UNIVERSITY OF TWENTE.

Optimizing BLE Gateway Positioning in Aviation Industry: An Algorithm Based on Link Budget and Log-Distance Path Loss

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Contents

Abstract

Utilizing BLE beacons and gateways to track assets can enable the optimization of logistical processes through data-driven insights. This research determines the positions and orientations of BLE gateways that ensure maximum coverage area when deployed in the aviation industry. We propose a Particle Swarm Optimization algorithm, called PSOP, to determine the optimal positions. PSOP maximizes the number of beacons in range of at least one gateway. A combination of the Link Budget and the Log Distance Path Loss model is used to determine the range of a gateway. We characterized the parameters used in these calculations via measurements.

The path loss exponent is determined for various zones inside an airplane hangar. Besides, the antenna pattern, RSSI at one meter distance and minimum required RSSI for data transmission parameters have been determined. The algorithm uses these parameters to find the optimal BLE gateway positions. The algorithm was able to position the gateways for a specific setup such that 100% of the sensors were in range of at least one gateway.

1 Introduction

1.1 Context and relevance

Being able to achieve more output with fewer resources is the definition of efficient. For companies, it is important to maximise their efficiency, since this ensures that fewer resources are wasted. When focussing on the logistical process, emissions and costs are reduced when moving assets (such as equipment, transport vehicles, or stock) in a more efficient way. Gathering data about these assets helps to visualise the logistical process. Though, gathering this data can be difficult for assets that move all around the globe. When gathering data via a Bluetooth beacon, important factors such as transmitting range, battery life and worldwide coverage have to be taken into account. Besides, the benefits of this tracking system should outweigh the costs of the system.

The company Undagrid, located in the Netherlands, has created a system that allows tracking assets while taking these important factors into account. Small Bluetooth beacons are attached to the assets. These beacons communicate with a gateway device via the Bluetooth Low Energy (BLE) protocol. The gateway devices are responsible for uploading the received beacon data to the so-called UNO-cloud. This is a custom cloud environment, developed by Undagrid. To upload the data, the gateway devices need a connection to the internet. Such a gateway device can be a mobile phone, but also separate BLE-4G gateways and BLE-WiFi gateways exist. Parts of this Undagrid system have already been implemented in the aviation industry, however, the BLE-WiFi gateways have not been deployed yet. The deployment of the BLE-WiFi gateways can result in increased accuracy and response time if their fixed position is chosen wisely. Position matters, because it ensures that beacon signals are received if the beacon is in the neighbourhood of the BLE-WiFi gateway. This is different from using mobile phone gateways. In that case, the network coverage will rely on a (moving) mobile phone to be near the sensor.

Figure 1: Schematic overview of the Undagrid system.

1.2 Problem statement and research questions

The placement of the BLE-WiFi gateways is important as it determines the signal coverage area of the system. The gateway setup includes the number of gateways used, their position, and their orientation. These parameters influence the total coverage area; i.e. the area in which beacon messages are received by the gateways. Preferably, this coverage area is maximised, while the number of gateways is minimised. This research focuses on solving this optimisation problem, applied to the aviation industry. Hence, it answers the question: How many gateways should be deployed, at what positions and with which orientation, to ensure efficient coverage of the area inside an airplane hangar?

To solve this problem, the range of a gateway has to be determined. This range not only depends on device characteristics but also on environmental characteristics. It is unknown yet, how the aviation industry environment influences signal propagation. The characteristics of the beacon and gateway are of importance as well. Their influence has to be determined to properly algorithm the range of a gateway.

Research questions

1. How many gateways should be deployed, at what positions and with which orientation, to ensure efficient signal coverage of the area inside an airplane hangar?
   (a) How do signals propagate inside an airplane hangar?
   (b) Which beacon and gateway device characteristics influence signal transmission, and how much?
      i. What is the minimum RSSI required for signal transmission?
      ii. What is the antenna pattern of the gateway?
      iii. What is the RSSI of the beacon at 1 meter?

The main research question will be answered by creating an algorithm that optimizes the gateway setup, by predicting the range of the gateways. This range estimation will be calculated by using the link budget equation. Several parameters in this equation depend on the environment and devices used. These parameters are determined by answering the sub-questions. Several parameters are characterised together. We do this by measuring the RSSI of the beacon at 1 meter. The environment is characterised by performing range measurements inside an airplane hangar. This ensures that the algorithm represents the environment in which the gateways will be deployed. Besides, we will do device characterisation measurements in an anechoic chamber.

Chapter 4 provides more information about the research methodology and measurements while Chapter 2 and Chapter 3 provide a theoretical overview and literature review, respectively.

2 Theoretical framework

This section gives an overview of the theory used to answer the research questions. It dives into the combination of the link budget equation with the Log Distance Path Loss model, which is then used in the gateway positioning algorithm.

2.1 Wave propagation of Bluetooth signals

Bluetooth devices exchange data by sending out electromagnetic waves at a frequency between 2400 MHz and 2480 MHz [4].This frequency range is split into channels, all 2 MHz apart. Any data transmission between a transmitter (TX) and receiver (RX) uses multiple of these channels one after another, which is called channel hopping. The standard hopping rate is 1600 times per second, which minimizes interference from other radio frequency systems.

A transmitter transmits signals with a certain power. Due to losses, this received power is lower than the transmitted power at the transmitter (TX). The received power is often indicated with the Received Signal Strength Indicator (RSSI). The RSSI is an important parameter for reliable data transfer because it is related to the Signal-To-Noise Ratio (SNR). For successful data transfer, this ratio has to be above a certain threshold[3].

The RSSI can be used to determine the position of a beacon by using trilateration. Trilateration is a technique used to determine the precise location of an object based on the distances measured from that point to three known reference points. In the case of BLE positioning, these reference points are the deployed gateways. By leveraging the relationship between RSSI and distance, it is possible to estimate the distance between a beacon and a gateway. Hence, trilateration can be used to determine the position of a beacon.

2.2 Link budget

The link budget can be used as an approach to show the influence of different parameters on the RSSI. The final RSSI is determined by calculating the signal gains and/or losses for different stages between RX and TX, as can be seen in Equation 1[3]. The identification of the different gains and losses is crucial for the accuracy of the link budget.

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} + G_{\mathrm{TX}} - L_{\mathrm{misc,TX}} - L_{\mathrm{pathloss}}(d) + G_{\mathrm{RX}}(\theta) - L_{\mathrm{misc,\ RX}} \tag{1}$$

where:

P = Received or Transmitted power [dB]

L_{misc} = Any miscellaneous losses [dB]

G = The sum of all the gains at TX/RX, these might depend on angle (θ) [dB]

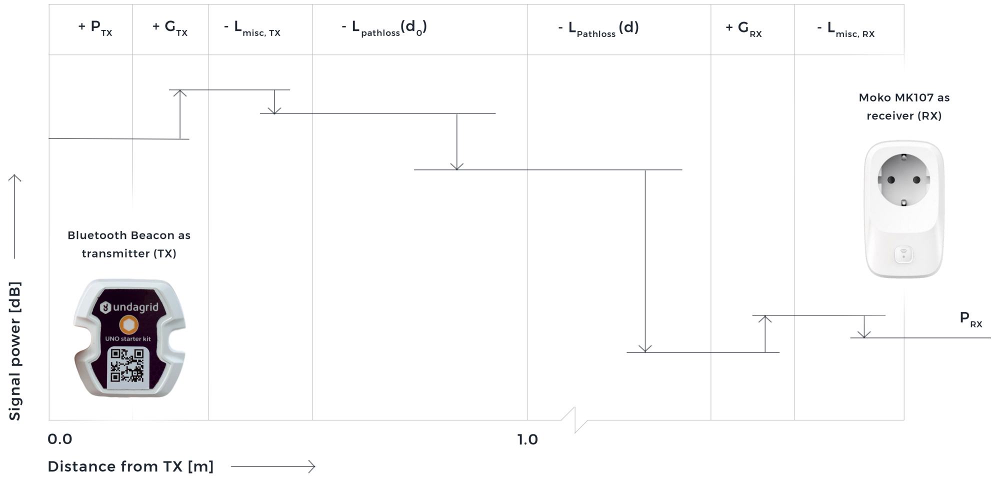


Figure 2: Overview of link budget, modified to fit from [5].

