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APtlas: A Tool For Visual Assessment of Wireless Network Coverage

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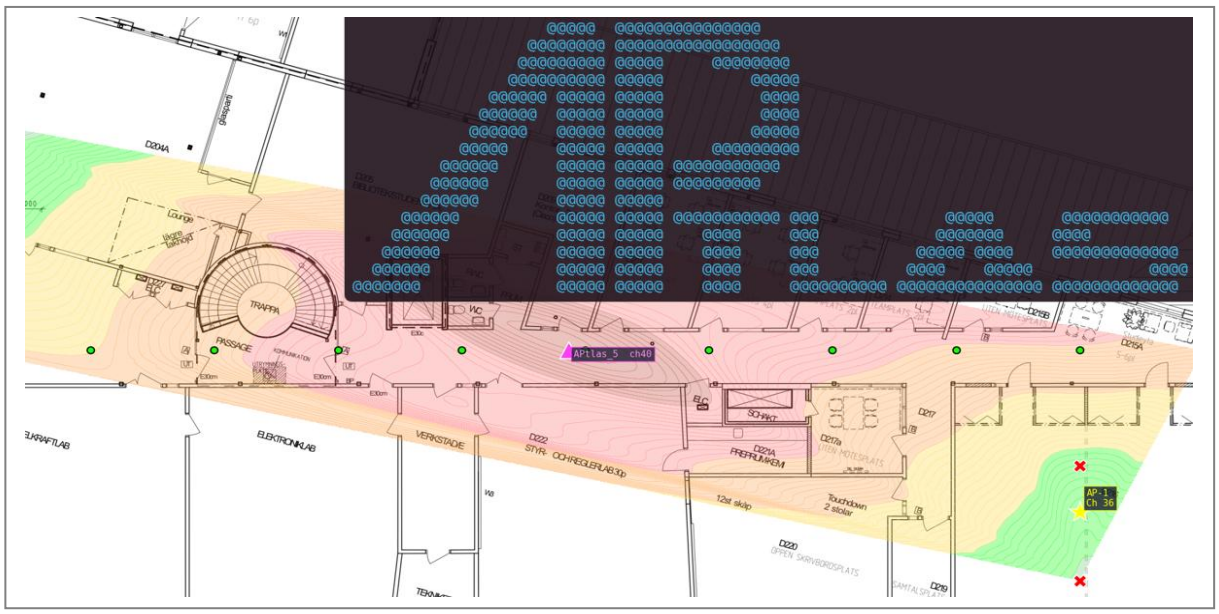

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Computer Engineering
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EXAMENSARBETE

APtlas: Ett Verktyg För Visuell Täckningsanalys av Trådlösa Nätverk

Sammanfattning

Detta examensarbete undersöker om ett egenutvecklat verktyg visuellt och pålitligt kan bedöma om täckningen av ett trådlöst nätverk uppnår definierade kriterier för optimal täckning. Arbetet bygger vidare på ett tidigare arbete av samma författare, där ett enklare RSSI-baserat heatmap-verktyg utvecklades. Både verktyget och dess omfattning vidareutvecklas för att åtgärda det tidigare arbetets begränsningar.

Optimal täckning definieras utifrån tre kompletterande mätvärden: ett minsta RSSI-värde på -67 dBm, ett minsta SNR-värde på 25 dB och kanalval som undviker kanalinterferens. Signalutbredning modelleras efter ITU-R P.1238:s ”site-general” modell där miljöspecifika koefficienter används för korridor- och kontorsmiljöer. En ”Greedy Set Cover”-algoritm används för att identifiera täckningsbrister och föreslår accesspunktsplaceringar för att åtgärda dem, med kanalindelning som sker samtidigt.

Verktyget består av fyra moduler: en gridmap-byggare för att definiera mätpunkter på en planritning, en skanner för insamling av RSSI-, SNR- och kanaldata i ”monitor mode”, en heatmap-generator för visualisering av uppmätt signalstyrka och en optimeringsalgoritm för förslag på accesspunktplacering. Mätningar genomfördes med en Raspberry Pi 4B och en extern trådlös nätverksadapter. På grund av hårdvarubegränsningar så genomfördes samtliga mätningar endast på 5 GHz bandet.

Verktyget testades i en korridor på Högskolan Väst med hjälp av tre lånade accesspunkter som konfigurerades till ett dedikerat testnätverk. Skannern bedömde täckningen exklusivt från detta nätverk, men behöll data från samtliga upptäckta accesspunkter för kanalvalshantering. Med utgångspunkt från noll täckning av testnätverket, så uppnådde verktyget full täckning på tre omgångar genom iterativa placeringsförslag. Både RSSI-begränsade och SNR-begränsade punkter identifierades korrekt. Placeringsförslagen validerades genom RMSE-analys med resultat på 4,62, 4,11 och 4,86 dB. Resultaten låg inom eller nära det förväntade avvikelseintervallet för ”site-general” modellen. De visar att verktyget visuellt och tillförlitligt kan bedöma trådlös nätverkstäckning med hjälp utav flera kvalitetsmått.

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DEGREE PROJECT

APtlas: A Tool For Visual Assessment of Wireless Network Coverage

Abstract

This project investigates if a self-developed tool can visually and reliably assess whether a wireless network meets defined optimal coverage criteria. It builds upon a previous project by the same authors, which produced a basic RSSI-based heatmap tool. This project extends both the tool and its scope to address the predecessor's limitations.

Optimal coverage is defined using three complementary metrics: a minimum RSSI of -67 dBm, a minimum SNR of 25 dB and channel assignments that avoid channel interference. Signal propagation is modelled using the ITU-R P.1238 site-general model, with environment-specific coefficients for corridor and office zones. A Greedy Set Cover algorithm identifies coverage deficiencies and suggests AP placements to resolve them, with simultaneous channel assignment.

The tool consists of four modules: a grid map builder for defining measurement points on a floor plan, a scanner for capturing RSSI, SNR and channel data in monitor mode, a heatmap generator for visualizing measured signal strength and an optimization algorithm for suggesting AP placements. Measurements were conducted using a Raspberry Pi 4B with an external WNIC. Due to hardware limitations in noise measurement on the 2.4 GHz band, all surveys were exclusively conducted on the 5 GHz band.

The tool was tested in a university corridor using three borrowed APs configured as a dedicated test network. The scanner assessed coverage exclusively from this network while retaining all detected surrounding networks for channel assignment awareness. Starting from zero test network coverage, the tool's iterative placement suggestions achieved full coverage in three rounds, correctly identifying both RSSI-limited and SNR-limited points. The propagation model's predictions were validated through RMSE analysis, yielding results of 4.62, 4.11 and 4.86 dB across the three iterations. The results were within or near the expected deviation range of the site-general model. These results demonstrate that the tool can visually and reliably assess wireless network coverage using multiple quality metrics.

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Preface

The work was divided based on the strengths of each author. Alexander Oprea was primarily responsible for the thesis writing and the gridmap and algorithm modules. Joel Bäckrud was primarily responsible for the heatmap and scanner modules, the driver modification for SNR measurement and the tool's system integration. Both authors contributed to the overall design, testing methodology and measurement campaigns.

We would like to thank our advisor Hani Alid for his guidance on structure, technical feedback and for lending us three Access Points from the university. We also thank Dr. Tudor I. Oprea for helping us crystallize the project's direction and our friend Burkay Akan for verifying our mathematical formulations.

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List of Abbreviations

AP – Access Point
BPF – Berkeley Packet Filter
BSSID – Basic Service Set Identifier
CCK – Complementary Code Keying
CLI – Command Line Interface
CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance
DS – Distribution System
EIRP – Effective Isotropic Radiated Power
FSPL – Free Space Path Loss
GUI – Graphical User Interface
HT – High Throughput
IEEE – Institute of Electrical and Electronics Engineers
ITU-R – International Telecommunication Union – Radiocommunication Sector
JSON – JavaScript Object Notation
LoS – Line of Sight
NIC – Network Interface Card
NLoS – Non-Line of Sight
OFDM – Orthogonal Frequency Division Multiplexing
PIL – Python Imaging Library
RF – Radio Frequency
RGB – Red Green Blue
RLAN – Radio Local Area Network
RMSE – Root Mean Square Error
RSSI – Received Signal Strength Indicator
SNR – Signal-to-Noise Ratio
SSH – Secure Shell
SSID – Service Set Identifier
USB – Universal Serial Bus
WNIC – Wireless Network Interface Card
WLC – Wireless LAN Controller
WLAN – Wireless Local Area Network

1 Introduction

Wireless connectivity has become a fundamental part of everyday life, from personal devices to industrial systems. Inter-device communication occurs over both wired and wireless mediums, with wireless becoming the preferred means of access for end-user devices due to its convenience [1]. Consequently, wireless networks that are both reliable and cost efficient have become an ideal that network administrators strive towards. However, achieving this ideal requires careful consideration of several factors: signal propagation, channel assignment and both the placement and quantity of access points (APs) [2]. Balancing these factors while maintaining reliable coverage is a non-trivial task.

Commercial tools that assist with network planning and optimization already exist, such as Netspot [3] and Ekahau [4]. These tools suggest AP placements with respect to specific infrastructure and architecture, providing coverage assessment through heatmap visualization. However, they are primarily designed for enterprise use, making them financially inaccessible for consumers, small businesses and academic environments.

In a previous project, the authors developed a tool that visualizes the coverage of wireless APs using a heatmap that changes hue based on received signal strength (RSSI). [5] This was done in order to analyze whether an existing wireless network environment on campus was optimal. However, this analysis was one-dimensional, relying entirely on using RSSI as the sole indicator of wireless network coverage quality. Signal quality factors such as noise interference and channel conflicts were not assessed, leaving the broader network environment unevaluated [5].

This project aims to extend the capability of the previous tool considerably by taking additional coverage metrics into account: Signal-to-Noise Ratio (SNR) and channel assignment analysis. Optimal coverage is defined as RSSI above -67 dBm [6], SNR above 25 dB [7] and channel assignments that avoid channel interference [8]. Together, these three criteria provide a more comprehensive assessment of whether a wireless network truly delivers reliable coverage. Based on this assessment, the tool also suggests new AP placements to resolve identified coverage deficiencies. This project aims to answer the following question: Can a self-developed tool visually and reliably assess whether a wireless network meets defined optimal coverage criteria?

To evaluate the tool's reliability, a controlled test environment was created in a corridor on University West's campus using three borrowed APs configured with a dedicated SSID. Starting from zero test network APs active, APs were iteratively placed based on the tool's suggestions. Each placement was followed by a new measurement survey, with the tool re-evaluating coverage after each addition. The tool's assessment was validated by comparing its predictions against real measurements at each step, with total prediction accuracy quantified using Root Mean Square Error (RMSE).

2 Background

This chapter introduces the technical concepts necessary to understand the methodology. The concepts are divided into three sections: Wireless Networking Concepts, Radio Propagation Concepts and Algorithm Concepts. Following the concept sections, the Development Platform section introduces the Raspberry Pi 4B microcomputer, Monitor Mode and Radiotap.

2.1 Wireless Networking Concepts

2.1.1 Access Points

APs are networking devices that enable wireless clients to connect to a network, as they act as a bridge between the wireless clients and the wired network [9]. APs can operate in a multitude of different modes which are best suited for different environments [10]. In large network environments such as universities, hospitals and airports, APs don't act as standalone devices. One or multiple WLCs can manage hundreds of APs. The benefit of this central management architecture is that all of the APs will have the same configuration, including SSID [11]. This is intentional, as the goal of a large wireless network with many APs, is for the end-user to have a pleasant user experience when roaming between different parts of a building without noticing the handover that occurs between APs in the background [12], [13].

