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MASTER BASIS MODULE – Communication Systems Group, Prof. Dr. Burkhard Stiller

Indoor Real-Time Locating System (RTLS) based on Bluetooth Low Energy (BLE)

Julius Willems
Zurich, Switzerland
Student ID: 16-920-217

Supervisor: Prof. Dr. Burkhard Stiller, Dr. Eryk Schiller, Sina Rafati
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University of Zurich
Department of Informatics (IFI)
Binzmuhlestrasse 14, CH-8050 Zurich, Switzerland

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Master Basis Module
Communication Systems Group (CSG)
Department of Informatics (IFI)
University of Zurich
Binzmuehlestrasse 14, CH-8050 Zurich, Switzerland
URL: https://www.csg.uzh.ch/

Abstract

Positioning and tracking of assets or people in indoor environments have great potential in various settings such as healthcare, retail, logistics, smart buildings and more. In indoor settings, an array of different technologies can be used to provide positioning services, and the suitability of a particular technology mainly depends on the use-case at hand. This work focuses on a use-case driven, prototypical implementation of an Indoor Real-Time Locating System (RTLS) in the healthcare sector based on Bluetooth Low-Energy.

Chapter 1

Acknowledgments

First of all, I would like to thank Prof. Dr. Burkhard Stiller for the opportunity to perform research in this work.

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Chapter 2

Introduction

2.1 Motivation

Positioning and tracking of assets or people in indoor environments have great potential in various settings such as healthcare, retail, logistics, smart buildings and more. Established positioning systems, such as GPS, are not available in an indoor setting due to the absence of a direct line of sight connection between the satellite and the object to track on Earth. In indoor settings, an array of different technologies can be used to provide positioning services, and the suitability of a particular technology mainly depends on the use-case at hand.

2.2 Description of Work

This work focuses on a use-case driven, prototypical implementation of an Indoor Real-Time Locating System (RTLS) in the healthcare sector. The ultimate goal is to track moving objects inside a building and perform data analysis on the collected data.

2.3 Thesis Outline

The rest of this work is structured as follows. Chapter 3 gives a brief overview on related work. In chapter 4 the underlying use-case of this work is specified. Chapter 5 covers the design and architecture of the solution. Following the design, chapter 6 describes the implementation of the prototype. Finally, chapter 7 ends with a conclusion and summary.

Chapter 3

Related Work

Bluetooth Low Energy (BLE) is a light-weight protocol to wirelessly exchange data between devices. It is targeted towards constrained, often battery powered devices such as wearables or sensors. Especially in the field of IoT it has become one of the popular protocols [7].

An (Indoor) Real-Time Locating Systems (RTLS) is an application that can be built leveraging the BLE technology. The RTLS attempts to provide the location information of mobile objects inside a building at any given moment. Implementations of RTLS systems often include RF technologies such as WiFi, RFID or BLE. The latter became popular in research and industry due to it's relative low cost and great support of the Bluetooth protocol across many different devices [3, 4].

RTLS are context independent systems and can be applied to various use-cases such as logistics, retail, healthcare and many more [5]. RTLS deployments in hospitals are proven to reduce seek times to locate assets, improve workflow optimization and enhance patient and staff safety. However, the adoption of RTLS in hospitals is still low due to high system complexity and cost of ownership [6].

Chapter 4

Use-Case

The RTLS developed in this work shall be targeted towards a use-case in the healthcare sector, specifically hospitals.

Hospitals maintain a large amount of medical equipment. A typical 500-bed hospital maintains approximately 5000 mobile medical assets [1]. These medical devices circulate through the many rooms of the hospital and have to be available for treatment at any moment. Managing and organizing the large amount of mobile assets imposes a challenge for hospital staff. On a normal shift, a nurse spends about 20 minutes searching for medical equipment (wheelchairs, infusion pumps, etc.). To guarantee sufficient availability of medical equipment, hospitals tend to buy more equipment than actually needed. The result is a huge cost-overhead and an asset utilization below 50%[1].