2.3 Log Distance Path Loss model

To estimate the path loss in an indoor environment, Equation 2 [8] can be used. The model starts with the path loss at a given reference distance (d_0) and uses the path loss exponent (n) to describe the propagation. This exponent is equal to 2 for free space , but it can differ based on the environment. Environments with a lot of obstructions can degrade signal quality, resulting in a high path loss exponent. However, obstructions can also cause signals to reflect. Reflections can cause interference. The case of constructive interference can cause a higher RSSI since more signal is reflected towards RX than in the free space attenuation case. This can be modelled with a path loss exponent smaller than 2, as can be seen in Table 1.

$$L_{\text{pathloss}}(d) = L_{\text{pathloss}}(d_0) + 10 \cdot n \cdot log\left(\frac{d}{d_o}\right) + X_\sigma \tag{2}$$

where:

$L_{\text{path loss}}(d_0)$ = path loss at reference distance d_0 [dB]

d = distance between RX and TX [m]

X_σ = zero-mean Gaussian distributed random variable [dB]

σ = standard deviation [dB]

The link budget equation can be extended by using the Log Distance Path Loss model to calculate the path loss. A path loss value at reference distance d_0 is needed to use the Log Distance Path Loss model. We set $d_0 = 1\,m$ and used measurements to find this reference path loss component, see Section 4.3. The Link Budget equation that is extended with the Log Distance Path Loss model can be seen in Equation 3.

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} + G_{\mathrm{TX}} - L_{\mathrm{misc,TX}} - L_{\mathrm{pathloss}}(d_0) - 10 \cdot n \cdot log\,(d) - X_\sigma + G_{\mathrm{RX}}(\theta) - L_{\mathrm{misc,\,RX}} \tag{3}$$

Environment	**Path loss exponent (n)**
Free Space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in buildings	4 to 6
Obstructed in factories	2 to 3

Table 1: Indication of path loss exponents in different environments. [12]

2.4 Fading

When transmitting data from TX to RX, the electromagnetic waves are often influenced by one or more objects before arriving at their final destination. The reflection coefficient of these objects and the direction of reflection influence the RSSI. [6] Due to the influence of these objects, large- and small-scale fading effects occur.

It is possible to obtain multiple different paths from TX to RX because of reflections. These paths can differ in length, causing interference. The resulting RSSI is a superposition of all these paths. [7] A small change (in the order of one wavelength) in RX position, can cause a different interference pattern, resulting in a significant change in RSSI. For Bluetooth, this means that changes in the order of $\pm 12\,cm$ cause small fading effects to be visible. The effect of small-scale fading compared to large-scale fading is visible in Figure 3. Large-scale fading becomes visible for changes in the order of magnitude of a few hundred wavelengths. For Bluetooth, this is in the order of $12\,m$. This type of fading is caused by the shadowing of wave signals. Shadowing can occur when objects obstruct the path between the transmitter and receiver, causing interference with signal propagation. Non-line-of-sight (NLOS) propagation refers to the scenario where signals can only reach the receiver through reflections.

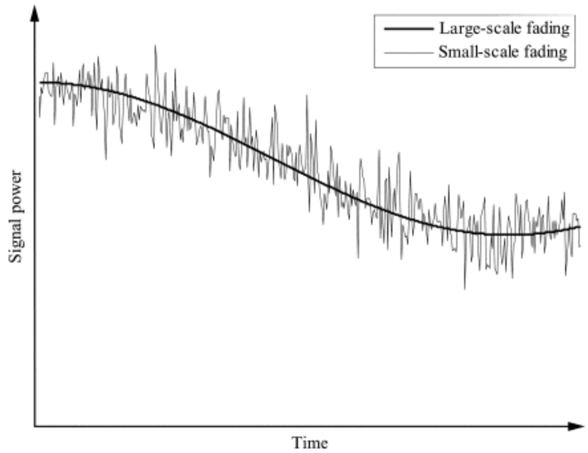


Figure 3: Comparison between small-scale and large-scale fading. Adapted from [13].

2.4.1 Rayleigh distribution

A big spread in RSSI measurements exists because of small-scale fading. In the case of a superposition of multipath components without a dominant line-of-sight, the RSSI follows a Rayleigh distribution. [7] This creates the opportunity to characterise the received RSSI by its spread (σ) and the starting location (LOC) of the Rayleigh distribution. Using the distribution, the mean can be calculated using Equation 4. The Rayleigh distribution assumes that the multipath components are independent and identically distributed random variables. This means that each multipath component follows the same distribution and is statistically unrelated to the others.

$$\text{Mean} = \text{LOC} + \sigma \cdot \sqrt{\frac{\pi}{2}} \tag{4}$$

In the case of a dominant line-of-sight component, the Rice distribution can be used to model the RSSI measurements. This research dives into the influence of components between RX and TX, hence the line-of-sight scenario is not relevant.

3 Literature review

This section provides a summary of previous research related to BLE gateway placement. It highlights the best practises and demonstrates their significance in addressing the main question of this research.

Gateway placement in mesh networks Zhou et al. [10] propose a gateway positioning algorithm based on Multi-Hop Traffic Flow Weight (MTW) for a mesh network. The throughput of such a network can be maximised by adding gateways. However, the addition of gateways can also cause interference. The algorithm follows an iterative approach that adds gateways to locations with the highest MTW. This value is influenced by the impact on throughput, number of mesh routers, number of clients, locations of other gateways, and interference with other gateways.

The advantages of the algorithm are that it positions gateways such that clients have fewer hops to take to reach a gateway and reduces traffic load on existing gateways. In addition, it takes interference into account. One disadvantage of the algorithm is that it applies to a mesh model and uses the Multi-Hop Traffic Flow Weight variable. This variable does not apply to our situation.

Gateway placement via clustering Matni et al. [9] leverage clustering to place gateways. Nodes are clustered via the Fuzzy C-means method. The optimal number of clusters is determined via the gap statistics method. This method describes the compactness of the clusters by comparing it with the compactness of clustered random data. A high gap statistic means that the nodes are clustered together efficiently, i.e. the distance from the centre of a cluster to the nodes in the cluster is minimised. The research translates the clustering model to the gateway setup by placing a gateway in the middle of every cluster. The number of gateways used is thus equal to the number of clusters.

The algorithm described above has an advantage in that it not only positions the gateways but also provides the optimal number of gateways needed. A disadvantage is that the research does not take the range of the LoRa gateways into account. Also, the influence of different environments is neglected. The signal propagation of indoor BLE signals can differ a lot, based on the environment. Hence, the algorithm must take this into account.

Gateway placement inside smart hospitals Luo et al. [11] investigated the robustness of gateway deployment within smart hospitals. The research is focused on guaranteeing full signal coverage. Due to deployment within a hospital, shadowing effects due to human bodies are taken into account. The researchers identify different indoor environments by their non-uniform user densities. Their gateway deployment algorithm for gateways in these scenarios is based on a set of rules. Initially, gateways are deployed in every corner of the room. New gateways are added iteratively; their position is determined by maximising the triangularity present in the setup.

The research is interesting because it takes into account the serving angles and the effects of human shadowing during the placement of the gateways. One disadvantage is that it does not use any other environmental conditions to establish the range of a gateway. Besides, the research strives to guarantee full signal coverage at all places, at all times. This requirement may be too strict for use in the aviation industry. Constant and comprehensive signal coverage may exceed what is practically necessary in aviation scenarios, where certain areas may not require full coverage at all times. Possible arguments for this different coverage might be because assets cannot be placed there or only shortly. It may differ per application whether full signal coverage is needed in the entire area. Flexibility in the algorithm such that this can be taken into account is therefore needed. This research does not show this flexibility. Hence, it is likely that this research places more gateways than would be required in the aviation industry.

Gaps in existing research There is research available on the placement of gateways, but it differs from our use case for several reasons. First, gateways are placed in other environments, such as hospitals or outside buildings. Environments can have a large influence on signal propagation, hence the model used should suit the environment. Second, different communication methods are used. A different communication method, such as LoRa, has a different frequency and therefore also influences signal propagation. Adapting the available literature to fit BLE gateways used in the aviation industry is hard since the models and results in the available literature are not based on the underlying physics of signal propagation. If this were the case, simple measurements would have been appropriate to fit existing models to the aviation industry.

The implementation of the channel model can solve these issues, as it provides a lot of flexibility to fit the model to different communication methods and environments. Software such as the NS3 Network Simulator can be used to create a channel model. This software is a comprehensive simulator, which makes it difficult to adapt it to our use case in the given time frame.

This research fills the gaps described above by creating a gateway positioning algorithm that determines the gateway setup that allows the best coverage in the area. The algorithm uses environmental parameters and the physics of signal propagation as a basis. The parameters used in the algorithm can be obtained via measurements, hence the algorithm can be easily adapted to fit in different indoor environments.

4 Research methodology

The link budget equation can be used to estimate the range of a gateway. This range estimate is of use when solving the main research question. Part of the sub-research questions help to quantify several components of the link budget equation. These sub-questions are answered by conducting measurements, the methodology of which is explained in this chapter. The relation between the research questions and the components of the link budget equation (Eq. 3) is described below. An overview of all measurements done is given in Table 2.

How do signals propagate inside an airplane hangar? The propagation of signals inside an airplane hangar can be estimated via the Log Distance Path Loss model. This model describes the power loss of a signal over distance. The path loss exponent (n) can be used to fit the model to the environment. We will divide the airplane hangar into three zones with different types of obstructions. We will measure the RSSI at various distances in the airplane hangar, such that it becomes possible to fit the measurements to the Log Distance Path Loss model and determine the path loss exponent values. Hence n in Equation 3 becomes known.