2.1.2 Beacon Frames

Beacon frames are a type of frame that is periodically sent out by APs to advertise themselves and their wireless networks to listening devices within their vicinity. The information that these advertisements include about their AP is: SSID, BSSID and Channel assignment information [14]. These values are vital for quantifying the performance of a wireless network environment.

2.1.3 Wi-Fi Frequencies and Channels

The two traditional frequency ranges used in Wi-Fi are known as the 2.4 GHz band and the 5 GHz band. The 2.4 GHz band lies between 2.400 and 2.4835 GHz, while the 5 GHz band lies between 5.150 and 5.825 GHz. The exact frequency within each band used for communication is sorted into channels. These channels are slices of the band which have been divided up for accessibility [15]. In modern networks, it is common for both bands to be deployed simultaneously, with devices connecting to the band that offers the best performance relative to their location [16].

The 2.4 GHz band consists of 13 channels in Europe; each spaced 5 MHz apart. The standard bandwidth of a 2.4 GHz Wi-Fi signal is 20 MHz wide. Consequently, the 2.4 GHz band only has three non-overlapping channels; 1, 6, and 11. While all channels overlap to some degree in theory, this overlap is considered negligible in practice unless it demonstrably affects networking performance [17].

In contrast, the 5 GHz band has significantly more non-overlapping channels available, making it more suitable for dense deployments where many APs operate in close proximity [16]. In Sweden, the permitted and widely adopted 5 GHz channels fall within two EU defined bands: RLAN 1 (divided into two sub-bands) and RLAN 2 [18].

Table 1. Widely Used 5 GHz Channels in Sweden

Band	**RLAN 1 Sub-Band 1**	**RLAN 1 Sub-Band 2**	**RLAN 2**
Channel	36, 40, 44, 48	52, 56, 60, 64	100, 104, 108, 112, 116, 120, 124, 128, 132, 136, 140, 144*

*Channel 144 is not widely adopted or implemented in hardware/software in Sweden.

The reason for the change in geographic scope when listing permitted channels for 2.4 GHz (Europe) and 5 GHz (Sweden) is due to a difference in practical adoption rather than regulatory requirements. Although Sweden follows EU regulatory standards, the final channel of the RLAN 2 band (Channel 144*) is not widely implemented in hardware or software in Sweden [18].

2.1.4 Received Signal Strength Indicator

Received Signal Strength Indicator (RSSI) measures the strength of the signal a client device receives from an AP and is measured in decibel milliwatt (dBm). A higher dBm value indicates a stronger connection, due to the received signal being stronger. Below is a table which serves to illustrate different RSSI values and an estimated minimum threshold needed for a service to be usable [6].

Table 2. RSSI Levels Vs Service Usability Thresholds [6]

Signal Strength	**Notation**	**Minimum Requirement**
-30 dBm	Essentially maximum signal strength.	
-50 dBm	Excellent signal strength.	
-60 dBm	Still good signal strength.	
-67 dBm	Minimum level required for services that require smooth and reliable data traffic.	VoIP, Video streaming (acceptable quality)
-70 dBm	Somewhat insufficient signal strength, enough for simpler web services.	Web, email, etc.
-80 dBm	Minimum value required to establish a connection. Most services are unusable at this level.	
-90 dBm	Very unlikely to be able to connect or make use of any services at this level.	

2.1.5 Signal-to-Noise Ratio

While RSSI measures the strength of the received signal, it does not account for the presence of background noise. The Signal-to-Noise Ratio (SNR) measures the signal quality relative to the noise floor [19]. The noise floor refers to the level of unwanted signals present in the environment. Any signal below this level will be indistinguishable from the noise which makes it difficult or impossible to detect [20].

SNR is expressed in dB as:

$$SNR(dB) = RSSI(dBm) - Noise\ Floor(dBm)$$

Below is a table that shows the SNR along with an indicator of the signal quality at the aforementioned SNR.

Table 3. SNR vs Wireless Signal Quality [7]

SNR (dB)	Signal Quality
≥ 25 dB	Sufficient for data and voice
20 – 24 dB	Sufficient for data only
< 20 dB	Insufficient

For the purposes of this project, a minimum SNR of 25 dB is used as the threshold for determining sufficient signal quality as it is the minimum requirement for networks which support voice and high bandwidth applications [7]. However, even a sufficient SNR fails to account for interference introduced by neighboring APs which operate on the same or adjacent channels.

2.1.6 Channel Interference

There are two types of wireless channel interference, co-channel interference and adjacent channel interference. Co-channel interference is interference which occurs on the same channel. Adjacent channel interference is interference which occurs on adjacent or partly overlapping channels. Neither forms of interference are observable when simply looking at RSSI or SNR values, which is why considering it is a necessity when analyzing wireless network environments [8].

In order to avoid collisions, APs must take turns before transmitting data. This is enabled by the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Collisions are avoided by listening for a pre-specified amount of time to determine if another AP is transmitting on the same channel [21].

Due to the 2.4 GHz band only having 3 non-overlapping channels (1, 6 and 11) [17], any 2.4 GHz deployment with more than three APs will inevitably have channel reuse. However, this can be mitigated with proper channel assignment that ensures overlapping APs use non-overlapping channels. For this reason, channel assignment is considered alongside RSSI and SNR when evaluating the wireless network environment.

2.2 Radio Propagation Concepts

2.2.1 Free Space Path Loss

Free Space Path Loss (FSPL) is the decrease in signal strength of a radio wave as it travels between two antennas due to the signal spreading out. It is a logarithmic function of distance and frequency, with signal strength falling off quickly near the point of origin and more gradually as it propagates [15]. While FSPL is a valuable foundation, because it assumes free space conditions, it cannot be directly applied to indoor environments that contain obstacles. This necessitates the use of models that build upon FSPL while incorporating additional environmental factors.

2.2.2 Basic Transmission Loss Model

According to ITU-R P.1238, there are two types of basic transmission loss models, commonly referred to as path loss models, site-general and site-specific ones. The former is designed to be widely applicable in different environments while requiring less input of specific data. In contrast, the site-specific model requires prior knowledge of the environment's exact geometry and material makeup [2].

The site-general model will serve the purpose of the tool that is built in this project well. This is because the tool is meant to be usable in many different environments, as opposed to just the testing environment used in this project. If the application requirements were different, a site-specific model would have been more appropriate.

The median basic transmission loss is given by [2]:

$$L_b(d, f) = 10\alpha \log_{10}(d) + \beta + 10\gamma \log_{10}(f) \quad \text{dB}$$

d: Distance between the transmitting and receiving stations (m)

f: Operating frequency (GHz)

α: Coefficient associated with the increase of basic transmission loss with distance.

β: Coefficient associated with the offset value of the basic transmission loss.

γ: Coefficient associated with the increase of basic transmission loss with frequency.

N: Since the site-general model is meant to represent a statistical average, deviation in real-world environments is acknowledged through an additive Gaussian random variable that isn't calculated, but which serves as a statistical description of uncertainty. Its standard deviation is σ, which indicates that while individual measurements may vary, the model itself carries no systematic bias in either direction.

The standard provides recommended values for α, β and γ for various indoor environments, including residential, office and corridor settings [2].

2.3 Algorithm Concepts

2.3.1 Greedy Set Cover

The Set Cover problem involves finding the minimum number of sets required to cover all elements of a given space. A Greedy algorithm takes in the entirety of a space and identifies the position of the point that would cover the greatest number of points not yet covered. It then marks those points as covered before repeating the process until the entire space is covered [22]. While this algorithm does not produce a perfect solution, it produces an acceptable solution quickly and efficiently. This is ideal when the computational power of the Raspberry Pi 4B is taken into consideration. Greedy algorithms have previously been applied to AP placement optimization where RSSI thresholds were used as coverage criteria [23].

2.3.2 Coverage Threshold Framework

A greedy algorithm has many applications; in this project it is used within a coverage threshold framework. Each point of measurement that is used to determine optimal AP placement is evaluated against minimum criteria rather than optimizing for maximum performance. This binary pass/fail evaluation is consistent with threshold satisfaction models previously applied to AP placement optimization [23].

2.3.3 Root Mean Square Error

Root Mean Square Error is a measure of the difference between a model's predicted values and the values observed in reality. A lower RMSE value is indicative of greater prediction accuracy [24].

In the context of propagation model validation, the formula for calculating RMSE is given by [25]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}$$

x_i: Measured signal strength at point i (dBm)

y_i: Predicted signal strength at point i (dBm)

n: Number of measurement points

In this project, RMSE is used to quantify the accuracy of the algorithm's propagation model and its predictions by comparing the predicted signal strength values against real measurement values collected during network surveys.

2.4 Development Platform

2.4.1 Raspberry Pi 4B

The Raspberry Pi 4B is a microcomputer which is ideal for computational tasks where a laptop or desktop PC is excessive in power. It is commonly used in embedded networking applications due to its small form factor and support for external USB devices such as external WNICs [26].

2.4.2 Monitor Mode

As Beacon Frames are advertisements sent to all wireless clients, they are invisible to WNICs operating in standard mode. This is because traffic that isn't specifically destined for the device's WNIC is discarded. Monitor Mode is a mode of operation in which a WNIC is instead able to listen to all wireless network traffic transmitted within its range, regardless of the frame's destination [27].

2.4.3 Radiotap

Radiotap is a metadata header used in monitor mode packet captures to provide additional information about received wireless frames. This metadata is not part of the original IEEE 802.11 frame itself, but is added by the wireless adapter and driver before the frame is passed to packet capture software. Examples of Radiotap metadata include channel frequency, data rate, RSSI, and, when supported, noise or signal quality information [28].

In this project, Radiotap metadata is used to extract measurement values needed for the network survey, including RSSI, channel information and noise values used for SNR calculation. However, the exact metadata exposed through Radiotap depends on the wireless adapter and driver, meaning that not all adapters expose the same measurement fields.

3 Methodology

This chapter describes the experiment methodology that is used to evaluate wireless network coverage and suggest improvements. The approach starts by defining optimal coverage criteria, building a wireless network from scratch and then measuring its performance. An optimization algorithm makes improvement suggestions based on the collected data to resolve coverage gaps. These suggestions are then implemented, after which the coverage of the wireless network is assessed to see if it fulfills the optimal coverage criteria.

3.1 Defining Optimal Coverage

Based on the concepts established in sections 2.1.4, 2.1.5 and 2.1.6, optimal coverage in this project is defined by the following three complementary metrics:

- Every point in the measured space achieves a minimum RSSI of -67 dBm
- Every point achieves a minimum SNR of 25 dB
- No two overlapping APs share the same or adjacent channels.

A minimum RSSI of -67 dBm is widely recognized as the threshold for reliable high bandwidth applications such as VoIP and video streaming [6]. While RSSI ensures sufficient signal strength, an SNR of 25 dB or higher is recommended for networks supporting voice and high bandwidth applications, as a strong signal in a noisy environment can still result in poor performance [7]. Finally, no two overlapping APs sharing the same or adjacent channels is essential for mitigating channel interference [8], which the two former metrics do not account for.

3.2 Indoor Propagation Model

The basic transmission loss is calculated using the site-general model described in section 2.2.2. The formula is given by [2]:

$$L_b(d, f) = 10\alpha \log_{10}(d) + \beta + 10\gamma \log_{10}(f) \quad \text{dB}$$

To maintain applicability across different building types, the tool accepts multiple environment classification as input. Depending on the classification, the corresponding α, β and γ coefficients are applied to the propagation model. This eliminates the need for environment-specific calibration. The environment classifications used in this project are Corridor and Office. The model also includes a zero-mean Gaussian random variable N (0, σ) to represent prediction uncertainty. The different coefficient and σ values are listed in Table 4.