To address these challenges, the proposed RTLS shall, therefore, assist staff to find medical assets faster, in order to reduce search time and enhance the availability of medical equipment. Specifically, the system shall provide the location of tracked equipment in Real-Time. In terms of granularity, the system shall be able to locate assets on a room-level. There is no requirement to go beyond and locate assets within a given room. Based on the tracking functionality, the system shall derive asset utilization, and provide historical data insights.

Furthermore, the setup of the system shall be as quick as possible, and must not interfere with the hospital environment or disturb the work of the staff in any way. In order to implement the system at a large scale (500 rooms / 5000 assets), installation overhead, hardware expenses and maintenance cost must be kept in mind when designing the system.

Chapter 5

Design

This section describes the proposed RTLS architecture in a bottom-up approach. Figure 5.1 shows the general architecture of the system.

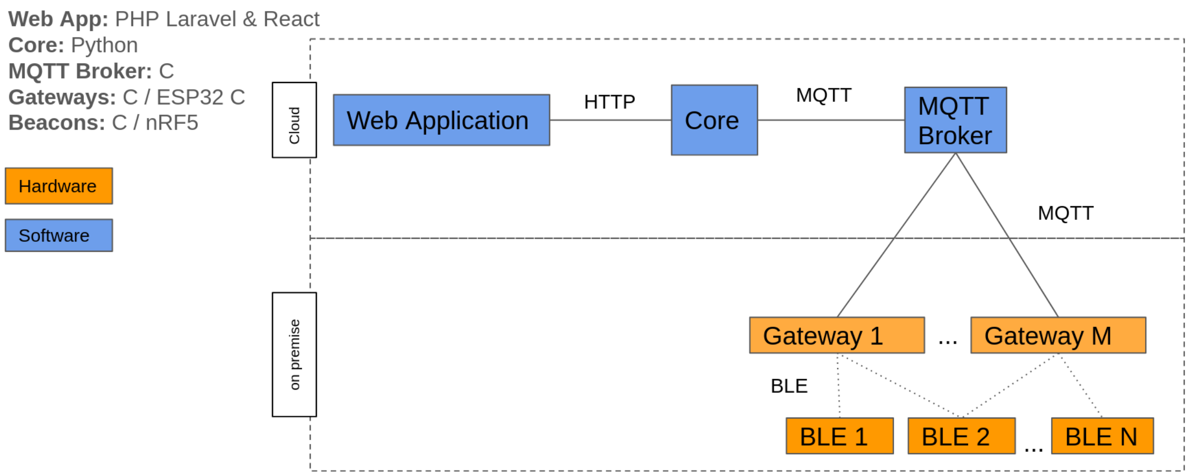

Figure 5.1: Architecture Diagram

5.1 Beacon

The BLE beacons or tags (c.f. BLE 1,... BLE N in figure 5.1) build the foundation of the RTLS solution. BLE beacons are small, battery powered devices in the size of a 2 Swiss Franc coin. The role of a beacon is to signal its presence by continuously broadcasting BLE advertising packets with their unique ID. The beacons are then attached to the assets a hospital wants to track. In the use-case at hand, these could be infusion pumps, wheelchairs and other kind of mobile medical equipment. The BLE beacon is equipped with an accelerometer to track activity in the form of movement. The potential benefits of an accelerometer sensor are manifold. Trivially, movement can be detected and used as an indicator for the asset's utilization. On the other hand, power consumption of the beacon can be optimized by putting the beacon into a sleep-mode when the asset is currently not in use. Since the beacon only advertises when it is moved, the advertising interval can be shortened, which leads to more advertising messages / second. This leads to more data, and can be used to achieve faster results in room prediction.

5.2 Gateway

At the next higher level is the gateway (c.f. Gateway 1,... Gateway N in figure 5.1). A gateway defines a location zone and is positioned at fixed locations within the building. In the use-case described, the gateway devices will be placed in the rooms of the hospital. Gateways are the beacon's counterpart. Their role is to observe BLE advertising packets emitted by the beacons that are in range. The gateway records the Received Signal Strength Indicator (RSSI) of the incoming advertising packets to roughly estimate the distance between the gateway and the beacon. The gateway then aggregates and forwards the recorded advertising packets to the central location engine.

