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# Monitoring and Predictive Maintenance (PDM) of Passive Distributed Antenna Systems (DAS)

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**Title**
Monitoring and Predictive Maintenance (PDM) of Passive Distributed Antenna Systems (DAS)

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**Abstract**
The passive distributed antenna system is a tool for bringing in mobile network signals into buildings. By being passive, there are no built-in diagnostic tools to inform faults or errors in the system. We analyze two IoT prototypes built to monitor this system in terms of performance, cost, and maintenance. We also compare these prototypes to the standard solutions. For performance, we set up a water bath experiment changing the water depth to simulate signal attenuation. We compiled data from electronics distributors as a cost estimate and then compared it to the price of equipment bench-marking procedures. Lastly, for maintenance, we deduced the total power consumption of our prototypes to estimate maintenance costs. The results show the capacity of our RF module prototype to respond well to attenuation as long as the signal remains above -65 dBm. The GSM module handles calls down to -90 dBm and is capable of additional features important for monitoring. Yet, they are still dependent on traditional diagnostic tools like the S332E for locating the exact problem. However, that is expected as our cost analysis shows that the S332E can go up to 100,000 SEK per unit compared to our 160 SEK (RF module) and 650 SEK (GSM module) without markup. We do see additional costs incurred by simple battery fees from our maintenance analysis that can reach up to 280,214 SEK annually. Therefore, while we see potential in IoT solutions for monitoring, we must make revisions to our prototypes that bring down the costs.

**Keywords**
Passive, Distributed, Antenna, Systems, Monitoring, Maintenance, IoT, DAS, P-DAS

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# List of Abbreviations

| | |
|---|---|
| **ADC** | **A**nalog to **D**igital **C**onverter |
| **BCCH** | **B**roadcast **C**ontrol **Ch**annel |
| **BDA** | **B**i-**D**irectional **A**ntenna |
| **BSC** | **B**ase **S**tation **C**ontroller |
| **BSS** | **B**ase **S**tation **S**ystem |
| **BTS** | **B**ase **T**ransceiver **S**tation |
| **CDMA** | **C**ode-**D**ivision **M**ultiple **A**ccess |
| **CSQ** | **C**ell **S**ignal **Q**uality |
| **DAS** | **D**istributed **A**ntenna **S**ystem |
| **EM** | **E**lectro-**M**agnetic |
| **FDD** | **F**requency **D**ivision **D**uplex |
| **GMSK** | **G**aussian **M**inimum **S**hift **K**eying |
| **GPRS** | **G**eneral **P**acket **R**adio **S**ervices |
| **GSM** | **G**lobal **S**ystem for **M**obile Communication |
| **HLR** | **H**ome **L**ocation **R**egister |
| **IoT** | **I**nternet **o**f **T**hings |
| **MOSFET** | **M**etal-**O**xide **S**emiconductor **F**ield-**E**ffect **T**ransistor |
| **MSC** | **M**obile **S**witching **C**enter |
| **MSK** | **M**inimum **S**hift **K**eying |
| **NOC** | **N**etwork **O**perations **C**enter |
| **OQPSK** | **O**ffset **Q**uadrature **P**hase **S**hift **K**eying |
| **P-DAS** | **P**assive-**D**istributed **A**ntenna **S**ystem |
| **PSTN** | **P**ublic **S**witched **T**elephone **N**etwork |
| **RAU** | **R**emote **A**ccess **U**nit |
| **RF** | **R**adio **F**requency |
| **RFID** | **R**adio **F**requency **Id**entification |
| **RNC** | **R**adio **N**etwork **C**ontroller |
| **RSS** | **R**ecieved **S**ignal **S**trength |
| **TDMA** | **T**ime **D**ivision **M**ultiple **A**ccess |
| **VLR** | **V**isitor **L**ocation **R**egister |
| **WWW** | **W**orld **W**ide **W**eb |

# Chapter 1

# Introduction

## 1.1 Motivation

One of the first examples of internet of things (IoT) was the modification of a Coke vending machine to monitor how many drinks were inside the machine. Likewise, in 1993 at the University of Cambridge connected a webcam to the internet in very programmer fashion to monitor the coffee. Similarly, the one who popularized the term IoT, Kevin Ashton (who preferred the term "internet for things") created the Auto-ID Radio Frequency Identification (RFID) tags. All of these examples highlight one of the essential IoT applications: the ability to monitor "things" or devices. This is why it is only logical to consider monitoring a crucial technology we call the distributed antenna system (DAS).