3.3 Testing Environment

The test environment used in this project is a straight corridor on campus that contains existing network infrastructure which remains active during testing. The existing infrastructure is treated as an immutable environmental factor and the algorithm accounts for this while not attempting to modify it. Within it, a dedicated test network is created using three ZyXEL NBG6815 APs supplied by University West. The scanner captures beacon frames from all wireless networks present in the environment. Coverage assessment is performed exclusively against the test network's SSID while channel assignment considers all detected APs regardless of network affiliation. This allows the algorithm to be evaluated from a baseline of zero coverage through full coverage.

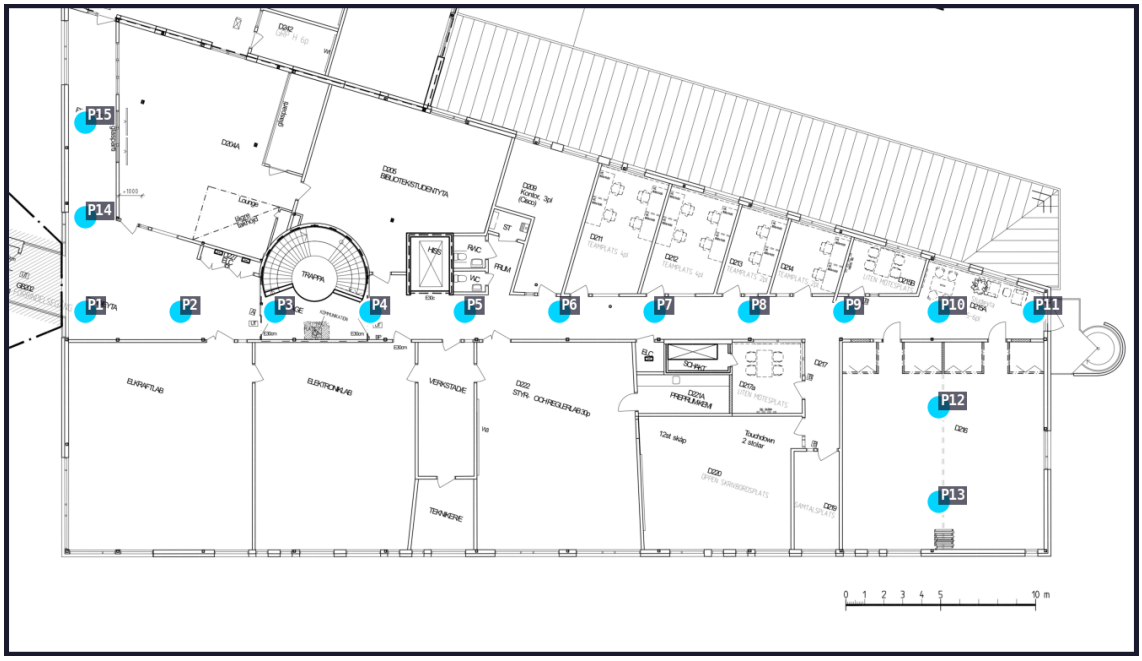

Figure 1: Annotated Floor Plan Showing Numbered Measurement Point Locations (Blue)

As shown in Figure 1, the corridor is flanked by office and laboratory rooms on each side which divide the environment into two distinct spatial zones. For the purposes of this project, measurements outside the corridor were taken in a laboratory room, classified as an office environment, as ITU-R P.1238 does not define separate coefficients for laboratory rooms and the office environment is the closest available match. The zone that is used during measurements is determined by the zone of the measurement point, with the corresponding coefficients applied per zone. Corridor coefficients are used for measurements taken within the corridor, while office coefficients are applied for measurements taken in the laboratory room. Measurements are either classified as Line of Sight (LoS) or Non-Line of Sight (NLoS), depending on whether a direct signal path exists between the AP and measurement point.

Table 4. Relevant ITU-R P.1238 Coefficient Values [2]

Environment	LoS/NLoS	Frequency Range (GHz)	α	β	γ	σ
Corridor	LoS	0.3-300.0	1.57	29.46	2.24	3.77
Corridor	NLoS	0.625-159.0	2.78	28.62	2.54	7.58
Office	LoS	0.3-294.0	1.47	34.17	2.08	3.68
Office	NLoS	0.3-255.0	2.39	30.13	2.40	5.01

While the tool supports both 2.4 GHz and 5 GHz, all surveys in this project were exclusively conducted using the 5 GHz band due to hardware limitations described in section 3.4.3. The 5 GHz operating frequency falls within the valid frequency ranges for all four environments in Table 4.

The distance ranges for office environments (2-27m LoS, 4-30m NLoS) are notably shorter than those for corridor environments (2-160m LoS, 3-94m NLoS)[2]. The shorter ranges for office environments may therefore limit the model's accuracy for larger office spaces. Initially, most measurements taken within the corridor were classified as LoS, while measurements taken around the corner or in a laboratory room were classified as NLoS. However, this changed when newly suggested APs were placed within a point's vicinity. The standard deviation σ represents the expected spread of real measurements around the model's predicted value, as established in section 2.2.2. In the validation phase, deviations between predicted and measured values are expected to fall within this range.

The floor plan image's scale factor was determined by measuring the pixel distance between tick marks on the unedited version of figure 1's embedded scale bar. With all non-essential layers hidden, the tick marks at 0, 5 and 10 meters were identified at pixel positions of 3584.5, 3879.5 and 4174.5 respectively, yielding a consistent spacing of 295 pixels per 5 meters. This produced a scale factor of 0.016942 meters per pixel. The floor plan used for testing was a cropped region of the full architectural drawing; as cropping does not alter pixel density, the scale factor applies unchanged. The scale factor was used throughout the tool to convert pixel distances to meters in the propagation model's path loss calculations, the algorithm's coverage radius evaluation and the RMSE validation in Appendix C.

3.4 Testing Procedure

The testing procedure follows an iterative approach using the dedicated test network configured with the SSID "APtlas_5" across all three borrowed APs. Starting with no test network APs active while filtering for it, a baseline survey established the ambient environment with the target network absent. Because no coverage data existed at this stage, the algorithm was operated in baseline mode. The first suggested AP was positioned at the center of the measured area on a channel that was determined to avoid conflict with existing networks detected during the baseline survey.

Figure 2: AP-1 Placed

After the suggested AP was placed, a new survey was conducted, and the algorithm was switched to operate in normal mode. This evaluated against the coverage criteria and suggested further placements to resolve remaining deficiencies. This cycle was repeated a total of three times not counting the baseline survey, until the algorithm reported that all measurement points met the optimal coverage criteria defined in section 3.1. After each iteration, the algorithm's primary suggestion was exported into a copy of the grid-map JSON for use in the next survey, alongside an updated placement reference image that showed the suggested position on the floor plan.

3.4.1 Testing Setup

The testing setup consists of a Raspberry Pi 4B, an A7000 Netgear Nighthawk AC1900 which operates in Monitor Mode and three ZyXEL NBG6815 APs supplied by University West. A Samsung Galaxy S8 is used to interact with the scanner to start surveying, but as its role is nonexistent beyond this, it isn't technically part of the testing setup. The architecture and justification for these hardware choices are described in section 4.2.

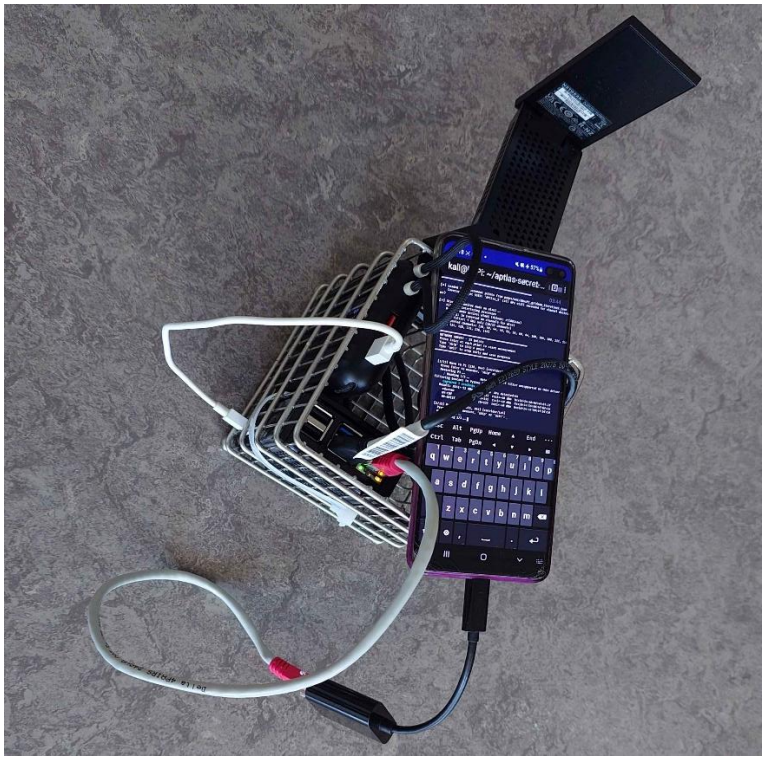

Figure 3: Measurement Device

3.4.2 Network Survey

The network survey consists of taking repeated measurements across the entire testing environment. Measurement points were placed approximately 5 meters apart, positioned manually using the grid map builder's 1-meter snap grid as a visual aid for consistent spacing.

Beacon frames are captured to gather RSSI values and channel assignment information. A survey is conducted after each new AP is placed, producing an updated heatmap for each iteration. The scanner's SSID filtering and band selection implementation is described further in section 4.3.2, while Figure 2 shows the start of the iteration 3 survey.

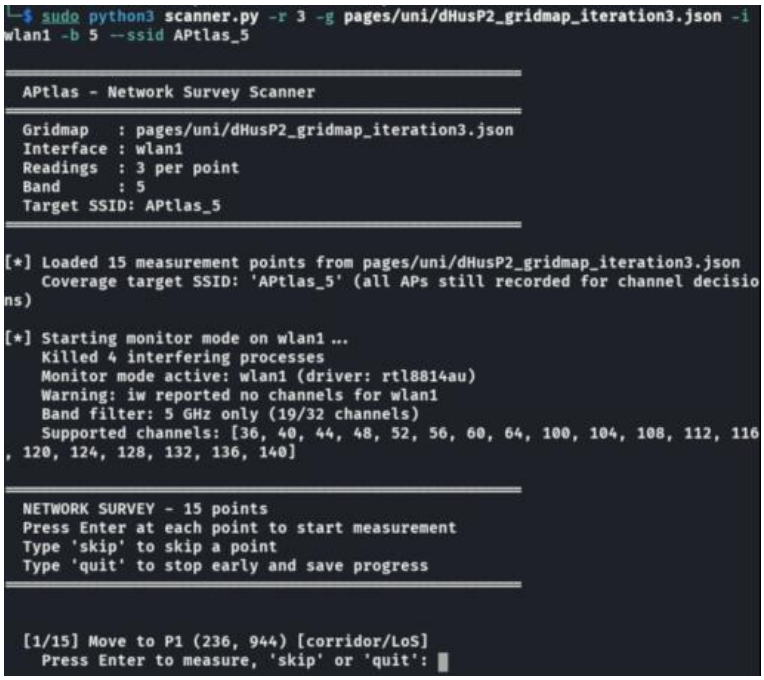

Figure 4: Iteration 3 Network Survey Start

3.4.3 SNR Measurement Rationale

SNR measurement requires access to noise floor data which is exposed through Radiotap metadata in monitor mode. The availability of this metadata depends on the wireless adapter and its driver. The A7000 WNIC was selected for this purpose, as described in section 3.4.1.