5.3 Location Engine

The most intelligent part of the RTLS is its location engine (c.f. Core in figure 5.1). It receives the aggregated advertising packets from the gateway devices and predicts the most probable location of each beacon. Before a location can be predicted, a number of pre-processing steps are performed to compensate for volatile and missing RSSI measurements due to radio frequency interference or signal loss. Once the location of the beacons is predicted, the result can be fed into use-case specific client applications to visualize the results.

5.4 Web Application

Finally, a web application consumes the output of the location engine and provides end users with an intuitive overview of the current asset locations. Data analysis can be run on the equipment's location history to estimate its utilization.

Chapter 6

Implementation

This chapter follows the same structure as the previous one, and elaborates on the implementation of the individual components.

6.1 Beacon

In a previous version of the system, commercial beacons based on the nRF51822 chip from Noric Semiconductor were used [8]. As these beacons don't embed an accelerometer and hardware modifications were not possible, a new, prototypical beacon had to be developed.

Eventually, the ESP32 microcontroller from Espressif Systems was chosen as development platform for the prototype beacon due to its native WiFi and Bluetooth support [9]. As accelerometer, the LIS3DH accelerometer form STMicroelectronics was used [10].

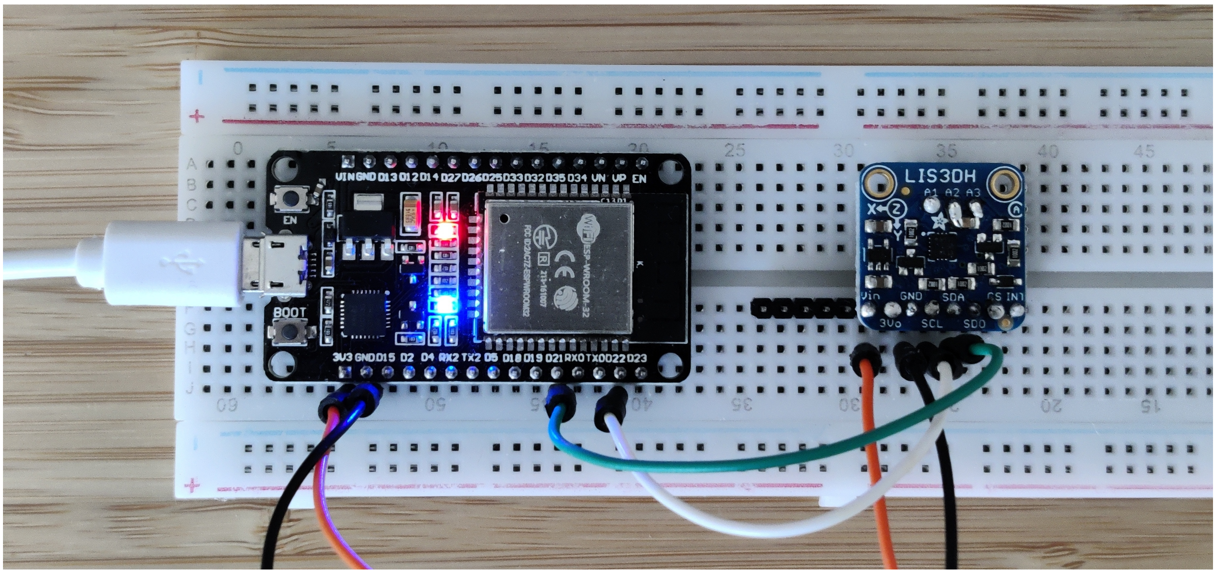

Figure 6.1: ESP32 (l) with LIS3DH (r)

The accelerometer is connected to the ESP32 via I2C on a breadboard and programmed to act as a BLE beacon. Whenever the accelerometer registers a moving force exceeding a certain threshold, the ESP32 starts to advertise BLE packets. When no more movement is registered, BLE advertising is stopped after a defined delay.

