor 1,4,16

Figure B.5: Case 5 by force-directed graph drawing with anchor 1,4,16
Figure B.6: Case 6 by force-directed graph drawing with anchor 1,4,16

Figure B.7: Case 7 by force-directed graph drawing with anchor 1,4,16

Figure B.8: Case 8 by force-directed graph drawing with anchor 1,4,16
APPENDIX B. 26 ADJACENCY GRAPHS

Figure B.9: Case 9 by force-directed graph drawing with anchor 1,4,16

Figure B.10: Case 10 by force-directed graph drawing with anchor 1,4,16

Figure B.11: Case 11 by force-directed graph drawing with anchor 1,4,16
Figure B.12: Case 12 by force-directed graph drawing with anchor 1,4,16

Figure B.13: Case 13 by force-directed graph drawing with anchor 1,4,16

Figure B.14: Case 14 by force-directed graph drawing with anchor 1,4,16
APPENDIX B. 26 ADJACENCY GRAPHS

Figure B.15: Case 15 by force-directed graph drawing with anchor 1,4,16

Figure B.16: Case 16 by force-directed graph drawing with anchor 1,4,16

Figure B.17: Case 17 by force-directed graph drawing with anchor 1,4,16
Figure B.18: Case 18 by force-directed graph drawing with anchor 1,4,16

Figure B.19: Case 19 by force-directed graph drawing with anchor 1,4,16

Figure B.20: Case 20 by force-directed graph drawing with anchor 1,4,16
Figure B.21: Case 21 by force-directed graph drawing with anchor 1,4,16

Figure B.22: Case 22 by force-directed graph drawing with anchor 1,4,16

Figure B.23: Case 23 by force-directed graph drawing with anchor 1,4,16
APPENDIX B. 26 ADJACENCY GRAPHS

Figure B.24: Case 24 by force-directed graph drawing with anchor 1,4,16

Figure B.25: Case 25 by force-directed graph drawing with anchor 1,4,16

Figure B.26: Case 26 by force-directed graph drawing with anchor 1,4,16