In today's society, over 30 billion devices connected through the internet . Whether it is your phone, laptop, or even your car. More than ever seen before have we seen such reliance on communicating with other devices. Even more, so that most of these devices are relying on wireless communications. Inside the comfort of your own home, most people rely on WiFi to connect to the internet. On the other hand, when you roam about in the outside world, you are most likely to rely on your cellphone operator to provide you with 3G/4G to access vital services. As cities grow and become denser, it becomes increasingly difficult to satisfy the demands of a stable network in terms of coverage and capacity. The massive buildings often dampen radio signals to the point where indoor connectivity has to rely on a DAS. The DAS was first conceptualized by Adel A. M. Saleh [1] to solve the issue. We are becoming more and more reliant on these systems for our indoor connectivity needs. Therefore, any failure can be detrimental to a large number of people and acts as a public safety concern. In the worst case, you will not be able to reach emergency services when it matters the most. As such, there is a need to keep these systems from failing or at least detect failures and remedy them quickly. Unfortunately, passive distributed antenna systems (P-DAS) - which are the most widely deployed form of DAS - are incapable of reporting errors or failures by themselves. As such, new solutions based on monitoring and IoT are starting to appear on the market [2] [3].

## 1.2 Aim

This thesis aims to study different approaches to Internet of Things (IoT) based solutions for the task of monitoring P-DAS. By monitoring, we mean obtaining data that can be used as an indication of P-DAS's performance. There is different information that you can extract from the signals transmitted by the antennas. However, we will mainly focus on the ability to read signal strength levels in decibel-milliwatts as our performance indicator. The different approaches will be compared for various metrics such as cost of implementation, maintenance, and performance. The solutions revolve around having small embedded systems with radio frequency (RF) receivers capable of transmitting measurements across a network. This will allow the monitoring of a system that is otherwise incapable of reporting faults, hence the term passive. The technology should be helpful as both a localization tool (detection of error source) and a preventive tool for noticing performance declines. The potential benefits culminate in the form of a more robust system with reduced downtime and a system that is easier to maintain. Studying the different approaches should give us a better understanding of how to deploy this technology, especially in large passive DAS networks such as hospitals and airports.

## 1.3 Research Questions

**Which approach of an IoT solution to monitor the passive distributed antenna system is better in terms of cost, performance and maintenance?**
This means we are interested in researching potential prototype IoT solutions for this problem and estimate the cost of the device with regards to the desired performance and battery life. If battery life is desired, then compromises will be needed in terms of the sampling frequency (once a day versus once a week) and information obtained (only the signal strength or also the carrier and cell id). This research will be supported both from literature and prototype solutions being developed in parallel for the System Engineering course. For a better idea of what these prototypes are, please visit section 3.2.

**How do our IoT solutions compare with industry-standard solutions based on research, patents, and or product documents?**
This means we are interested in researching modern solutions that have been developed by companies based on IoT and monitoring. Additionally, we are interested in comparing our solutions to the old, more widespread approach of analyzing faults in passive DAS systems, which have traditionally required manual scanning for the error source and use larger bulkier equipment than modern monitoring solutions.