What is the antenna pattern of the gateway? The WiFi and BLE connectivity is possible due to the ESP32-WROOM component that is installed on the PCB of the Moko MK107 gateway [1]. The component uses an antenna integrated into the PCB. Typically these PCB antennas have an omnidirectional antenna pattern. The antenna pattern of the gateway might differ from the pattern of the ESP32-WROOM due to interference with other components and the location of the antenna inside the gateway. Hence we will characterize the antenna pattern of the gateway via measurements. We will determine the antenna pattern by using a beacon to send signals to the gateway at various angles, for constant distances. Via this, the relation between angle and antenna gain ($G_{RX}(\theta)$, in Equation 3) can be determined.

What is the RSSI of the beacon at 1 meter? To evaluate the sum of the terms $P_{\text{TX}} + G_{\text{TX}} - L_{\text{misc,TX}} - L_{\text{pathloss}}(d_0)$ in Equation 3, we will measure the RSSI of the beacon at a distance of 1 meter.

What is the minimum RSSI required for data transmission? Equation 3 can be used to calculate the signal strength that the receiver receives, given a distance (d) and by using the parameters described above. However, it is also important to know how much power should be received for successful data transfer. We will determine this minimum required RSSI by analyzing the RSSI of received beacon messages of a gateway. The received messages are logged in log files, these files are used during this analysis. The gateways can only log beacons that are in range, hence the minimum RSSI in this log file can be used as the minimum RSSI that is required for proper data transmission. The antenna sensitivity of the ESP32-WROOM module that is used for BLE communication is -97 dBm [2]. The minimum RSSI value we find via measurements should be close to this receiver sensitivity.

The following subsections dive deeper into the methodology used to obtain values for the parameters described above.

Date	**Duration**	**Location**	**Goal**
11-05-2023	~ One afternoon	Lufthansa, hangar 7	Determine environmental influence on signal propagation
11-05-2023	114 minutes	Lufthansa, hangar 7	Determine minimum RSSI required for data transfer
12-05-2023	~ One morning	Lufthansa, hangar 7	Determine environmental influence on signal propagation
30-05-2023	~ 2 hours	University of Twente, anechoic room	Determine antenna pattern of gateway
30-05-2023	~ 30 mins	University of Twente, anechoic room	Determine RSSI value at 1m

Table 2: Overview of all measurements done to answer the sub-questions.

4.1 Signal propagation inside an airplane hangar

We conducted measurements in an airplane hangar to answer the dependency of the aviation environment on BLE signal propagation. Hangar 7 at Lufthansa Technik (Hamburg) was used to classify this dependency. The dimensions of the hall are roughly 181 x 107 meters. We divided the hall into three zones with different obstacles, see Figure 4. Please see Figure 27 in the appendix for an example of obstacles in zone B.

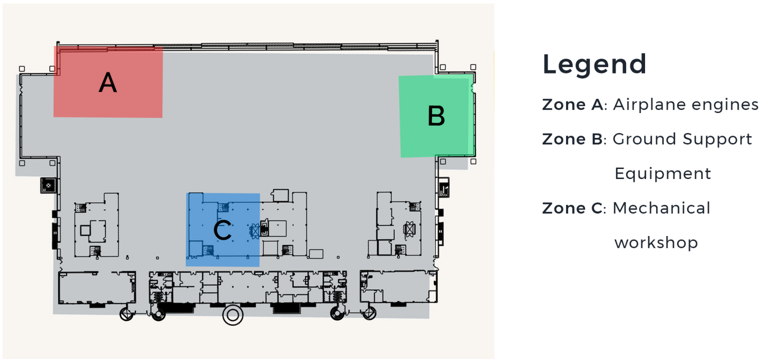


Figure 4: The division of the airplane hangar into different zones with different obstacles.

Equipment used

- Moko MK107 BLE-WiFi Gateway
- Confidex Bluetooth beacon

Data acquisition The Moko MK07 gateway was set up and connected to the WiFi by following the user manual [1]. During this setup, we also connected the gateway to a storage server. All BLE packets that the gateway receives, are redirected to this server via the Message Queuing Telemetry

Transport (MQTT) protocol. A Bluetooth beacon can send out such packets. During these measurements, we used a Bluetooth Low Energy beacon from Confidex. The packets this beacon sends out contain information such as sensor data, MAC addresses and timestamps.

The gateway receives these packets and adds new information to this packet, before redirecting it to the storage server. This information includes the Received Signal Strength Indicator (RSSI). The RSSI value is eventually used to determine the influence of the environment on signal propagation. All information is stored on the server and can be requested later for further analysis.

Method We plugged the gateway into a power outlet and determined its position by using the floor plan. We noted the height and heading of the gateway, together with the start time of the measurement.

We positioned the Confidex Bluetooth Beacon at 10 to 15 different distances between 2 and 40 meters for approximately 80 seconds per distance. During the measurements, we recorded the following information: start and end time of the measurement, description of objects in between the gateway and beacon and the height of the beacon.

We repeated the method described above for all zones, as shown in Figure 4. Besides, measurements at zone A and B were repeated on another day.

4.2 Determination of antenna pattern

We conducted measurements to intending to determine the antenna pattern of the Moko MK107 gateway. This allows mapping the antenna gain for various angles of incidence. This can be important in case the antenna gain is not distributed homogeneously since this causes the RSSI to depend on the angle of incidence.

Equipment used

- Moko MK107 BLE-WiFi Gateway, attached to an extension cord
- Confidex Bluetooth beacon
- Compass
- WiFi Router with external antenna

Method The measurements took place inside an anechoic chamber, to minimize the influence of the environment on the measurements. Inside this room, any reflections of electromagnetic waves are damped, hence minimizing the influence of interference on the measurements.

We used the same gateway and beacon, hence the data was gathered again via the same method as described in Section 4.1. A WiFi connection is required for the gateway to upload data to the server, but the anechoic room blocks any electromagnetic waves coming from outside the chamber. To establish a WiFi signal, we inserted a single WiFi antenna into the room. To minimize the interference with the measurements, the WiFi router was left outside and only one antenna was used. Besides, WiFi channel 11 was used, since this frequency overlaps the least with the BLE frequencies used.

Inside the room, the gateway was placed on a rotatable tripod. Power was delivered to the gateway via an extension cord. The beacon was positioned on the other side of the room, both devices were placed at the same height. We tested different angles of incidence by rotating the gateway in a clockwise direction. Rotating the gateway increases accuracy when compared to moving the beacon because the distance between the gateway and beacon stays constant. However, the gateway will be stationary when using it for its actual purpose. Hence, when processing the measurements we convert them to mimic a moving beacon.

For every angle, data was gathered for a period of approximately 60 seconds. After one full rotation, the orientation of the gateway was changed by rotating it 90 degrees. This ensures that the antenna gain can be constructed for all axes.

4.3 RSSI value at one meter

Equipment used

- Moko MK107 BLE-WiFi Gateway, attached to an extension cord
- Confidex Bluetooth beacon
- Tape measure
- WiFi Router with external antenna

Method To determine the RSSI at one meter distance, we positioned the gateway and beacon such that the devices were facing each other (i.e. angle of incidence equal to 0 degrees). The distance between the devices during this measurement was 1 meter. A measurement period of approximately 90 seconds was used. We used the same data acquisition method as above. Besides, this experiment was also conducted inside the anechoic chamber.

4.4 Minimum required RSSI value for data transmission

Equipment used

- Moko MK107 BLE-WiFi Gateway
- Different Bluetooth beacons

Method We plugged the gateways into several different positions inside the hangar. All gateways were set up to log received messages to the server, again by making use of the MQTT protocol. Different Bluetooth beacons were present in the hangar, hence their beacon messages were logged if the beacons were in the range of a gateway. If a beacon were to move outside the range of a gateway, no messages are logged anymore. Hence the lowest RSSI value for which signal transmission is still possible can simply be determined by finding the lowest RSSI value in the logs. We have logged messages for 114 minutes.

5 Gateway positioning algorithm (PSOP)

This section dives into the algorithm used to answer the main research question. The algorithm has the goal to determine the positions and angles of the different gateways, that ensure the largest coverage area. To do this, the algorithm estimates the signal coverage area of one gateway. The Log Distance Path Loss model (Chap. 2.3) is used to determine the path loss of the signal, i.e. the propagation of the signal strength over distance. Together with the other link budget components, a final Received Signal Strength Indicator can be computed. For signals to be received, this RSSI has to be above a threshold. Hence, RSSI can be related to the coverage area of a gateway. To fit this gateway coverage area to reality as best as possible, the measurements as discussed in Section 4 are used to define the proper path loss and link budget values.

Based on the coverage area of all gateways, an error term can be computed. This error term is increased if a beacon within the area is not in the range of any gateway. Other factors influence this error term also, these are described below. The error term is minimized by using a Particle Swarm Optimization (PSO) algorithm. As a result, the positions and angles of the gateways for which the error term is the lowest are given. Hence, this implies that the coverage area is maximized for the given gateway setup.