Valid noise values are only available for frames transmitted using Orthogonal Frequency Division Multiplexing (OFDM)-based modulation, while legacy Complementary Code Keying (CCK) frames do not expose equivalent metadata. Because CCK-modulated frames may still be used in 2.4 GHz networks, these frames are still used for AP identification and RSSI mapping but are excluded from noise and SNR calculations. This hardware limitation is acknowledged as a source of measurement error (section 3.4.5) and informed the decision to support band-restricting surveying. A 5 GHz survey ensures all captured frames use OFDM and therefore produce SNR data. If no valid noise data can be captured, the optimization algorithm falls back to only considering RSSI values.

3.4.4 Measurement Precautions

To ensure that measurements are as standardized as possible, the following precautions were taken:

- Each point on the heatmap was measured three times, with the reported measurement values being an average of the three runs. This was done to ensure accurate measurement values.
- Measurements were taken at the same time of day and during low traffic periods to minimize population variation.
- The height of the Raspberry Pi and suggested APs were kept at the same height level during measurements as variations in height introduce performance inconsistencies.
- Time between measurement runs was kept as short as possible to minimize environmental drift.
- The same Raspberry Pi 4B, WNIC and measurement program was used to eliminate possible device specific inconsistencies.
- Settings such as transmit power, channel and band selection were kept identical across all runs and borrowed APs.

3.4.5 Sources of Measurement Error

Despite the measures taken to ensure consistency between measurements, there are certain factors that are outside of the authors' control. These are acknowledged as problematic:

- All surveys were restricted to the 5 GHz band due to the A7000 WNIC being unable to produce reliable noise values on 2.4 GHz CCK-modulated frames.
- Due to noise being observed by the receiving adapter on the tuned channel rather than being specific to an SSID, valid noise samples were treated as channel-level measurements. If no valid noise value was available for a channel at a measurement point, the SNR value was estimated using the closest available valid noise measurement from the same frequency band, where applicable. If no suitable nearby measurement was available, a conservative estimated noise value was used.
- The laboratory room used for measurements was classified using the office environment coefficients, as ITU-R P.1238 does not define separate coefficients for laboratory rooms. Differences in room geometry or material composition between a typical office may affect the prediction accuracy at those points.
- Other wireless devices and networks present in the environment naturally contribute to the noise floor. This creates an element of external signal interference.
- Multipath variation refers to reflections of radio signals that change slightly as conditions shift. The σ coefficient is meant to take this into account [2], but it is not infallible.

- The addition of new APs to the environment may affect the noise floor at nearby measurement points, potentially causing marginal SNR values to cross the coverage threshold between surveys.
- The presence of human bodies, even if just the authors, has an impact on measurement values. Slight, but natural position variation of the aforementioned during measurements is to be expected, but not inconsequential.

3.5 Optimization Algorithm

A Greedy Set Cover algorithm is used to suggest AP placements that resolve coverage deficiencies. The algorithm takes the measurement grid from the network survey as input, along with each point's RSSI, SNR, environment classification and channel assignment information. A Greedy algorithm was chosen due to its computational efficiency, with the Raspberry Pi 4B in mind and because of its previous use in AP placement optimization [23].

The algorithm has two modes of operation: baseline mode and normal mode. Baseline mode is used before the test network is deployed and it suggests a single starting AP in the center of the measured area on a channel that is chosen to avoid conflicts with the ones detected from other networks during the baseline survey. In normal mode, the algorithm follows a greedy set cover approach, evaluating candidate AP positions against uncovered measurement points and iteratively placing APs until all points meet the coverage criteria defined in section 3.1.

As candidate APs have no predictable SNR, candidate coverage is evaluated on predicted RSSI alone. The propagation model only outputs predictions for RSSI, not SNR. Applying a point's measured SNR to a hypothetical AP would be incorrect, and without this separation, points heard with poor measured SNR would be considered unreachable by any suggested AP, causing the algorithm to terminate prematurely. A point with poor measured SNR is correctly identified as uncovered, but the algorithm is permitted to suggest an AP to improve it.

The algorithm follows a coverage threshold approach, placing APs until all points fulfil the criteria rather than attempting to find a mathematically optimal global solution. Each candidate is also confined to a maximum coverage radius to prevent the model's optimistic long-range predictions from crediting a single AP with covering the entire floor plan. The implementation details are described in section 4.3.5.

3.5.1 Channel Assignment

Channel assignment and AP placement occur simultaneously, as the two decisions directly influence one another. Each AP is assigned the least conflicting available channel based on the channels assigned to neighboring APs within overlapping range. In 2.4 GHz networks, the algorithm only chooses between channels 1, 6 and 11 as they have

no overlap [17]. In 5 GHz networks, a significantly larger set of non-overlapping channels is available: 36, 40, 44, 48, 52, 56, 60, 64, 100, 104, 108, 112, 116, 120, 124, 128, 132, 136 and 140 [18]. As testing was exclusively conducted on the 5 GHz band, only the 5 GHz channel set was used during evaluation.

3.5.2 Algorithm Limitations

As described in section 2.3.1, the use of a greedy algorithm does not guarantee a perfect solution, only an acceptable one. Each AP is placed based on the current state of uncovered points without reconsidering previous placements. An installed AP's coverage is reflected in the measured RSSI and treated as fixed.

The predicted reach of the propagation model tends to exceed the physical dimensions of the test environment. While the capped coverage radius mitigates this somewhat, the model's predictions remain optimistic within that radius.

In denser 2.4 GHz networks, channel reuse becomes unavoidable when the number of APs required is larger than the three available non-overlapping channels. This limitation is significantly reduced in 5 GHz networks where the larger channel set makes channel interference unlikely at this scale.

Despite these limitations, the results produced by the optimization algorithm were sufficient for the purposes of this project.

4 Results

This chapter describes the tool's requirements, architecture, design and implementation, followed by the testing and evaluation of the finished tool.

4.1 Requirements

The following functional requirements were defined for the tool based on the research question and the methodology described in Chapter 3.

1. The tool shall capture beacon frames from a specified SSID for coverage assessment, and from all surrounding networks for channel assignment awareness.
2. The tool shall record RSSI and SNR at each measurement point
3. The tool shall generate a heatmap overlaid on a floor plan image
4. The tool shall identify measurement points not meeting optimal coverage criteria
5. The tool shall suggest placement positions for new APs if coverage criteria are not met
6. The tool shall assign non-overlapping channels to suggested APs

7. The tool shall support both 2.4 GHz and 5 GHz frequency bands
8. The tool shall export measurement data in a reusable JSON format
9. The tool shall validate suggestions through before/after comparison
10. The tool shall allow the user to define measurement positions on a floor plan image with environment classification per point.

4.2 Architecture Overview

The tool is executed by running the orchestrator module `aptlas.py [29]`, which provides a menu-driven interface with four stages. The scanner module is fully operable via Command Line Interface (CLI), allowing surveys to be conducted over SSH in a headless environment. The remaining modules require a Graphical User Interface (GUI) to display figures and heatmaps. The tool's complete source code and documentation for all modules is available in Appendix A.

Table 5 showcases the pipeline of the four modules, communicating through a shared JSON file.

Table 5. APtlas Pipeline

Stage	Module	Purpose
Stage 1: Build the map and plan the survey	`gridmap.py`	Defines measurement points on a floor plan, with points snapping to a grid.
Stage 2: Survey the map by following the plan	`scanner.py`	Capture RSSI, SNR and channel information per point in monitor mode
Stage 3: Visualize the survey results	`heatmap.py`	Interpolated signal strength map for visualization
Stage 4: Suggest AP placements for points that do not meet optimal coverage criteria	`echidna.py`	Greedy Set Cover AP Placement Suggestions

The JSON file stores the floorplan path, scale factor and measurement point data that includes; coordinates, environment classification, RSSI, SNR and detected AP information. Each stage of operation reads and writes to this one JSON file, ensuring a smooth data flow through the pipeline that does not require direct module-to-module communication. The four stages were also designed to be independently executable for modularity.

A shared directory stores floor plan images and gridmap files together. The floor plan path stored inside each `gridmap.JSON` is resolved relative to the gridmap file's own location rather than the working directory. This is to ensure that the floor plan and its

associated gridmap remain portable regardless of which directory the tool is executed in.

The hardware platform consists of a Raspberry Pi 4B which hosts the tool, the A7000 Netgear Nighthawk AC1900 WNIC in Monitor Mode for RSSI and SNR measurement, and three ZyXEL NBG6815 APs supplied by University West that are used to build the test network. As described in section 2.4.1, its small form factor and I/O options make the Raspberry Pi 4B well suited for hosting embedded networking tools. The external WNIC is connected to the Raspberry Pi via USB and is required for SNR measurement, as the internal WNIC does not support it natively.

4.3 Design and Implementation

This section describes each module and its implementation in the tool's pipeline. The modules are presented in the order of use during a network survey. The source code for all modules described below is publicly available in Appendix A.

4.3.1 Gridmap Module

The grid map builder is implemented in `gridmap.py` and provides an interactive GUI for defining measurement points on a floor plan. Using this, the order of measurement points is predefined before the network survey. The module supports arguments for specifying the floor plan image, image scale factor and grid spacing.

The floorplan is loaded using `PIL` and converted to RGB. The figure size is calculated dynamically to preserve the floor plan's aspect ratio. The user places measurement points or APs, depending on the mode, by clicking on the floor plan. The user can also select environment or LoS condition for each measurement point. Each click snaps to the nearest grid intersection, which ensures alignment to the measurement grid.

On export, two files are produced. The first is a reference floor plan image with measurement points and APs overlaid. Measurement points are numbered in placement order for ease of use, with APs having an optional label. The second file is a gridmap JSON file which stores each point's pixel coordinate values, environment classification, LoS/NLoS condition, scale factor, grid spacing and placeholder fields for RSSI and SNR values that will be populated during the network survey.

4.3.2 Scanner Module

The scanner is implemented in `scanner.py` and it is used to conduct the network survey by walking through each measurement point defined in the `gridmap.JSON` produced by `gridmap.py`, capturing beacon frames and recording RSSI, SNR and channel data. The reference image from the gridmap module is used as a guide for where the user should be positioned when conducting each reading. The module supports arguments for specifying the monitor mode interface, target SSID, frequency band, number of readings per point and gridmap JSON file that stores the survey results.

Monitor mode is managed by airmon-ng, which handles killing interfering processes and starting the monitor mode interface. The name of the monitor mode interface is detected by enumerating all interfaces via iw dev before and after airmon-ng start, rather than assuming that the name follows a specific convention. This was a necessity due to different drivers behaving in different ways; the Raspberry Pi's built-in adapter creates a new interface with the suffix "mon", while the A7000 WNIC's driver, RTL8814AU, switches the existing interface to monitor mode without renaming it.

A list of supported channels is detected through a layered lookup. First, the scanner queries the physical frequency list of the device via `iw phy`, falling back to `iwlist` if the former method fails to return a result. The fallback triggers a warning rather than proceeding silently with no channels, which would cause the capture loop to never execute. Using the RTL8814AU with a patched out-of-tree driver, the available frequencies are not exposed through `iw phy`, so the fallback `iwlist` method is a necessity.

Beacon frame capture uses a Berkeley Packet Filter (BPF) where one is supported. If the filter fails to compile, which occurs when the interface's datalink type does not match the expected 802.11 Radiotap format, the scanner falls back to using a Python level filter that selects the same frames without involving the packet capture library. The first time this fallback is triggered, it latches to avoid repeating a failed attempt on every channel.

The channel number for each detected AP gets extracted from the DS Parameter Set element via element ID rather than its position in the frame. This differs from the original approach which produced incorrect channel numbers when other elements preceded the DS set in the beacon. In one case, a Country element was misread as channel 256. As selection by element ID is independent of order, it reliably extracts the correct channel regardless of how the frame's headers are ordered. For APs operating in 5 GHz, which may omit the DS Parameter Set, the HT Operation element is used as a fallback.