## 1.4 Method

To answer our research questions, we will require to experiment with real hardware prototypes that we have developed for the System Engineering course. We believe this is the best

course of action to supplement the fact that we lack access to proprietary data controlled by emerging companies attempting to solve the same issue of monitoring P-DAS systems. The legitimacy of these devices might be called into question. Therefore, there will be a focus on evaluating these systems and their performance in a controlled environment. Consequently, we will have an experimental setup in place. On the other hand, the other metric, such as cost, will be evaluated based on data from global electronics distributors and data from our employer Assimilatus AB. This data will be analyzed to conclude the cost of employing these systems versus the more traditional approach. This type of process will be considered as a secondary analysis method. The final method where we will collect our own data to draw conclusions about maintenance costs we will employ primary analysis. To summarize, our techniques are Experimental setup, primary and secondary analysis.

## 1.5 Limitations

Our thesis has several limitations that are born out of lack of expertise or resources that would allow for a much more in-depth analysis. The first limitation is access to a test site. P-DAS systems are installed in all kinds of environments, from buildings on the ground to tunnels underground. Having access to different environments would allow us to test and assess our approach in a meaningful way. Furthermore, a test site would allow us to simulate bad installations and damage to evaluate our devices. However, as we did not have access to such places and could only test on public P-DAS installations without tinkering, our analysis will be limited to manipulating our devices themselves rather than the P-DAS system. A minor limitation is that we don't calculate an accurate theoretical RSS (Received Signal Strength) due to the complexity of the theoretical calculations, and lack of control of all the variables in the experiment. It also a limited use to experiment as we need an accurate attenuation of the signal. We use the attenuation of the signal to see if the system can accurately detect change. The second major limitation is data. There is a considerable lack of data on P-DAS monitoring solutions. Information about the technology and performance of these devices is minimal and highly guarded by the companies offering them. We have tried to contact them several times, only to be rejected as the information is "proprietary." As such, our comparison to other monitoring solutions is limited to reported data such as general features and maintenance intervals. Lastly, we did not have enough resources to be able to produce more than two prototypes. In a real-world scenario deploying 100s of sensors would not be unrealistic for monitoring every antenna, and it would be interesting to see how our prototypes would perform in such a large sensor network.

# Chapter 2

# Related Work

## 2.1 Literature

The overall results of the literature on the topic of systems to monitor P-DAS is rather bleak. Finding peer-reviewed articles and publications detailing such systems has proven to be ineffective with our current resources. That is not to say that such systems have not been developed. Instead, the data surrounding them is being kept in the dark by competing companies and will be discussed in further detail in the section below.

What is currently known from our literature review is that we are demanding more out of our passive DAS systems. Several patents indicate that sub-systems are being built to complement the otherwise limited functionality that passive devices offer. Gerald Graham and Paul Liber at P. G. Electronics, filed a patent for a system consisting of a measurement unit with a measurement circuit capable of measuring the current draw of a distributed antenna and matching it against the expected current draw [4]. The comparison result is forwarded to a central monitoring unit that could generate alarms. This system is one of many attempts to overcome the shortages of using passive component's inability to report or monitor their status similar to the goals of this dissertation. On the other hand, Baljit Singh at Commscope Technologies LLC filed a patent for monitoring the noise levels at DAS remote access units (RAU) [5]. The patent highlights the problem of reconfiguration of DAS systems after deployment. By having a self-adjusting DAS system based on the current noise level, the antennas can transmit at a different frequency band. While this does not help in the event of system failure, it still manages to capture indirect errors caused by noisy environments. Lastly, Igor Berlin et al. at Corning Optical Communications LLC filed a patent detailing a system to monitor non-supported wireless signals within DAS coverage areas [6]. This is intended as a solution that overcomes the need for a parallel monitoring system for signs of interest. Instead, by leveraging the DAS infrastructure, they can draw data related to non-supported wireless signals by using the same infrastructure. It is safe to say that this system does the exact opposite of what we need. We want to leverage a non-supported wireless signal infrastructure to monitor the passive DAS operation status.