The gateways need power and hence power outlets need to be near their deployment locations. The swarm optimization algorithm does not take this into account, hence the opportunity is added to adjust the gateway locations manually. This also allows us to correct any mistakes made by the Particle Swarm Optimization algorithm. Proper results can be derived by following the flowchart, see Figure 5. The swarm optimization algorithm can be repeated with a different number of gateways, until the required coverage is achieved. The resulting gateway positions can be changed manually to ensure deployment at these positions is possible. The final coverage area can be checked by running the manual setup script. This script does not involve any optimization algorithm but solely calculates the area coverage based on the input positions of the gateways. To increase user experience, a simple GUI has been created that allows placing the gateways by clicking inside the simulation area. See Figure 16.

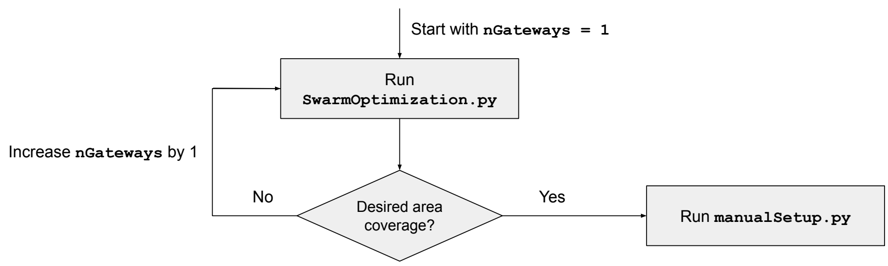


Figure 5: Schematic overview of the total PSOP algorithm.

5.1 Assumptions

We assume that the path loss follows the Log Distance Path Loss model. This model uses a single path loss exponent to model the path loss over distance. In case multiple different path loss exponents exist in the trajectory, we assume that the final path loss exponent can be determined via a weighted average of all the exponents, weighted by the propagation distance.

The sum of the terms $P_{\text{TX}} + G_{\text{TX}} - L_{\text{misc,TX}} - L_{\text{pathloss}}(d_0)$ has been determined inside an anechoic chamber. This term contains the only constant damping factor that is used inside the link budget calculations. We assume that the aviation industry environment does not add any extra constant damping when compared to the anechoic room. Besides, we assume that the antenna pattern of the beacon is omnidirectional.

The radiation pattern for the gateways has been included in the calculations, hence the antenna gain is not assumed to be constant for all angles. Gateways are often plugged into a wall or any other construction. We assume that these obstructions add 10dB signal loss to the radiation pattern, but only for angles between 90 and 270 degrees.

The total area can be divided into smaller sub-areas. The optimized gateway setup for these sub-areas forms an optimized gateway setup for the total gateway area.

Any changes in environmental conditions, such as changes in temperature or humidity, are assumed to not influence on the coverage area of the gateways. Besides, the algorithm assumes that the beacon and gateways are positioned at the same height.

5.2 Algorithm inputs and outputs

To allow for proper path loss calculation, the algorithm requires the path loss exponent as input. These exponents might differ per position, hence the path loss exponents are saved in a grid. The complete area is initialized with a path loss component of 2 and it can be updated via the `updatePLGrid()` function. This allows setting a new path loss exponent value for a rectangle with corners at given locations. Figure 6 shows the path loss exponent grid, after updating three zones with different path loss exponents.

Together with the path loss exponent grid, the algorithm uses the following inputs:

1. Size of Particle Swarm; a higher size will increase the likelihood of finding the minimum of the error function, but will also require more computations.
2. Number of beacons; the beacons are distributed evenly across the area and are used to test whether the gateways receive their signals. More beacons ensure more accuracy but again require more computations.
3. Number of gateways; the number of gateways is fixed. If coverage is not as desired, the number of gateways can be changed.
4. Width of area
5. Length of area
6. Minimum RSSI required for signals to be received by gateway; any signals that arrive with an RSSI lower than this threshold, are categorized as 'not received by gateway'. This threshold value has been determined via measurements, as discussed in Section 4.4.
7. The sum of $P_{\text{TX}} + G_{\text{TX}} - L_{\text{misc,TX}} - L_{\text{pathloss}}(d_0)$; this value has been derived via measurements, as discussed in Section 4.3.
8. Gateway Antenna gain for various angles; these values have been derived via measurements, as discussed in Section 4.2.
9. Safety margin; margin can be added, to improve the robustness of the gateway setup.

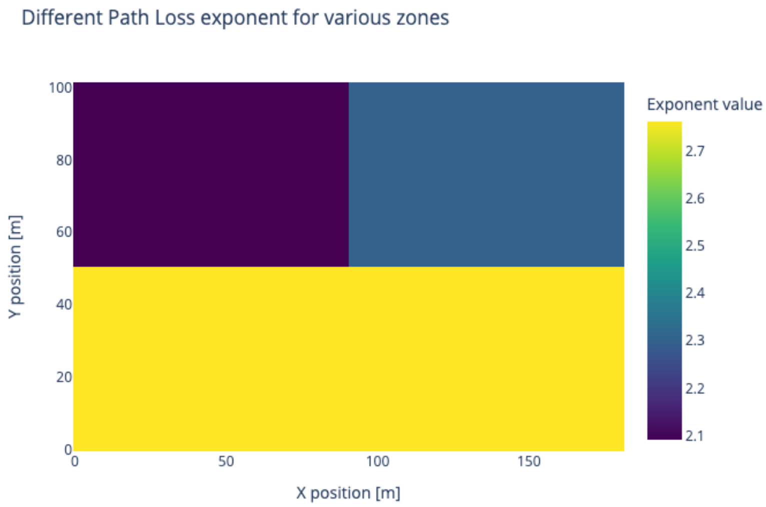


Figure 6: Example map showing different path loss exponents for different points in space.

The algorithm optimizes the gateway positions and their angles, using the given inputs. As output, the most optimal gateway setup is returned. This thus includes the positions and their angles. Besides, the number of beacons in the range is returned. This number can be used to judge the performance of the setup when compared to the total number of beacons.

5.3 Algorithm Formulation

The total area has been divided into four sub-areas. These subareas are optimized irrespective of each other, which lowers the total number of computations required. The `minimize()` function is called for every subarea. This function is imported from the Psopy python package and requires an initial gateway setup. This is achieved by initializing the gateways at the center of the subarea with an angle of 0 degrees. The minimize function takes care of the implementation of the Particle Swarm Optimization. This optimization method uses particles as candidate solutions and tries to find the best candidate solution. Particles move along the search space with a velocity that depends on its local and global best-known candidate solution. Hence, all the particles together can find the best candidate solution.

The gateway setup is judged via the `errorFcn()`, hence this is the core of the algorithm. It assigns an error value to the setup. This is done by using beacons that are distributed uniformly across the area. The error function increases if beacons exist that are not in the range of at least three gateways. The error is updated based on the number of gateways in the range. Beacons with no gateways in range create a larger error than beacons with one or two gateways in range. Being in range of at least three gateways is preferred since allows one to determine the position via trilateration. Accuracy is increased if the three gateways are not close together. Hence, the angle between the beacon and gateways in the range is also taken into account. The standard deviation of these angles is calculated. This standard deviation should be maximized, hence it lowers the error term.

To determine which beacons are in the range of a gateway, the function `getSensorsInRange()` is used. The function loops through all beacons, also called sensors, and determines the link budget between the gateway and beacon. The RSSI is calculated via this link budget and should be above a certain threshold to ensure the gateway receives the beacon signal. This threshold is measured and a 10dBm safety margin is added to this threshold. This ensures that no beacons are placed on the edge of the range of a gateway.

Needed for the link budget calculation are the angle, distance and path loss exponent. The angle between the gateway and the beacon, as seen from the perspective of the gateway, is calculated with geometry. The initial orientation of the gateway is taken into account during this calculation. The antenna gain measurements are used to convert the angle into a value for the gateway antenna gain. A moving average with a window size of 7 is applied to the measurements. Besides, 10 dB loss is applied to angles from 90 to 270 degrees, to mimic the signal losses due to the constructions to which the gateways are attached.

The last value used in the link budget calculation is the path loss exponent. It is possible for a signal to cross multiple zones with different path loss exponents, before arriving at the gateway. An example of path loss exponent distribution is given in Figure 6. A weighted average is used to take the change of path loss exponent into account, see Equation 5.

$$n_{\text{weighted}} = \frac{\sum\limits_{i} n_i \cdot \text{distance in zone } i}{\text{total distance}} \tag{5}$$

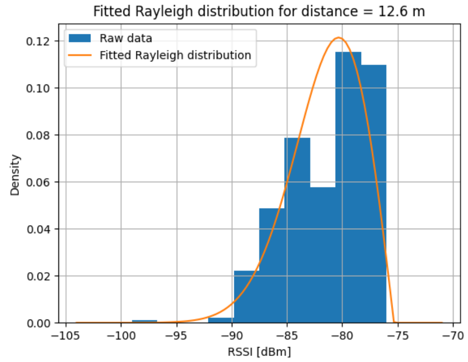
6 Results

This section describes the results of the measurements done to determine the parameters used for the calculations in the algorithm. Besides, it shows the results gathered via the algorithm.