SSID filtering is supported and implemented by capturing beacon frames from all networks but only using frames matching the specified test network's signal for coverage assessment. Regardless of the filter, all detected APs are retained for channel assignment awareness. Band selection is also supported, notably, 5 GHz only filtering ensures that all captured frames use OFDM modulation. This produces reliable SNR data as described in section 3.4.3. For APs operating in 2.4 GHz, CCK-modulated frames are excluded from SNR calculations as described in section 4.3.3.

At each measurement point, three readings are captured and the RSSI per detected AP is averaged across all readings to reduce the impact of sudden signal fluctuations. When the final point has been surveyed, the results are written back to the `gridmap.JSON` file.

4.3.3 Driver Modification and SNR Implementation

The A7000 WNIC was operated using a modified version of a third-party out-of-tree Linux driver [30], as the required noise metadata was not exposed by the unmodified third-party driver [31] or the default in-tree Linux driver [32]. The unmodified forked driver source was pinned to a specific commit to ensure reproducibility, as the upstream repository's main branch had been overwritten with compiled build artefacts and no longer contained the original source that the modification built upon [31].

The modification specifically involved the driver's Radiotap output through a single-file patch which was done to expose the noise value derived from the received signal strength and the driver's per-frame SNR field. This required three changes: emitting the noise field, omitting an incorrectly declared signal quality field that desynchronized the Radiotap header and adding a padding byte to maintain 2-byte alignment for subsequent fields. The pinned source and standalone patch were preserved in a private mirror so that the build remains reproducible independently of the upstream repository [30].

To ensure measurement integrity, reported noise values are validated before use. A reading is accepted only if the noise floor falls between -100 and -50 dBm and the implied SNR is between 0 and 70 dB. The lower bound of -100 dBm is inferred from the theoretical thermal noise power of a 20 MHz channel at room temperature (290 K). It is given by $N = kTB$, where k is Boltzmann's constant (1.38×10^{-23} J/K), T is the absolute temperature in Kelvin and B is the channel bandwidth in Hz, which yields approximately -101 dBm. The upper bound of -50 dBm was set empirically, as a noise floor stronger than this was not considered credible in the testing environment. The 70 dB SNR cap was determined through observation of the adapter's behavior during testing. The driver's per-frame SNR field is stored as a single signed byte, which saturates at approximately 63. When the field saturates on weak OFDM frames, the noise value derived by subtraction underflows and wraps to a positive value (e.g. 108 dBm), which produced a highly inaccurate reading. CCK-modulated frames, used by all 2.4 GHz beacons at basic rates, reported an SNR of zero, regardless of actual signal quality, which yielded a noise value equal to the RSSI. Both of these failure modes produce values that fall outside the defined bounds and are therefore discarded. Per-point SNR is deduced from the median noise floor across all valid readings in the relevant frequency band, rather than from any single frame, reducing the impact of outlier readings.

4.3.4 Heatmap Module

The heatmap is implemented in `heatmap.py` and visualizes measured signal strength by interpolating RSSI values between the measurement points and overlaying the result onto the floor plan. Each measurement point is represented by a coordinate pair and an associated RSSI value. The module supports arguments for specifying a gridmap JSON file and a filter that will only visualize results from the specified SSID.

The floor plan is loaded as the background layer using `PIL` and converted to RGB to ensure correct color rendering. This conversion is done to prevent `matplotlib` from applying the signal strength colormap to the floor plan itself. Without RGB conversion, the floor plan's grayscale color is interpreted as single-channel data and it gets rendered through whichever `colormap` is active, thus distorting its appearance. The figure size is calculated dynamically to preserve the floor plan's aspect ratio. A minimum of four measurement points with RSSI data is required, as cubic interpolation needs at least four points to construct a surface.

Signal strength values are interpolated across a 1000x1000 grid spanning the full floor plan dimensions using cubic interpolation via `SciPy`. This estimates signal strength between measurement points and produces a continuous surface from individual measurements. To ensure the heatmap only renders within the measured area, a convex hull polygon of the measurement points is computed. Grid points outside of the boundary are set to NaN which means they are interpreted as missing data by `contourf`, leaving them transparent.

The color scheme follows a cold to hot convention, with a frigid deep blue representing the weakest signal and a scorching deep red representing the strongest signal. A `BoundaryNorm` maps the colors proportionally to the signal strength bounds. A color bar is attached to the right side of the axes, preserving the floor plan's proportions while showing the color scheme's relationship to signal strength. The scale starts at -15 dBm, higher than Table 2's max value, to properly represent survey data higher than -30 dBm. Without this adjustment, the heatmap would not render near certain measurement points due to exceeding the -30 dBm limit. The measurement points are marked as white scatter points.

The reference image exported by `gridmap.py` is generated using `PIL`'s `ImageDraw` rather than `matplotlib`'s `savefig`. This ensures that the exported image has the same exact pixel dimensions as the original floor plan. Without this, `matplotlib` adds padding and potentially resizes the image during export. This would lead to misalignment between the measurement point coordinates and the floor plan when the heatmap is rendered.

4.3.5 Algorithm Module

The optimization algorithm is implemented in `echidna.py`. It reads measurement point coordinates, RSSI values, SNR values and environment classifications from the gridmap JSON file. The module supports arguments for specifying the gridmap JSON file, the floor plan image, frequency band, baseline mode, coverage radius and a filter to only analyze and optimize coverage from a specified SSID.

The algorithm has two modes of operation; baseline mode and normal mode. Baseline mode, described in section 3.5, suggests a single starting AP before the test network exists. In normal mode, measurement points that do not meet the optimal coverage

criteria defined in section 3.1 are identified and marked as uncovered. If all points already meet the criteria, the algorithm terminates after stating this.

Candidate AP positions are generated at every grid intersection across the floor plan, with the spacing and scale factor to convert pixel distances to meters both being stored in the gridmap JSON. In order to prevent suggested placements in unmeasured areas, candidates are filtered to only include positions within the convex hull of the measurement points. In addition to the hull, there is a small buffer of 1.5 times the grid spacing to allow for placement suggestions slightly outside of the measured boundary. This reduces the number of candidate positions evaluated significantly.

For each candidate position, the ITU-R P.1238 propagation model [2] is applied using the environment-specific coefficients from section 3.3 to predict the received signal strength at each uncovered point. The environment and LoS condition classification of the target measurement point determine which coefficients are used, as the candidate position has no associated environment data. A candidate is credited with covering a point if two conditions are met: the predicted RSSI exceeds the -67 dBm threshold, and the point is within a configurable coverage radius (default 15 meters). The default coverage radius value was selected as a conservative estimate of typical indoor AP coverage, falling within the valid distance ranges specified for all environment types used in this project [2]. Candidate coverage is evaluated on predicted RSSI alone, for the reasons described in section 3.5.

The greedy placement loop selects the candidate position that covers the greatest number of uncovered points. When multiple candidates cover equally many points, the position whose weakest covered point has the strongest predicted RSSI is preferred. This tie-breaking strategy centers the suggested AP on the cluster it serves rather than defaulting to a position at the edge of the measurement area. Channel assignment occurs simultaneously, as described in section 3.5.1. The algorithm checks which channels are used by both already-placed suggested APs and existing APs detected during the survey within overlapping range. User placed APs take priority as their positions are accurate, while survey-detected neighbors fill any additional BSSIDs, deduplicated to avoid counting the same AP twice.

After each placement, newly covered points are removed from the set of uncovered points, and the process repeats until all points meet the coverage criteria or no candidate position can cover any remaining uncovered points. The latter case indicates that the remaining points may be unreachable given the measurement grid and propagation model constraints.

The algorithm's primary suggestion can be exported into a copy of the gridmap JSON used for the current run, for use in the next survey iteration. The exported suggestion includes the AP position, its assigned channel and a placement reference image, generated to show the suggested position on the floor plan. Only the first suggestion is exported to the gridmap JSON per run, as the testing procedure places one physical AP

per iteration. However, more than one suggested AP can show up on the exported reference image to visualize all present coverage gaps.

Testing was conducted exclusively on 5 GHz, though the implementation retains 2.4 GHz support. Results are presented both in the terminal as a summary that lists suggested AP positions and channel assignments, and visually as yellow star markers overlaid on the heatmap. The uncovered points are highlighted as red crosses to distinguish them from the covered measurement points in green.

4.4 Testing and Evaluation

The testing procedure described in section 3.4 was carried out in a corridor on University West's campus across four survey rounds: one baseline and three AP placement iterations. A total of fifteen measurement points were placed: eleven points along the main hall with the conditions set to corridor/LoS, two points in an adjacent laboratory room classified as office/NLoS points on the bottom-right and two corridor/NLoS points on the top-left. The initially NLoS marked points P12 to P15 were updated to LoS as new APs were introduced over time. Table 6 is based on the complete measurement data which can be found in Appendix B. The table summarizes the coverage progression across all iterations and Figure 1 displays the positions of all measurement points.

Table 6. Coverage Progression

Iteration	**New AP Position (m) Channel**	**Covered**	**Uncovered**	**RSSI: Median, Minimum, Maximum**	**SNR: Median, Minimum, Maximum**
Baseline	N/A	0/15	All (Null RSSI)	N/A	N/A
Iteration 1	AP-1 (28, 16) Channel 40	12/15 (80%)	P12, P13, P15	Median: -42 Minimum: -73 Maximum: -24	Median: 46 Minimum: 13 Maximum: 63
Iteration 2	AP-2 (49, 23) Channel 36	13/15 (87%)	P14, P15	Median: -41 Minimum: -74 Maximum: -24	Median: 47 Minimum: 10 Maximum: 63
Iteration 3	AP3 (4, 8) Channel 60	15/15 (100%)	None	Median: -36 Minimum: -50 Maximum: -19	Median: 51 Minimum: 37 Maximum: 66

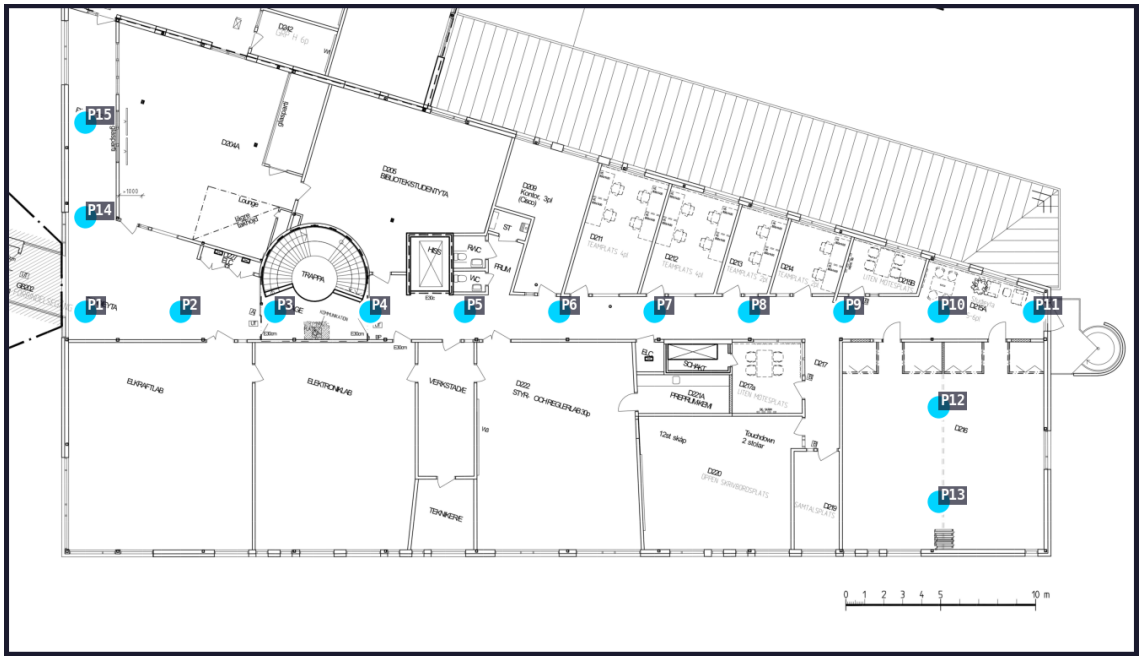

Figure 1: Annotated Floor Plan Showing Numbered Measurement Point Locations (Blue)

4.4.1 Baseline Survey

The baseline survey was carried out before the test network APs with the SSID of "APtlas_5" were powered on. Because it filtered for a network that did not exist yet, the gridmap it produced was one with all null RSSI values. Thus, all measurement points were marked as red crosses due to null being below the -67 dBm RSSI threshold. The baseline survey still collected information from all other APs present in the corridor for channel assignment purposes.