Algorithm 1 Beacon

```
lastAdvertised ← 0
count ← 0
while True do
    count++
    if accelerometer.isMoved() then
        startAdvertising()
        lastAdvertised++
        continue
    else if count - lastAdvertised > threshold then
        stopAdvertising()
        count ← 0
        lastAdvertised ← 0
```

6.2 Gateway

As for the gateway, the ESP32 microcontroller was chosen once again due to its versatile radio frequency capabilities. The ESP32 is installed in the zones to be tracked (e.g. in each room) and connected to the local WiFi network of the building. The role of the gateway device is to listen to BLE advertisement packets, store them in a buffer, and forward them to the location engine where the data is being processed. Buffering the data is necessary to avoid flooding the network when many BLE beacons are present in the range of the gateway. The communication between the gateway and the location engine follows a publish-subscribe pattern where the gateway device is the publisher and the location engines acts as the subscriber. To achieve Real-Time data, the delay between a BLE advertisement is observed by the gateway and the time it is processed by the location engine is critical. Thus, the MQTT protocol was chosen, due to its publish-subscribe architecture and its lightweight network footprint.

6.3 MQTT Broker

To facilitate the communication between the gateways and the location engine, Eclipse Mosquitto's MQTT broker was used [11].

6.4 Location Engine

The location engine processes the incoming data from the gateway devices and predicts the most probable location for each BLE beacon. The process of predicting the location of a beacon was divided into 3 steps, which all run in their own thread:

6.4.1 Data ingestion

In this step, an MQTT client connects to the MQTT broker and subscribes to the incoming data. To keep the MQTT client from blocking the thread and delaying the processing of other messages, the incoming data is timestamped and pushed into a queue as is. There exists one queue for each gateway.

6.4.2 Data pre-processing

Raw RSSI values contain a considerable amount of noise, due to many factors such as signal interference, shadowing or multi-path propagation. Thus, raw RSSI values are not well suited to be directly used in a prediction model [2]. To address this issue, the incoming data is smoothed with a Kalman Filter. The result is a smoothed and less volatile RSSI signal.