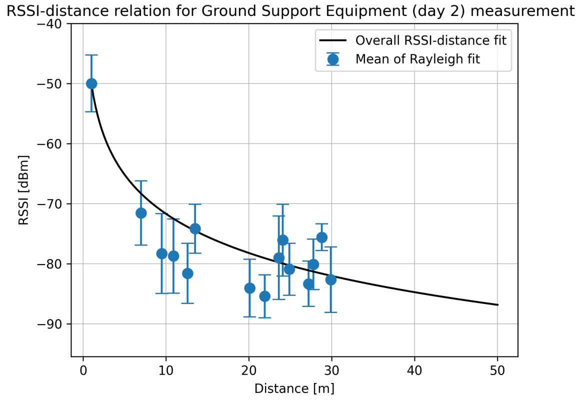
6.1 Signal propagation inside an airplane hangar

As discussed in Section 2.4.1, the RSSI measurements are expected to be distributed according to the Rayleigh distribution. We applied a fit to the measurements, as can be seen in Figure 7a. The scale value of the fit can be determined. This is a measure for the spread of the measurements, hence indirectly also a measure for accuracy. Using the scale and starting point of the fit, the mean value can be calculated. This gave an RSSI of $-80.09 \pm 4.19 dBm$ for the 12.6 meter distance measurements.

The scale and mean values of the Rayleigh fit are used to create the final RSSI-distance fit. Weights are applied, such that measurements with a large scale are weighted less during the fitting progress. The mean values of the data points are visible in Figure 7b. The size of the error bars corresponds to the scale value. This graph only contains the Ground Support Equipment (day 2) measurements for visibility reasons. Please see Figures 22, 23, 24 and 25 in the appendix for all the measurements in the other environments. All the final fits are visible in Figure 8. Table 3 shows their numeric path loss exponent (n) values.



(a) Individual fit of RSSI measurements at 12.6 meter distance between TX and RX.



(b) Fitted RSSI-distance relation by using all individual fitted distance measurements.

Figure 7: Individual and total fit for Ground support equipment (day 2) measurement series.

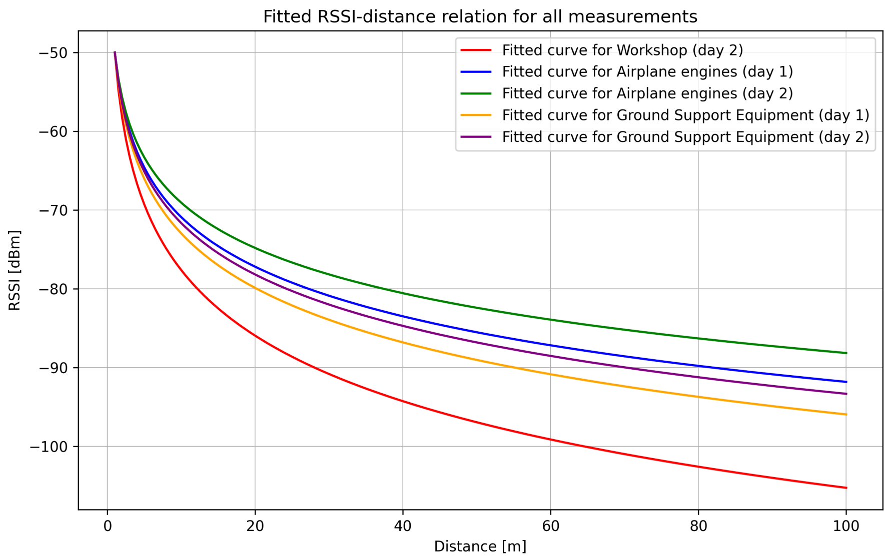


Figure 8: Modelled power of signals propagating in different environments. To see the comparison with the measured data, please see Figures 21 to 25.

Measurement environment	Path loss exponent
Workshop (day 2)	2.764
Airplane engines (day 1)	2.091
Airplane engines (day 2)	1.908
Ground Support Equipment (day 1)	2.298
Ground Support Equipment (day 2)	2.167

Table 3: Resulting path loss exponent (n) values after fit

6.2 Determination of antenna pattern

Figure 9 shows that the RSSI is high for a pitch angle between 270 and 90 degrees when compared to angles between 90 and 270 degrees. This can be explained by the antenna location, see Figures 19 and 20. The gateway was plugged into an extension cord to power the device. This additional mechanical structure is probably the cause of the drop in RSSI value between pitch angles of 90 and 270 degrees.

The height difference between TX and RX is neglected in the algorithm. Hence, the pitch axis is not investigated any further. A moving average has been applied to the yaw axis measurements since the antenna pattern is expected to be omnidirectional and huge fluctuations have a big influence on the positioning algorithm. This can be seen in Figure 10. This moving average is eventually used in the algorithm as antenna gain.

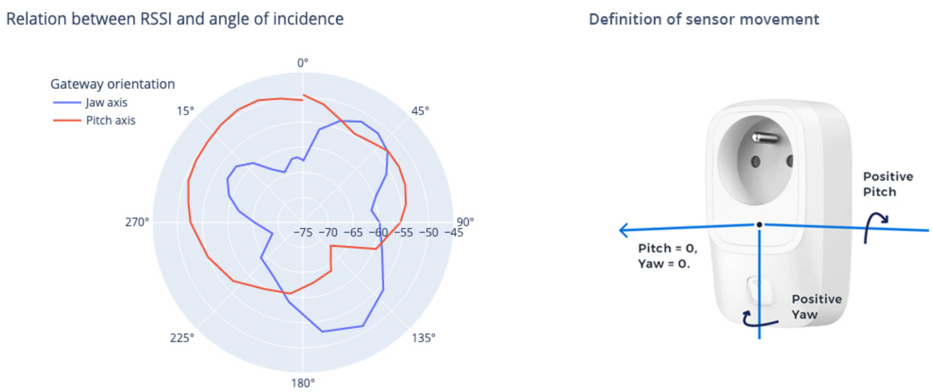


Figure 9: Left: RSSI-angle dependency plotted for various angles along various axes. Right: Definition of rotation around the axes.

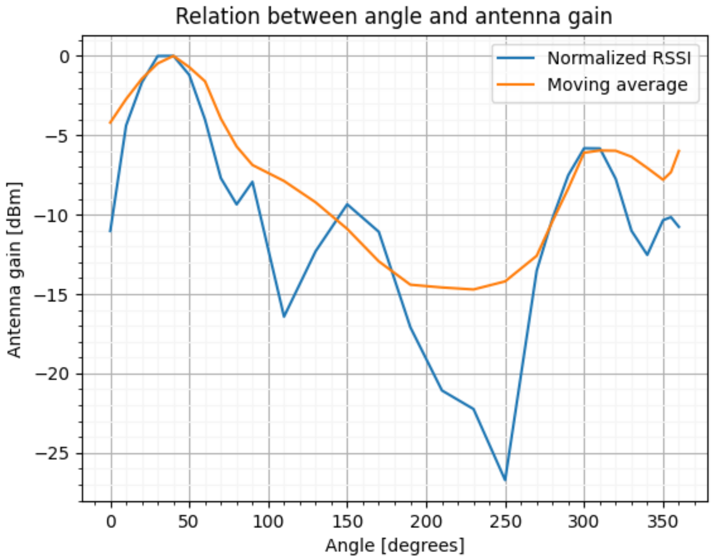


Figure 10: Relation between antenna gain and angle used in algorithm.

6.3 RSSI value at one meter

Figure 11 shows the boxplot of the RSSI values for 1 meter distance between the gateway and beacon. The Raylay distribution has not been used to fit since the distribution does not apply to cases with a strong Line Of Sight component. The median of the RSSI is -50 dBm, with the first and third quartile at -53 dBm and -47 dBm, respectively. This value is used as sum of the terms $P_{\text{TX}} + G_{\text{TX}} - L_{\text{misc,TX}} - L_{\text{pathloss}}(d_0)$ in equation 3.

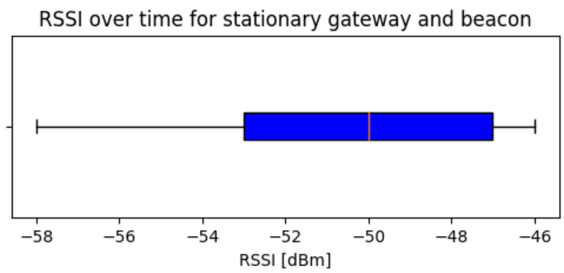


Figure 11: RSSI for 90 seconds with 1 meter distance between gateway and beacon.