AP-1 is suggested in the center of the figure to cover the most surface area possible, displayed as a yellow star with the suggested channel of 40.

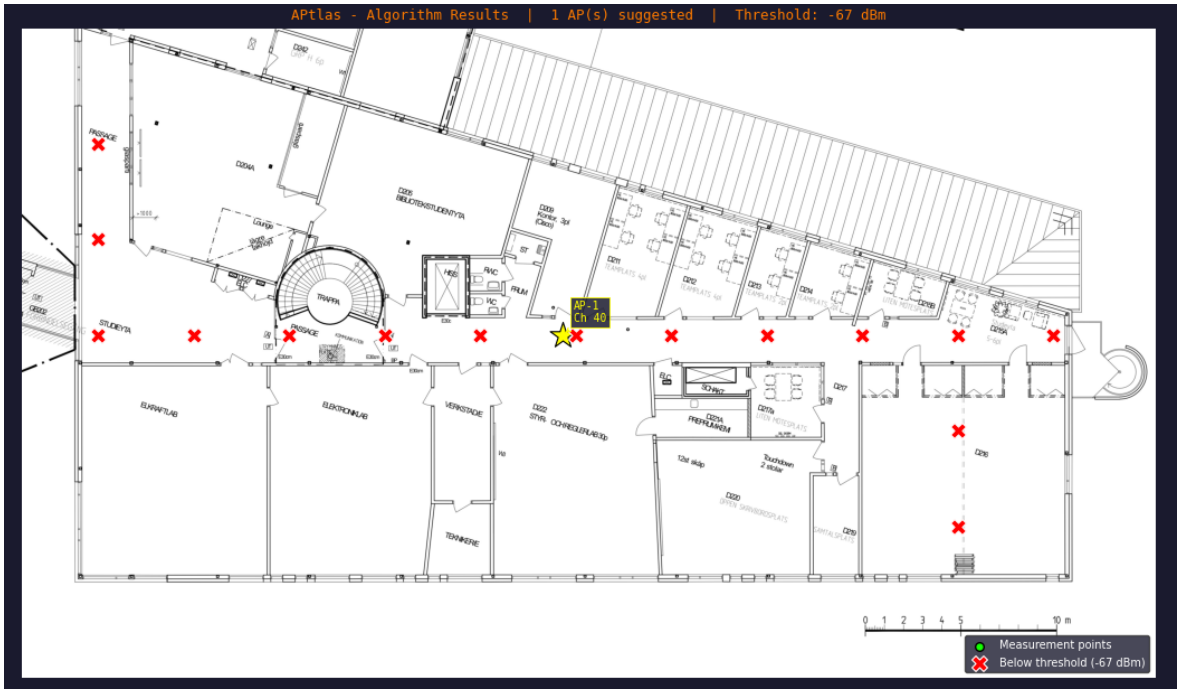

Figure 5: Baseline Survey Optimization Map

```
└─[P main]─>> python3 .\echidna.py -g .\pages\uni\dHusP2_gridmap_baseline.json --baseline --ssid APtlas_5 -b 5 -f .\pages\uni\dHusP2_spin.png
WARNING: No libpcap provider available ! pcap won't be used

==================================================
  APtlas - Optimization Algorithm
==================================================
Loaded 15 measurement points from .\pages\uni\dHusP2_gridmap_baseline.json
  Warning: 15 points have no RSSI value (None) - these will be treated as uncovered.
  Scale        : 0.016942 m/px
  Grid spacing : 59 px (1.0m)
  Floor plan   : 3500x2000 px  (59.3x33.9m)
  RSSI threshold: -67 dBm
  SNR threshold : 25 dB (placeholder)
  TX power      : 20 dBm
  Band          : 5 GHz  (channels [36, 40, 44, 48, 52, 56, 60, 64, 100, 104, 108, 112, 116, 120, 124, 128, 132, 136, 140])
  Frequency     : 5.0 GHz
  Coverage radius: 15.0 m per AP
  Mode          : baseline (1 AP at centre)
  Existing APs detected    : 245

==================================================
  BASELINE - single starting AP at the centre of the measured area
==================================================
  Measurement points       : 15
  Existing/neighbor APs    : 245
  Suggested AP-1           : (1672, 944) px  (28.3m, 16.0m)  channel 40
==================================================

Generating visualisation...
  Not enough measured RSSI for a heatmap (0 of 15 points measured, need 4) — showing floor plan only
```

Figure 6: Baseline Survey Terminal Output

4.4.2 Iteration 1

AP-1 was placed at the algorithm's suggested position (28, 16) m on channel 40, near the center of the corridor. After re-surveying, 12 out of 15 measurement points met both coverage criteria. Three points remained uncovered, P12, P13 and P15.

All eleven corridor LoS points (P1-P11) were covered and within comfortable margins, with RSSI ranging from -24 to -48 dBm and SNR from 37 to 63 dB. P14, despite being classified as corridor NLoS, also met both thresholds with an RSSI of -60 dBm and SNR of 26 dB.

The three uncovered points failed for different reasons and both failure modes were correctly detected by the tool. P12 had an acceptable RSSI of -62 dBm but failed the

SNR criterion with 21 dB. This suggests that the failure reason was due to noise interference as opposed to a complete coverage gap. This precise case demonstrates the value of evaluating SNR alongside RSSI, as assessing RSSI alone would have marked P12 as covered due to the signal strength being adequate, despite the poor quality of the signal. P13 and P15 failed both criteria (RSSI of -68 and -73 dBm, SNR of 16 and 13 dB), representing NLoS coverage gaps at the far ends of the measurement area. The complete measurement data for iteration 1 can be found in Appendix B.

Based on the survey results, the algorithm suggested AP-2 at position (49, 23) m on channel 36 to address the highest number of remaining coverage deficiencies. AP-3 was tentatively suggested at position (4, 6) m on channel 60 but not placed until iteration 3. The previously suggested AP-1 from the baseline survey is now displayed as a "Known AP" and visualized as a magenta triangle.

Figure 7: Iteration 1 Optimization Heatmap

Figure 8: Iteration 1 Terminal Output

4.4.3 Iteration 2

AP-2 was placed at (49, 23) m on channel 36, directly on the P12/P13 branch rather than centrally. This placement demonstrates the coverage radius cap and the tie-break described in sections 3.5 and 4.3.5 respectively.

After re-surveying, 13 of 15 points were covered. P12 improved dramatically from -62 to -24 dBm RSSI and from 21 to 60 dB SNR. P13 similarly improved from -68 to -32 dBm RSSI and 16 to 51 dB SNR. Both points were now comfortable within both coverage thresholds.

Notably, P14 regressed from covered to uncovered between iterations. Its RSSI remained stable (-60 to -61 dBm), but its SNR dropped from 26 to 24 dB, crossing the 25 dB SNR threshold by 1 dB. The addition of AP-2 seems to have nudged the local noise floor just enough to tip this marginal point. The tool correctly flagged this regression rather than hiding it, demonstrating sensitivity to marginal coverage changes. P15 remained uncovered with RSSI of -74 dBm and SNR of 10 dB. The complete measurement data for iteration 2 can be found in Appendix B.

Based on the survey results, the algorithm suggested placing the next AP (AP-3) at position (4, 8) m on channel 60. This position varies slightly from its tentatively suggested position of (4, 9) m in iteration 1.

Figure 9: Iteration 2 Optimization Heatmap

```
└─[ main]─>> python3 .\echidna.py -g .\pages\uni\dHusP2_gridmap_iteration2.json --ssid APtlas_5 -b 5 -f .\pages\uni\dHusP2_spin.png
WARNING: No libpcap provider available ! pcap won't be used

==================================================
  APtlas - Optimization Algorithm
==================================================
Loaded 15 measurement points from .\pages\uni\dHusP2_gridmap_iteration2.json
  Scale        : 0.016942 m/px
  Grid spacing : 59 px (1.0m)
  Floor plan   : 3500x2000 px  (59.3x33.9m)
  RSSI threshold: -67 dBm
  SNR threshold : 25 dB (placeholder)
  TX power      : 20 dBm
  Band          : 5 GHz  (channels [36, 40, 44, 48, 52, 56, 60, 64, 100, 104, 108, 112, 116, 120, 124, 128, 132, 136, 140])
  Frequency     : 5.0 GHz
  Coverage radius: 15.0 m per AP
  Mode          : coverage optimisation

==================================================
  GREEDY SET COVER ALGORITHM
==================================================
  Total measurement points : 15
  Already covered          : 13
  Uncovered (need APs)     : 2
  Existing APs detected    : 207
  User-placed APs          : 2
  Candidate positions      : 531 (filtered from grid)
  Placement 1: Placed AP-3 at (236, 472) px  | Channel 60  | Covers 2 points  | Remaining uncovered: 0

==================================================
  RESULT: 1 AP(s) suggested
==================================================
  AP-3    position: (4.0m, 8.0m)  channel: 60  covers: 2 points
==================================================
```

Figure 10: Iteration 2 Terminal Output

4.4.4 Iteration 3

AP-3 was placed at (4, 8) m on channel 60, covering the far-left cluster where P14 and P15 were located. After the final survey, all 15 measurement points met both coverage criteria and 100% coverage was achieved. The three suggested APs were assigned channels 40, 36 and 60; three distinct 5 GHz channels with no channel interference between them. Upon this result, the algorithm correctly terminated and produced a heatmap to visualize the fully covered floor plan with no additional APs suggested.

The two previously uncovered points improved substantially. P14 went from -61 to -20 dBm RSSI and from 24 to 66 dB SNR. P15 went from -74 to -30 dBm RSSI and

from 10 to 55 dB SNR. Both points now had comfortable margins above both coverage thresholds.

The final state showed no marginal points with the weakest RSSI across all 15 points being -50 dBm (P2) and the lowest SNR being 37 dB (P1 and P2), both well above the coverage thresholds. The complete measurement data for iteration 3 can be found in Appendix B.