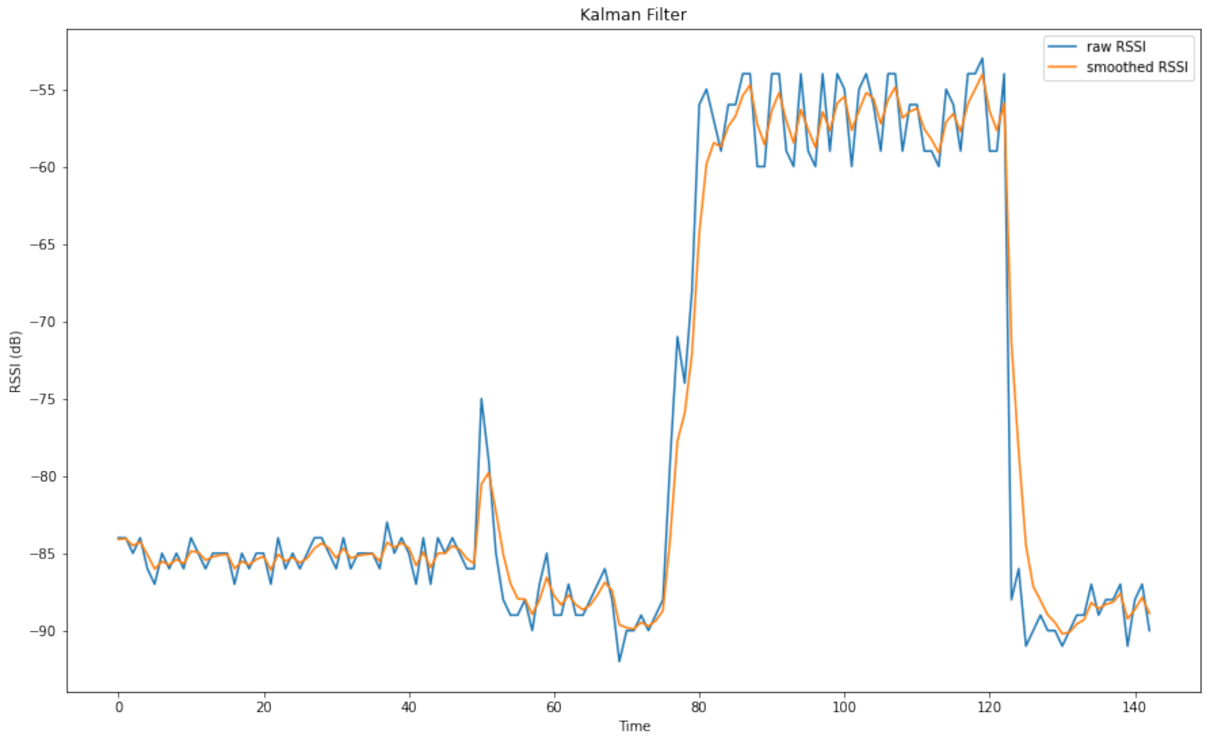

Figure 6.2: Kalman Filter applied to RSSI

Another aspect addressed in the pre-processing step is the imputation of missing data. For example, if the beacon's signal is picked up by 3 gateways (A, B and C), the number of observations recorded by each gateway are as in table 6.1.

Table 6.1: RSSI observations by reader

Time	**Gateway A**	**Gateway B**	**Gateway C**
0	-67		
1	-65	-82	
2	-72	-78	-89
3	-68	-81	
# Observations	4	2	1

To impute the missing observations in gateway B and C, a moving average is used to impute the missing values. Afterwards, the data is fed into a priority queue to maintain the historical order of the observations for further processing.

6.4.3 Prediction

After the described pre-processing steps, the location of the beacons can finally be predicted. The following paragraph describes a prediction for a single beacon.

```
df_ = df.fillna(df.mean())
df_ = df_.add(100)
df_ = df_.pow(3)
df_ = df_.sum()
sum = df_
df_ = df_.apply(lambda x: x / sum)
max_gateway_id = df_.idxmax()
max_rssi = df[max_gateway_id].mean()
```

First, a collection of observations is gathered from the queue of each reader. Because RSSI is measured in dB and lies in the range between -50 and -90, a constant of 100 is added to each observation to get rid of negative values. Then, a non-linear transformation is applied to boost larger values compared to smaller ones. The transformed samples are added up per column (=gateway). This ensures that samples of a particular gateway for a particular beacon can compensate each other. Finally, percentages of each gateway are calculated and interpreted as probabilities that the beacon is located in the range of the particular gateway. Finally, the gateway with the highest probability is chosen as the most probable location for the beacon.

6.5 Web Application

The asset locations predicted in the location engine are fed over a REST API into a web application to visualize the results (c.f. figure 6.3). Further analytical processing can be performed on the location history data of a given asset.