6.4 Minimum required RSSI value for data transmission

Figure 12 shows a histogram with the RSSI for all received beacon messages. This data is combined data from multiple gateways. In total, more than 2 million messages are received within a period of 114 minutes. The minimum RSSI is -103 dBm, while the maximum goes up to -42 dBm. No messages are received with RSSI values lower than -103dBm, hence we conclude that the minimum RSSI required for successful data transmission is -103dBm.

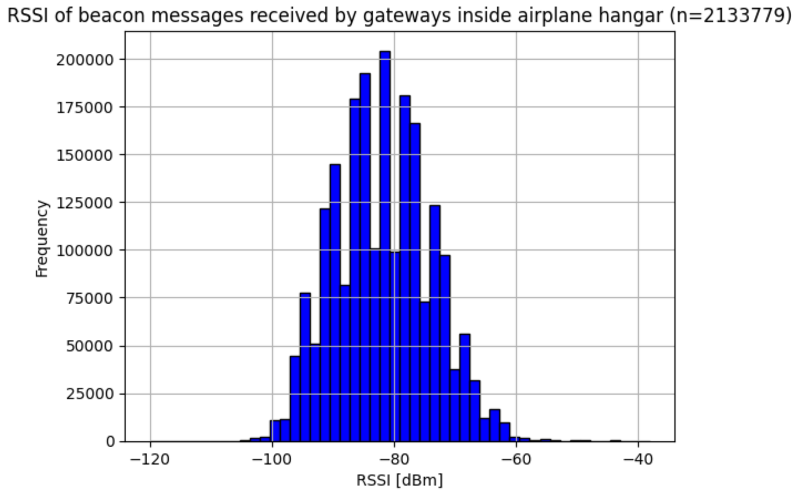


Figure 12: Histogram of RSSI values received by multiple gateways in hangar.

6.5 Gateway positioning algorithm

The algorithm determines the range of a gateway by using Equation 3 together with the minimum required RSSI value for successful data transfer. This range depends on the angle of incidence due to the antenna pattern of the gateway. This can be seen in Figure 13. The position of the gateway has been set to $(x, y) = (250, 250)$, to ensure the range lies within simulation boundaries. This simulation uses a path loss exponent of 2.

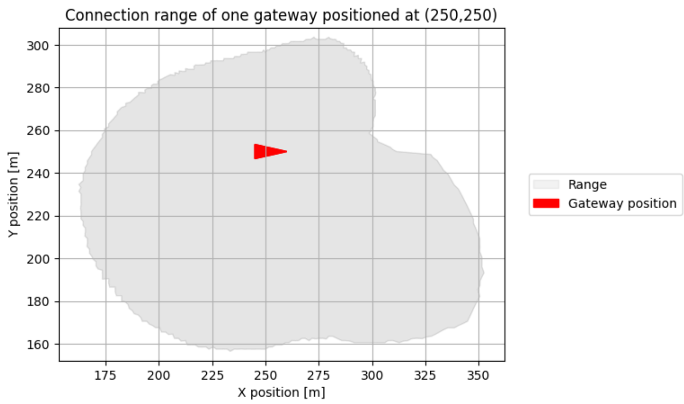
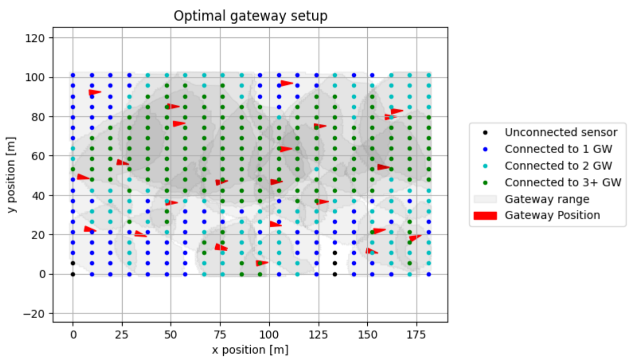


Figure 13: Range of a single gateway, if a transmitter is used with signal strength of -50 dBm at 1 meter.

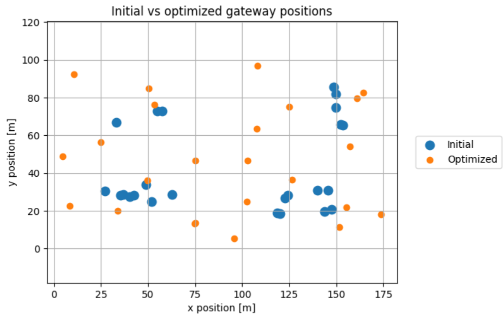
Figure 14a shows the gateway setup of 24 gateways divided over an area with dimensions of 181 to 100 meters. The gateways are shown as arrows since their orientation is important due to their antenna pattern. All 1000 beacons are plotted as dots on the map. Their colour changes based on the number of gateways in the range. Figure 14b illustrates the difference between the gateway positions initially set as a starting point before employing the PSO algorithm and the optimal positions determined by the PSO algorithm.

The path loss exponent map follows the map as shown earlier in Figure 6, since this setup mimics the situation inside the airplane hangar. This means that the path loss exponent is the largest for Y positions between 0 and 50 meters. Signals attenuate faster in this area causing a reduced gateway range.

The Particle Swarm Optimization achieved a gateway setup such that 98.8% of the beacons is in the range of at least one gateway. 100% coverage is achieved by manually adjusting some gateway positions. The final result is presented in Figure 15.



(a) Gateway setup and resulting coverage.



(b) Figure illustrating the difference between initial positions and results of the Particle Swarm Optimization.

Figure 14: Optimal gateway positions and orientation determined by the Particle Swarm Optimization algorithm.

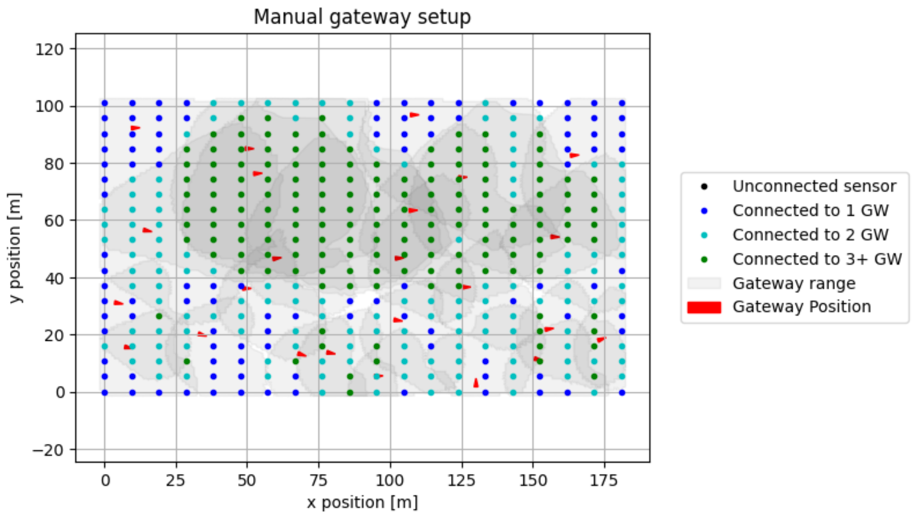


Figure 15: Final gateway setup after manual tuning.

7 Discussion

7.1 Key findings and implications

It can be seen that measured RSSI values at fixed distances indeed follow the Rayleigh distribution. The accuracy of measurements at the same distance is thus increased by fitting them to this distribution. Measurement data taken at different distances show that the RSSI indeed follows the Log Distance Path Loss model. Hence, by fitting these measurements to the Log Distance Path Loss model, it is possible to determine the path loss exponent for the environment.

The antenna pattern measurements show variation in the antenna gain for various angles of incidence. These variations are taken into account by the link budget equation, as well as the RSSI at one meter and the minimum required RSSI for data transfer. The combination of the Link Budget equation with the Log Distance Path Loss model allows for the range estimation of a single gateway.

Data shows that this range estimate can be used in combination with a Particle Swarm Optimization algorithm to determine the gateway positions, such that area coverage is maximized. Manually adjusting the position of some gateways may be necessary to achieve 100% coverage. This is because the Particle Swarm optimization relies on the particles to find the global minimum by chance. This chance can be increased by increasing the number of particles used during the calculations. However, this also increases the number of computations needed to find a solution. The PSO algorithm together with manual adjustments has shown to successfully achieve 100% area coverage.

The research shows that the method described is suitable for the determination of the gateway setup. Hence, a method now exists that determines the BLE gateway setup that guarantees optimal coverage inside the aviation industry. The physics behind signal propagation in indoor areas is used to determine the range of a single BLE gateway. Because of this, this method can be easily extended to suit different indoor communication systems.

The following subsection states a discussion on different parts of this research.

7.2 Discussion on the methodology used

General points The spread in received RSSI for measurements done in the anechoic room is relatively small when compared to the measurements done in the airplane hangar. This supports the effectiveness of the anechoic room, since the spread of this value is related to the number of reflections present in the room (as discussed in Chapter 2.4.1).