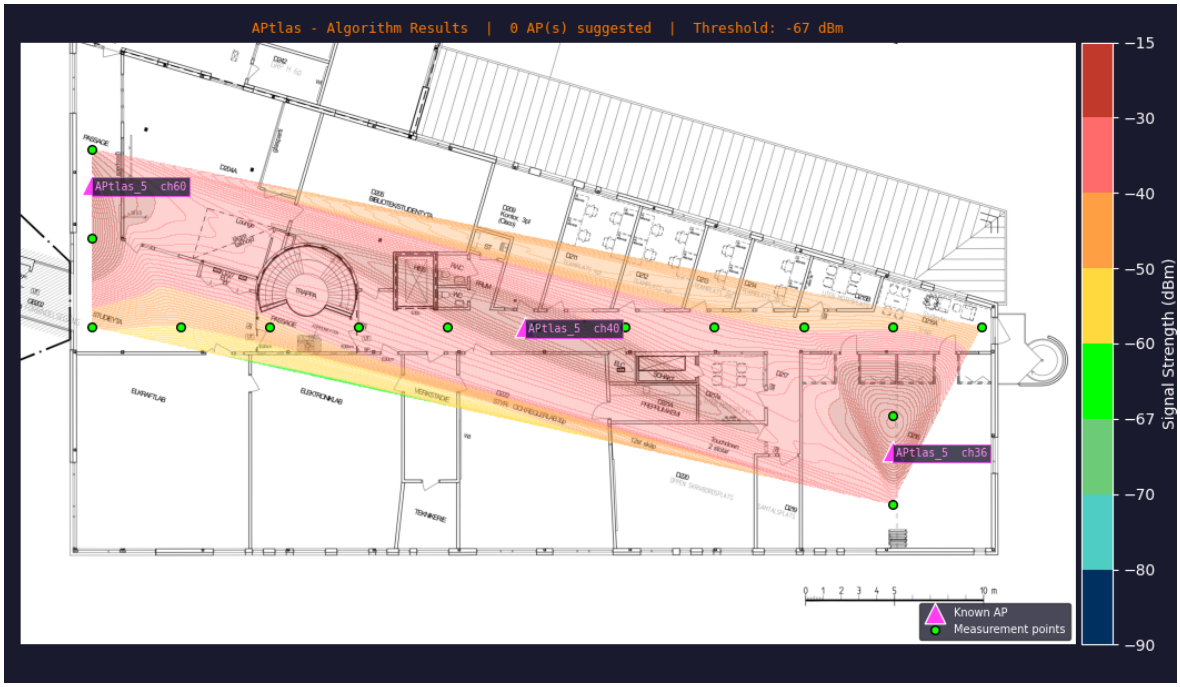

Figure 11: Iteration 3 Heatmap

Figure 12: Iteration 3 Terminal Output

4.4.5 Validation of AP Placement Suggestions

The accuracy of the optimization algorithm's AP placement suggestions depends on the accuracy of the indoor propagation model that drives it. When the algorithm suggests placing an AP at a specific position, it does so because the site-general propagation

model predicts that the position would provide sufficient coverage to uncovered points. Its predictions were evaluated by comparing the predicted RSSI at each measurement point against the measured RSSI after each iteration. The difference was quantified using RMSE as described in section 2.3.3.

For each iteration, the predicted RSSI at every measurement point was calculated using the ITU-R P.1238 formula with the following parameters: the Effective Isotropic Radiated Power (EIRP) of each AP was 22 dBm (20 dBm transmit power + 2 dBi antenna gain) and the operating frequency was 5 GHz. The environment classification and LoS/NLoS conditions that each point is assigned during gridmap construction determined which coefficients were inserted into the formula. As new APs were placed within the line of sight of previously NLoS classified points, the condition for the respective points was reclassified to LoS for subsequent predictions. For points within range of multiple APs, the strongest predicted signal was used, following the algorithm's own logic. The standard deviation σ represents the expected spread of real measurements around the model's predicted value, used for RMSE error quantification.

As an example, point 5 in iteration 1 is located 4 meters from AP-1 in a corridor LoS environment. Applying the basic transmission loss formula yields Lb = 54.57 dB, producing a predicted RSSI of -32.6 dBm. The measured RSSI at P5 was -32 dBm, resulting in a prediction error of -0.6 dB. The table below presents the RMSE for each iteration alongside the applicable σ reference range from Table 4. The full per-point calculations across all iterations, which the table summarizes, are available in Appendix C.

Table 7. Comparison of RMSE and σ Reference Range Values

Iteration	APs Active	Environment Conditions	RMSE (dB)	σ Reference Range (dB)
1	AP-1	Corridor LoS + Office NLoS + Corridor NLoS	4.62	3.77 – 7.58
2	AP-1 + AP-2	Corridor LoS + Office LoS + Corridor NLoS	4.11	3.68 – 7.58
3	AP-1 + AP-2 + AP-3	Corridor LoS + Office LoS	4.86	3.68 – 3.77

The RMSE values for both iterations 1 and 2 (4.62 and 4.11 dB) fall within the expected deviation range defined by the corresponding σ values. Both iterations include NLoS measurement points with σ values up to 7.58 dB, with the overall RMSE being far below this threshold. This result indicates that the propagation model and the placement decisions it informed, performed within the expected bounds for a site-general model without environment specific calibration.

The RMSE value of 4.86 dB in iteration 3 differs from its predecessors by exceeding the expected σ range. This is notable because of the fact that by this iteration, all measurement points had been reclassified to LoS conditions, which narrowed the expected

range from 3.68 – 7.58 dB to 3.68 – 3.77 dB. This deviation is attributable to prediction errors at points P12 (-12.2 dB) and P14 (-10.6 dB), where the measured signal was significantly stronger than predicted. Both points are in close proximity to their serving AP (2 and 3 meters respectively), suggesting that the model overestimates path loss at very short distances in these environments. The remaining 13 points exhibit errors within ±6.8 dB, which is consistent with the model's expected performance. Without P12 and P14, the RMSE for iteration 3 would be approximately 3.1 dB, which is well within the LoS σ range. Despite these individual prediction inaccuracies, the placements suggested by the model achieved full coverage by iteration 3.

4.4.6 Requirements Compliance

Table 8 maps each functional requirement defined in section 4.1 to its fulfilment status based on the testing and evaluation conducted in sections 4.4.1 through 4.4.5.

Table 8. Requirement Compliance Table

#	Requirement	Status	Evidence
1	Capture beacon frames from a specified SSID for coverage assessment, and from all surrounding networks for channel assignment	Fulfilled	Scanner filtered for "APtlas_5" while retaining all detected APs for channel assignment (section 4.4.1-4.4.4, Appendix A)
2	Record RSSI and SNR at each measurement point	Fulfilled	All 15 points recorded both values across all iterations (Appendix B)
3	Generate a heatmap overlaid on a floor plan image	Fulfilled	Heatmaps generated for iterations 1-3 (figures 7, 9 and 11)
4	Identify measurement points not meeting optimal coverage criteria	Fulfilled	Uncovered points correctly identified in every iteration, including the P12 SNR-only failure (section 4.4.2)
5	Suggest placement positions for new APs if coverage criteria are not met	Fulfilled	Algorithm suggested AP positions in baseline and iterations 1-2, achieving full coverage by iteration 3
6	Assign non-overlapping channels to suggested APs	Fulfilled	Three APs assigned channels 40, 36 and 60 with no channel interference
7	Support both 2.4 GHz and 5 GHz frequency bands	Partially Fulfilled	Tool supports both bands, but testing was conducted exclusively on 5 GHz due to hardware limitations (section 3.4.3)
8	Export measurement data in a reusable JSON format	Fulfilled	All survey data exported to gridmap JSON files (Appendix A)
9	Validate suggestions through before/after comparison	Fulfilled	Each iteration compared against the previous, with RMSE quantifying prediction accuracy (section 4.4.5)

10	Allow the user to define measurement positions on a floor plan with environment classification per point	Fulfilled	Grid map builder used to place 15 points with corridor/office and LoS/NLoS classifications (section 4.3.1)

5 Discussion

The tool successfully assessed the coverage of a wireless network across all testing iterations, correctly identifying coverage deficiencies and suggesting AP placements to resolve them. The iterative introduction of the three APs progressed coverage from 0% to 100% in three iterations, with each AP suggestion targeting the observed coverage gap, rather than redundantly reinforcing areas that were already covered. The algorithm's placement behavior of positioning AP-2 on the bottom-right corner and AP-3 on the top-left corner rather than placing additional central APs demonstrated that the coverage radius cap and tie-break strategy described in section 3.5 produced spatially sensible suggestions.

The coverage assessment criteria considering both RSSI and SNR for placement suggestions proved their value during iteration 1 (section 4.4.2), where acceptable RSSI masked poor signal quality that only the SNR criterion detected. A tool relying on RSSI alone, such as the predecessor [5], would have missed it. This validates the project's central premise, that RSSI alone is insufficient for reliable coverage assessment.

The P14 regression observed in iteration 2 demonstrates both the sensitivity of marginal SNR values and the tool's ability to detect degradation. While the 1 dB change is within the precision limits of the per-frame SNR measurement, not hiding the regression is arguably more valuable than only detecting improvements. A tool that only reports the good without the bad is not trustworthy.

The RMSE results highlight a fundamental characteristic of the site-general model [2]: the statistical averages that it applies may not reflect the specific propagation conditions at individual measurement points. The accuracy of the model is the highest when the environment classification closely matches the actual physical conditions. The accuracy is at its lowest when local factors such as wall materials, corridor geometry, reflections and obstructions deviate from the statistical assumptions. This is observable in iteration 3, where two points in close proximity to their serving APs (P12 at 2m and P14 at 3m) exhibited errors of -12.2 and -10.6 dB respectively, while the remaining 13 points maintained errors within ±6.8 dB. The classification of the laboratory room as an office environment may also contribute to prediction errors, as the physical characteristics of the laboratory may differ from the statistical office environment represented by the coefficients. Despite the outliers, the predictions produced by the model had practical utility for coverage assessment, demonstrating that a site-general model without environment-specific calibration has practical utility for coverage assessment.

All surveys were restricted to the 5 GHz band due to the inability of the A7000 WNIC to produce reliable noise data on 2.4 GHz CCK-modulated frames. This means that the tool's coverage assessment was only verified on 5 GHz networks. While this is a hardware limitation rather than a tool limitation, it remains a notable limitation. The 5 GHz restriction did however provide two advantages: all captured frames used OFDM modulation, ensuring consistent SNR data throughout, and the larger number of available non-overlapping channels made channel interference between the three test APs and all other APs unlikely.

Compared to the previous project [5], the tool has been substantially improved. The addition of SNR measurement, channel assignment awareness and the optimization algorithm transform it from a one-dimensional and passive visualization tool into one that's capable of active assessment and planning. The previous tool could show where the signal was weak; this tool can explain why it is weak and suggest how to remedy it.

The tool and methodology could generalize to other indoor environments, as the site-general model provides coefficients for multiple environment types. However, the testing for this project was conducted on a single floor with a single adapter and one survey run per iteration. The results demonstrate that the tool tracks coverage and produces sensible placement suggestions for new APs, but a statistically repeated benchmark across multiple environments would be needed to make broader claims about its reliability.

6 Conclusions

This project set out to answer whether a self-developed tool can visually and reliably assess if a wireless network meets defined optimal coverage criteria. Based on the results, the answer is yes; with qualifications.

The tool correctly identified coverage deficiencies in every iteration, distinguishing between RSSI-limited points, SNR-limited points and points failing both criteria. Its heatmap visualization provided an immediate visual representation of coverage quality across the measurement area. Alongside it, the optimization algorithm suggested AP placements that achieved full coverage in three iterations.

The propagation model's predictions, validated through RMSE analysis, performed within the expected bounds of the site-general model [2] for iterations 1 and 2 (RMSE of 4.62 and 4.11 dB against σ values of 3.77-7.58 dB). Iteration 3's higher RMSE of 4.86 dB, while exceeding the narrowed LoS σ range, was attributable to two specific outlier points and did not prevent the tool from achieving full coverage.

The inclusion of SNR alongside RSSI proved essential, as demonstrated by the P12 case where RSSI-only assessment would have incorrectly marked an interference-limited point as covered. This validates the three criteria definition of optimal coverage adopted by this project.