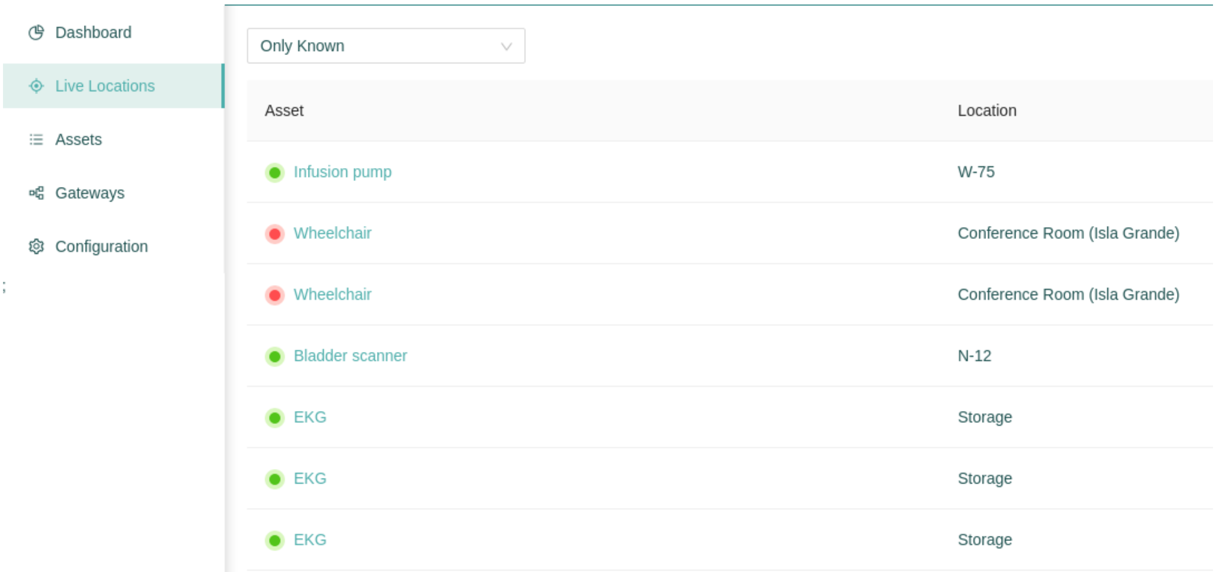

Figure 6.3: Web application

Chapter 7

Evaluation & Conclusion

The prototype was evaluated in an office building with 11 rooms (c.f. floor plan in figure 7.1). The first aspect under evaluation was the complexity of the setup. The gateways were configured with the SSID and key of the local WiFi network in advance. On premise, the gateways are distributed among the rooms and plugged into a free power socket of each room. The gateway boots up, connects to the WiFi network and starts observing BLE packets. Seconds later, the gateway shows up in the web application and can be mapped to a location name (e.g. <Gateway_42> = 'Meeting room'). The setup of the system ran smoothly and the installation of a gateway is a matter of seconds.

Figure 7.1: Floor plan

The second aspect concerns the overall costs of the system. Due to the early stage of the project the costs can't be evaluated at this time. However, from the use-case at hand we can argue that there are roughly 10 times more BLE beacons than gateway devices. Thus, the price of a single BLE beacon has a higher impact on the initial infrastructure costs than that of a single gateway. As BLE beacons are battery powered, maintenance costs are mainly driven by expenses for battery replacements and time spend by technicians to replace them. Thus, long battery life is critical.

To enhance the battery life of the beacon, BLE advertising can be paused when the beacon is not moved. An accelerometer enables the beacon to go into sleep-mode when it is stationary for extended periods. Once it is moved, it wakes up and starts advertising. An evaluation of the power consumption was not possible due to the lack of a multimeter, but could be investigated in a future work.

The accelerometer data further enables dynamic advertising intervals. When the beacon is moved, advertising bursts in a short interval can be emitted. When the beacon is stationary, advertising can be shut down completely. Shorter BLE advertising intervals should generate more data points / second. In turn, this should yield faster predictions as more data is available in shorter time. To evaluate the impact of different advertising intervals we move the beacon between rooms and measure how long the system takes to update the beacons location. We call this the time to prediction TTP. The results are presented in table 7.1.

Table 7.1: TTP of different advertising intervals

Advertising interval	**TTP (mean of 10 samples)**
20ms	30.57s
200ms	30.12s
2000ms	83.23s
10'000ms	>5 min

The results show that the larger the BLE advertising interval, the larger the latency of the location prediction. The system predicts the location once it gathered a sufficient number of data points. The larger the advertising interval, the longer it takes to achieve the threshold of data samples.

This work provides a prototypical implementation of an RTLS based on BLE. The integration of an accelerometer sensor on BLE beacons was achieved and evaluated. The results show that the application of an accelerometer has multiple use-cases. It was shown that the accelerometer enables dynamic advertising intervals, which lead to faster location predictions. An evaluation on power consumption remains an open issue.

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Appendix A

Installation Guidelines

Appendix B

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