A bias might be introduced into the result since only one gateway has been used during all measurements.

Antenna pattern measurements A compass has been used to rotate the gateway to a new angle for a new measurement. Though, this might introduce a cumulative error causing an offset in the measurements. The use of a wind rose might have been more accurate. Though, a measure for accuracy is the fact that the measurements of 0 and 360 degrees overlap. This overlap can be seen in the graphs and hence it can be concluded that there is little to no offset.

Discussion on path loss exponent determination The RSSI measurements only behave according to a Rayleigh distribution if no dominant Line-Of-Sight (LOS) component is present. Most measurements are done with obstructions in between TX and RX, though it is difficult to guarantee that no LOS was present for all the measurements. The Rice distribution should be used in case a dominant LOS is present, instead of the Rayleigh distribution that is used now. Using the Rayleigh instead of the of the Rice distribution is not beneficial [7] for the range of a gateway. Hence, the range of a gateway might increase for LOS cases.

Measurements were done in the same zone but on different dates. This resulted in a different path loss exponent, even though the type of obstructions stayed the same. Hence, the difference in signal propagation has to be explained by some other environmental variable. For example, a different humidity and/or temperature could have caused this change in the path loss exponent. Though more research is needed to substantiate this. The highest path loss exponent is used in the algorithm since this causes the algorithm to predict a worst-case scenario.

7.3 Discussion on Gateway Positioning algorithm

The results show that the algorithm can position the gateways, such the area coverage is optimized. Different path loss exponents can be used as input, such that different types of environments can be modelled together. For demonstrating purposes a higher path loss exponent has been used as input for the algorithm. The path loss exponent has been set to 2.71 for y values between 0 and 50m. The result shown in Figure 14 show that the model places more gateways in this area, to deal with the higher attenuation of the signal strength in this area.

The model divides the area into four subareas to lower the required number of computations. This means that the gateways are divided amongst those subareas before the optimization starts. The division takes the average path loss exponent of a subarea into account. Though, because of this gateway distribution before optimization, it is still possible that a subarea has a surplus in coverage area, while another subarea has a deficit. Optimizing the entire area in once will solve this issue, but requires more computations.

The error function plays a crucial role in optimizing the gateway setup and largely influences the output results of the Particle Swarm Optimization algorithm. The results are obtained with an error that is increased if a beacon is not in the range of a gateway, hence optimizing the total coverage area. The inclusion of other factors such as optimizing beacons to be in the range of at least three gateways or optimizing the spread in angle between a beacon and its connected gateways have been tested as well. All these factors combined did not provide reliable results.

The Particle Swarm Optimization method relies on particles to find the minimum of the error function. Particles are spawned randomly, hence the probability that the particles find a minimum increases for a higher number of spawned particles. The results of the PSO algorithm can differ, even with the same initial settings. This is because of this reliability on probability and the random initial conditions of the particles. Increasing the size of the particle swarm helps to generate more consistent results, but one disadvantage is that this requires a lot of computation power. It is difficult to implement other optimization algorithms because the objective function is discontinuous. This makes optimization of the function difficult since all methods that rely on the use of derivatives cannot be used.

The Particle Swarm Optimization algorithm does not take into account that the gateways need a power outlet near their deployment position. Hence, we made a manual setup script to convert the optimal gateway positions of the Particle Swarm Optimization algorithm to feasible positions for deployment. This conversion step can be made redundant by extending the algorithm with positioning constraints.

7.4 Future Enhancements

The algorithm has been limited to considering only the 2D position and does not use height information in its calculations. If the height is taken into account, it adds the possibility to model the reflections of the signal via the ground. This might increase the accuracy of the algorithm.

The Particle Swarm Optimization algorithm provides optimization, but requires a lot of computations for reliable results. Some gateways are positioned at questionable positions, probably due to the reliability of the Particle Swarm Optimization algorithm on chance. More research can be done to improve the implementation of the PSO algorithm. Besides, the implementation of other algorithms can be tested. Algorithms such as the clustering method described in Section 3, might give more consistent results.

8 Conclusion

This research shows the development of an algorithm that determines the optimal position and orientation of BLE gateways such that coverage area inside an airplane hangar is maximized. The algorithm estimates the range of an individual gateway, based on the Link Budget and Log Distance Path Loss model. The optimal gateway setup is determined via a Particle Swarm Optimization algorithm.

The use of the Particle Swarm Algorithm is logical since the problem that requires minimization is represented by a discontinuous objective function. The algorithm relies on particles to find the minimum 'by chance'. This chance is increased if more particles are used, but this also increases computation power. Any future research could dive into the use of other algorithms to solve the minimization problem, such as clustering.

The research fills the gap in the existing literature by providing an algorithm that describes optimal BLE gateway deployment in the aviation industry. Moreover, the use of the algorithm can be extended, since the Link Budget and Log Distance Path Loss models are not limited to use in BLE scenarios only. The method used in this research can thus be easily adapted. As a result, this methodology can be applied to various indoor environments and other communication systems.

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9 Appendix

9.1 Supplementary figures

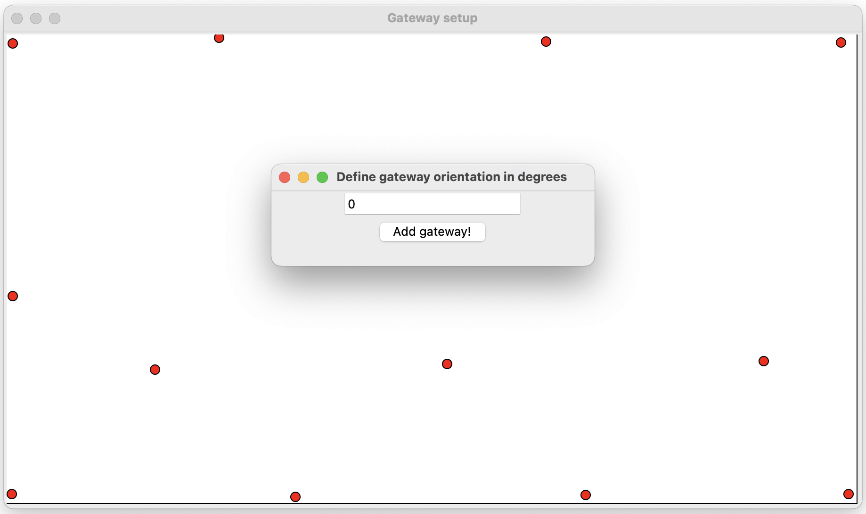

Figure 16: GUI that allows to manually position the gateways by clicking within the simulation area. The gateways are displayed as red circles.

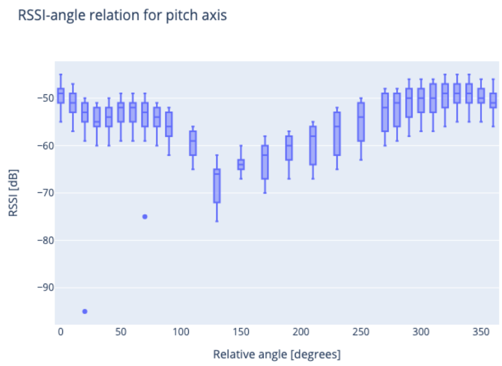

Figure 17: RSSI-angle dependency plotted for various angles along pitch axis. See Figure 9 for definitions of axes.

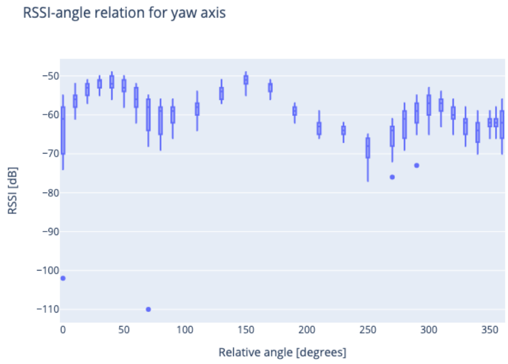

Figure 18: RSSI-angle dependency plotted for various angles along yaw axis. See Figure 9 for definitions of axes.

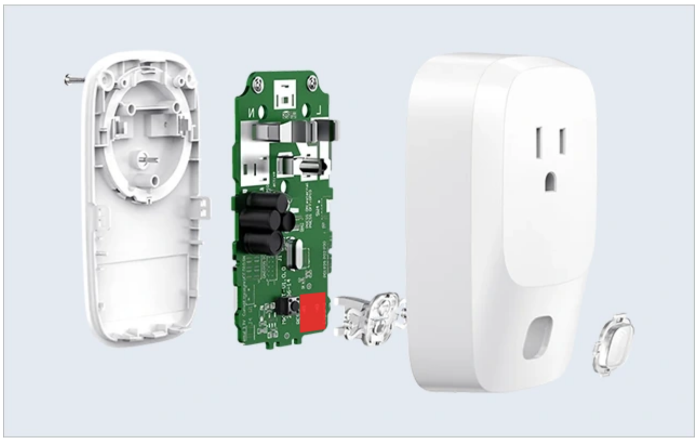

Figure 19: Hardware overview of Moko MK107 gateway, the WiFi-BLE antenna is located on the backside of the PCB, at the red marked position. Adapted from [1].