The tool met every functional requirement except one, which was only partially fulfilled. This primary limitation is due to the restriction to 5 GHz networks, caused by the hardware's inability to measure noise on 2.4 GHz CCK frames. Within the 5 GHz band, the tool demonstrated reliable, visual and quantitative coverage assessment across all testing iterations.

7 Future Work

The following areas were identified during the project as potential extensions that fell outside the current project's scope.

Determining the minimum number of APs required for optimal coverage is a natural extension of this project, with the tool's iterative placement approach providing a foundation for this analysis. However, proving mathematical optimality requires exhaustive evaluation beyond the scope of this project. Relatedly, the algorithm's initial AP placement currently defaults to the center of the measurement area. A more informed starting position based on the baseline survey's detected infrastructure could improve the first iteration's coverage.

The tool's frequency support could be extended in two ways. Conducting 2.4 GHz surveys would require either a different WNIC with native noise measurement support for CCK frames or an alternative approach to SNR estimation. Because of this, validating the capability of the tool's coverage assessment on 2.4 GHz remains an area for future investigation. Looking ahead, as the 6 GHz spectrum and Wi-Fi 7 become widely adopted, extending the tool's frequency support would increase its relevance for modern network deployments. This possibility depends on the potential availability of a Wi-Fi 7 adapter that exposes noise data through its driver.

On the modelling side, the site-general model [2] does not account for specific wall positions or materials. Integrating wall-aware propagation modelling would improve prediction accuracy, particularly for the NLoS cases where the largest RMSE errors were observed. The current tool also operates on a single floor plan. Extending support to multi-floor environments with floor penetration loss would broaden its applicability to larger buildings. Lastly, integration with existing network management platforms such as WLC interfaces could allow the tool to import AP configurations directly rather than relying on manual beacon frame capture.

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A. Project Repositories and Raw Survey Data

Main Repository: https://github.com/aawadeus/APtlas

Custom Driver Repository: https://github.com/aawadeus/aptlas-8814au

Raw Survey Data: https://github.com/aawadeus/APtlas/tree/main/thesis/surveys

B. Per-Point Measurement Data For All Iterations

The table below shows the measurement data for all measurement points across all iterations. As the baseline surveys reported null RSSI and SNR, it is excluded from this table for the sake of visual clarity. The table is based on the raw survey data, which includes the baseline survey. The link to both can be found in Appendix A.

Table B.1: Per-Point Measurement Data Across All Iterations

Point	Environment	Condition	Iter 1 RSSI (dBm)	Iter 1 SNR (dB)	Iter 2 RSSI (dBm)	Iter 2 SNR (dB)	Iter 3 RSSI (dBm)	Iter 3 SNR (dB)
P1	Corridor	LoS	-48	37	-48	37	-48	37
P2	Corridor	LoS	-50	37	-50	37	-50	37
P3	Corridor	LoS	-42	46	-42	46	-42	46
P4	Corridor	LoS	-36	52	-36	52	-36	52
P5	Corridor	LoS	-32	56	-32	56	-32	56
P6	Corridor	LoS	-24	63	-24	63	-24	63
P7	Corridor	LoS	-33	54	-33	54	-33	54
P8	Corridor	LoS	-37	51	-37	51	-37	51
P9	Corridor	LoS	-41	47	-41	47	-41	47
P10	Corridor	LoS	-41	47	-41	47	-41	47
P11	Corridor	LoS	-43	45	-43	45	-47	39
P12	Office	NLoS*	-62	21	-24	60	-19	63
P13	Office	NLoS*	-68	16	-32	51	-35	49
P14	Corridor	NLoS*	-60	26	-61	24	-20	66
P15	Corridor	NLoS*	-73	13	-74	10	-30	55

*Conditions marked with an asterisk were reclassified to LoS in later iterations as new APs were placed within the point's line of sight.

C. RMSE of Predicted RSSI vs Measured RSSI

Calculating the difference between the predicted RSSI and measured RSSI can be done in five steps. These calculations were performed for every single point, to determine the error of all points in every iteration, before a total RMSE is calculated. Calculations are divided by iteration, with each having its own corresponding subsection in this Appendix.

An example showing the steps taken when calculating the error of one point (P5, Iteration 1) can be found below, with the coefficients taken from Table 4:

Step 1: Determine EIRP

$EIRP = 20 + 2 = 22\ dBm$

Step 2: Determine Distance

AP-1 is at (1653, 944) pixels, P5 is at (1416, 944) pixels.

$\text{Distance in pixels} = \sqrt{(1653 - 1416)^2 + (944 - 944)^2} = 237\ pixels$

$\text{Distance in meters} = 237 \times 0.016942 = 4.0\ m$

Step 3: Determine Basic Transmission Path Loss (corridor/LoS):

$L_b = 10\alpha \log_{10}(d) + \beta + 10\gamma \log_{10}(f)$

$L_b = 10 \times 1.57 \times \log_{10}(4.0) + 29.46 + 10 \times 2.24 \times \log_{10}(5.0)$

$L_b = 15.7 \times 0.602 + 29.46 + 22.4 \times 0.699$

$L_b = 9.45 + 29.46 + 22.4 + 15.66$

$L_b = 54.57\ dB$

Step 4: Determine Predicted RSSI

$Predicted\ RSSI = 22 - 54.57 = -32.6\ dBm$

Step 5: Determine Error

$Measured\ RSSI = -32\ dBm$

$Error = -32.6 - (-32) = -0.6\ dB$

C.1 Iteration 1 RMSE

Table C.1: Per-Point Error of Iteration 1:

Point	Environment	Condition	Best AP	Distance (m)	Predicted (dBm)	Measured (dBm)	Error (dB)
P1	Corridor	LoS	AP-1	24.0	-44.8	-48.0	+3.2
P2	Corridor	LoS	AP-1	19.0	-43.2	-50.0	+6.8
P3	Corridor	LoS	AP-1	14.0	-41.1	-42.0	+0.9
P4	Corridor	LoS	AP-1	9.0	-38.1	-36.0	-2.1
P5	Corridor	LoS	AP-1	4.0	-32.6	-32.0	-0.6
P6	Corridor	LoS	AP-1	1.0	-23.0	-24.0	+1.0
P7	Corridor	LoS	AP-1	6.0	-35.3	-33.0	-2.3
P8	Corridor	LoS	AP-1	11.0	-39.5	-37.0	-2.5
P9	Corridor	LoS	AP-1	16.0	-42.0	-41.0	-1.0
P10	Corridor	LoS	AP-1	21.0	-43.9	-41.0	-2.9
P11	Corridor	LoS	AP-1	26.0	-45.3	-43.0	-2.3
P12	Office	NLoS	AP-1	21.6	-56.8	-62.0	+5.2
P13	Office	NLoS	AP-1	23.3	-57.6	-68.0	+10.4
P14	Corridor	NLoS	AP-1	24.5	-63.0	-60.0	-3.0
P15	Corridor	NLoS	AP-1	26.0	-63.7	-73.0	+9.3

Total RMSE of Iteration 1 (AP-1):

$$RMSE = \sqrt{(\Sigma errors^2 \div n)}$$

$$RMSE = \sqrt{\frac{(3.2^2+6.8^2+0.9^2+2.1^2+0.6^2+1.0^2+2.3^2+2.5^2+1.0^2+2.9^2+2.3^2+5.2^2+10.4^2+3.0^2+9.3^2)}{15}}$$

$$RMSE = \sqrt{\frac{320.18}{15}}$$

$$RMSE = \sqrt{21.35}$$

$$RMSE = 4.62\ dB$$

C.2 Iteration 2 RMSE

Table C.2: Per-Point Error of Iteration 2:

Point	Environment	Condition	Best AP	Distance (m)	Predicted (dBm)	Measured (dBm)	Error (dB)
P1	Corridor	LoS	AP-1	24.0	-44.8	-48.0	+3.2
P2	Corridor	LoS	AP-1	19.0	-43.2	-50.0	+6.8
P3	Corridor	LoS	AP-1	14.0	-41.1	-42.0	+0.9
P4	Corridor	LoS	AP-1	9.0	-38.1	-36.0	-2.1
P5	Corridor	LoS	AP-1	4.0	-32.6	-32.0	-0.6
P6	Corridor	LoS	AP-1	1.0	-23.0	-24.0	+1.0
P7	Corridor	LoS	AP-1	6.0	-35.3	-33.0	-2.3
P8	Corridor	LoS	AP-1	11.0	-39.5	-37.0	-2.5
P9	Corridor	LoS	AP-1	16.0	-42.0	-41.0	-1.0
P10	Corridor	LoS	AP-1	21.0	-43.9	-41.0	-2.9
P11	Corridor	LoS	AP-1	26.0	-45.3	-43.0	-2.3
P12	Office	LoS	AP-2	2.0	-31.2	-24.0	-7.2
P13	Office	LoS	AP-2	3.0	-33.7	-32.0	-1.7
P14	Corridor	NLoS	AP-1	24.5	-63.0	-61.0	-2.0
P15	Corridor	NLoS	AP-1	26.0	-63.7	-74.0	+10.3

Total RMSE of Iteration 2 (AP-1 + AP-2):

$$RMSE = \sqrt{(\Sigma errors^2 \div n)}$$

$$RMSE = \sqrt{\frac{(3.2^2+6.8^2+0.9^2+2.1^2+0.6^2+1.0^2+2.3^2+2.5^2+1.0^2+2.9^2+2.3^2+7.2^2+1.7^2+2.0^2+10.3^2)}{15}}$$

$$RMSE = \sqrt{\frac{253.57}{15}}$$

$$RMSE = \sqrt{16.90}$$

$$RMSE = 4.11\ dB$$

C.3 Iteration 3 RMSE

Table C.3: Per-Point Error of Iteration 3:

Point	Environment	Condition	Best AP	Distance (m)	Predicted (dBm)	Measured (dBm)	Error (dB)
P1	Corridor	LoS	AP-1	24.0	-44.8	-48.0	+3.2
P2	Corridor	LoS	AP-1	19.0	-43.2	-50.0	+6.8
P3	Corridor	LoS	AP-1	14.0	-41.1	-42.0	+0.9
P4	Corridor	LoS	AP-1	9.0	-38.1	-36.0	-2.1
P5	Corridor	LoS	AP-1	4.0	-32.6	-32.0	-0.6
P6	Corridor	LoS	AP-1	1.0	-23.0	-24.0	+1.0
P7	Corridor	LoS	AP-1	6.0	-35.3	-33.0	-2.3
P8	Corridor	LoS	AP-1	11.0	-39.5	-37.0	-2.5
P9	Corridor	LoS	AP-1	16.0	-42.0	-41.0	-1.0
P10	Corridor	LoS	AP-1	21.0	-43.9	-41.0	-2.9
P11	Corridor	LoS	AP-1	26.0	-45.3	-47.0	+1.7
P12	Office	LoS	AP-2	2.0	-31.2	-19.0	-12.2
P13	Office	LoS	AP-2	3.0	-33.7	-35.0	+1.3
P14	Corridor	LoS	AP-3	3.0	-30.6	-20.0	-10.6
P15	Corridor	LoS	AP-3	2.0	-27.8	-30.0	+2.2

Total RMSE of Iteration 3 (AP-1 + AP-2 + AP-3):

$$RMSE = \sqrt{(\Sigma errors^2 \div n)}$$

$$RMSE = \sqrt{\frac{(3.2^2+6.8^2+0.9^2+2.1^2+0.6^2+1.0^2+2.3^2+2.5^2+1.0^2+2.9^2+1.7^2+12.2^2+1.3^2+10.6^2+2.2^2)}{15}}$$

$$RMSE = \sqrt{\frac{353.97}{15}}$$

$$RMSE = \sqrt{23.60}$$

$$RMSE = 4.86\ dB$$