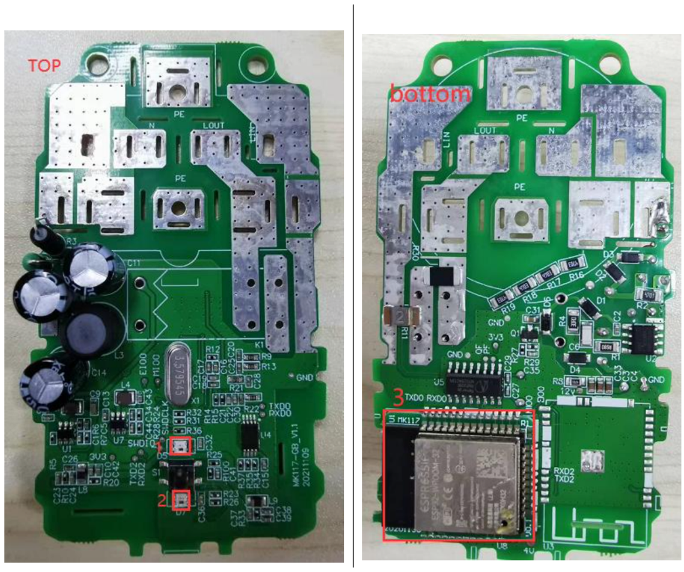

Figure 20: PCB overview of the Moko MK107. Adapted from [1].

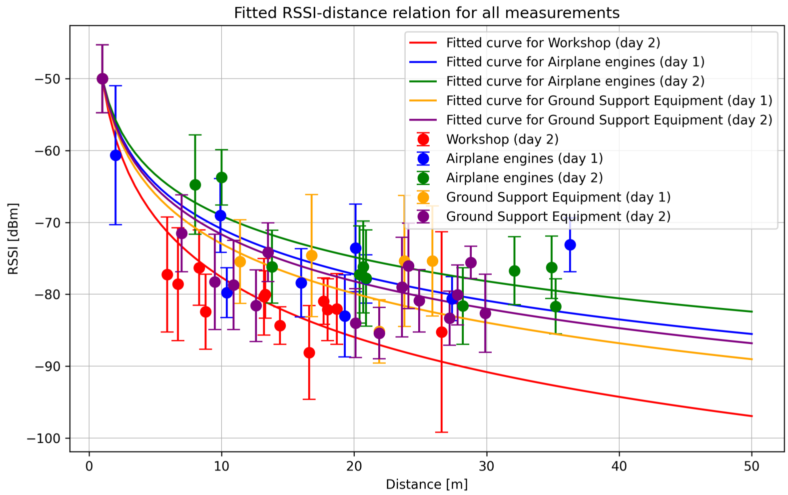

Figure 21: All fitted RSSI -Distance models in one figure.

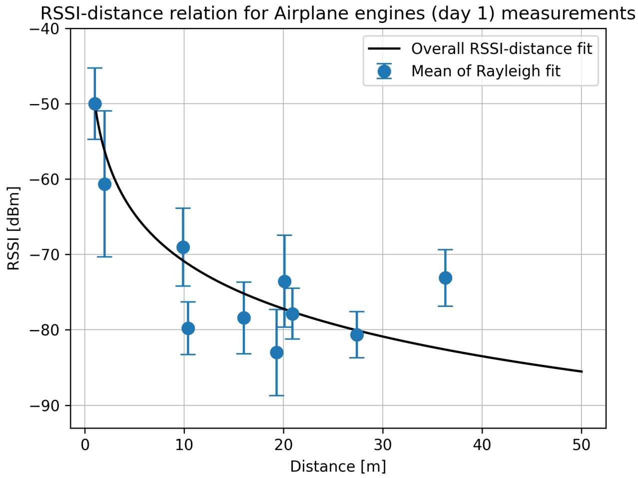

Figure 22: Fitted RSSI distance relation by using the individual Rayleigh fit of all distance measurements.

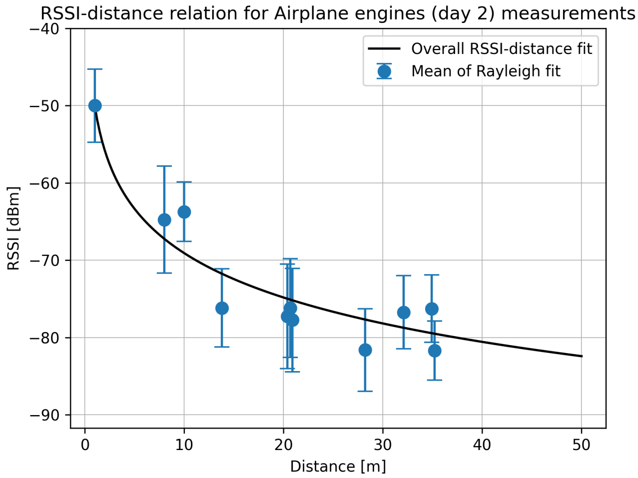

Figure 23: Fitted RSSI distance relation by using the individual Rayleigh fit of all distance measurements.

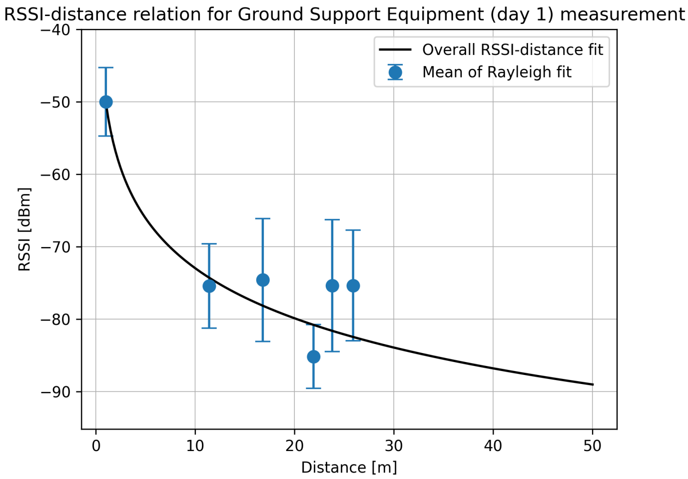

Figure 24: Fitted RSSI distance relation by using the individual Rayleigh fit of all distance measurements.

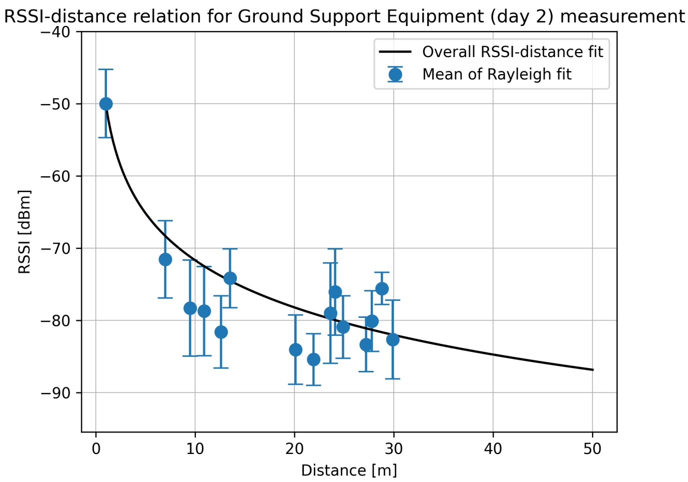

Figure 25: Fitted RSSI distance relation by using the individual Rayleigh fit of all distance measurements.

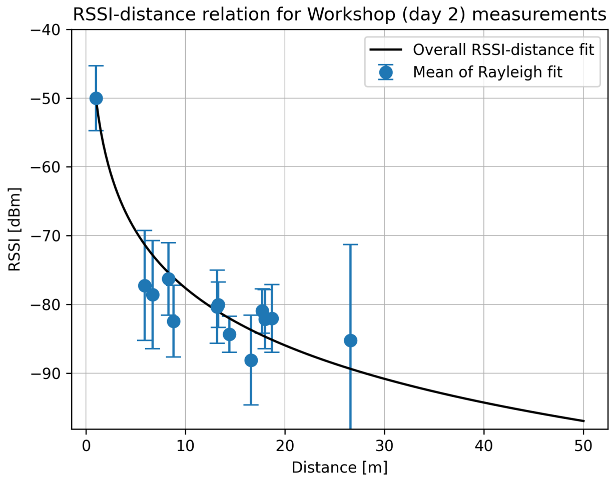

Figure 26: Fitted RSSI distance relation by using the individual Rayleigh fit of all distance measurements.

9.2 Figures

Figure 27: Example of obstacles in zone B (Ground Support Equipment)