There is an important key takeaway from examining the systems mentioned above. None of the systems make use of IoT platform capabilities to access performance data and fault reports remotely. Furthermore, only one of them is related to the monitoring of passive DAS faults directly. This, however, does not mean that there is a lack of utilization of IoT platforms for monitoring sensor activity. On the contrary, there are many applications of

IoT platforms in several industries. Xenofon Fafoutis et al. describe such a platform called SPHERE applied in the area of healthcare [7]. They focus on a low-powered sensor network that uses different communication protocols to a local gateway. The sensors capture data related to humidity, temperature, and on-body sensor data capable of measuring acceleration data. The data from the sensor network is cross-examined to interpret the current environment of elderly citizens. This monitored data allows what is called ambient assisted living. The elderly are encouraged to manage their health with the help of technology that could, for example, remind them of taking their medication, brushing their teeth, or call emergency services in case of an accident.

In conclusion, we see that an IoT solution is viable for monitoring solutions and can offer essential data regarding the functionality and operation status of passive DAS systems. We understand that monitoring passive DAS systems directly can only be seen in the industry. That published studies have mainly focused on capturing the environment in which the DAS systems are in rather than their operation status.

## 2.2 Industry

As previously stated, there are some solutions available on the market to monitor the passive DAS systems. However, upon requesting more data from the providers, we got the response that this data is proprietary and cannot be shared publicly. This means that there is currently no way of knowing exactly how the systems that have been developed function. This emphasizes the need for studying approaches to this problem. One of the solutions is provided by Consultix Wireless [2]. Their system is composed of a probe that can monitor the signal quality at several frequency bands and communicate a status report to a gateway. The gateway allows the system to communicate with a server where data is stored, and administrative accounts can access sensitive information. The second system developed by Radio Network Solutions provides for the measurement of signal strength with a probe that sits on the antenna site. The probe can communicate over a radio, and each "DASTAG" has its id [3].

Concerning this thesis, it might seem unnecessary to research this problem when the industry has already provided some solutions. However, the lack of transparency means we cannot conclude the exact means of how these devices operate. Furthermore, these solutions are new to the market and have yet to be widespread. Therefore the value in this research lies in uncovering ways in which this problem can be tackled and evaluate the different approaches which can serve as a guideline to accelerate the adoption rate of this technology into today's passive DAS networks. As stated previously, we see it as an essential process to make the systems that we rely on more robust and easy to maintain.

# Chapter 3

# Background

## 3.1 Distributed Antenna Systems

With the increasing reliance on wireless communication, with not only the addition of cellphones but smartphones with the ability to access fast internet speeds. Over the years, more and more people started surfing on the internet with their phones. [8] This, of course, came with issues. The current systems were incapable of handling the increased load demands and converge requirements. Thus deploying the necessary infrastructure became a huge concern, especially in highly dense areas like cities. Landline telephony has become a relic and mostly ignored from a consumer's standpoint.

The large culprit of the growing coverage issue was: [9] that common building materials all block signals in varying degree. Even glass Low-E glass or low-emissivity glass used in many buildings to reduce the amount of heat generated blocks a significant amount of mobile wireless signals.[9] The thicker the material, the more electro-magnetic signal it can block. We do not expect signals to penetrate a skyscraper generally. While signals can reflect surfaces to allow connection even if there is no direct line to the antenna, it still not enough to ensure connectivity inside large buildings and complexes.

To solve this growing issue, a new system was implemented. Instead of trying to overcome the blocking of signals caused by the layer of building materials, a cheap workaround was developed by instead placing antennas everywhere inside the building and duplicating the outside signal to transfer it indoors. This, in turn, allowed the mobile wireless connection inside of the building to reach much higher levels than it would typically be able to due to signal loss from the surrounding building material.

### 3.1.1 Donor Site

The donor site or cellphone tower, where the signal comes from, is referred to as a donor since Passive DAS systems are "passive." This means that there are no active components that produce signals by themselves. Instead, they rely on repeaters and amplifiers to retransmit the signal indoors.

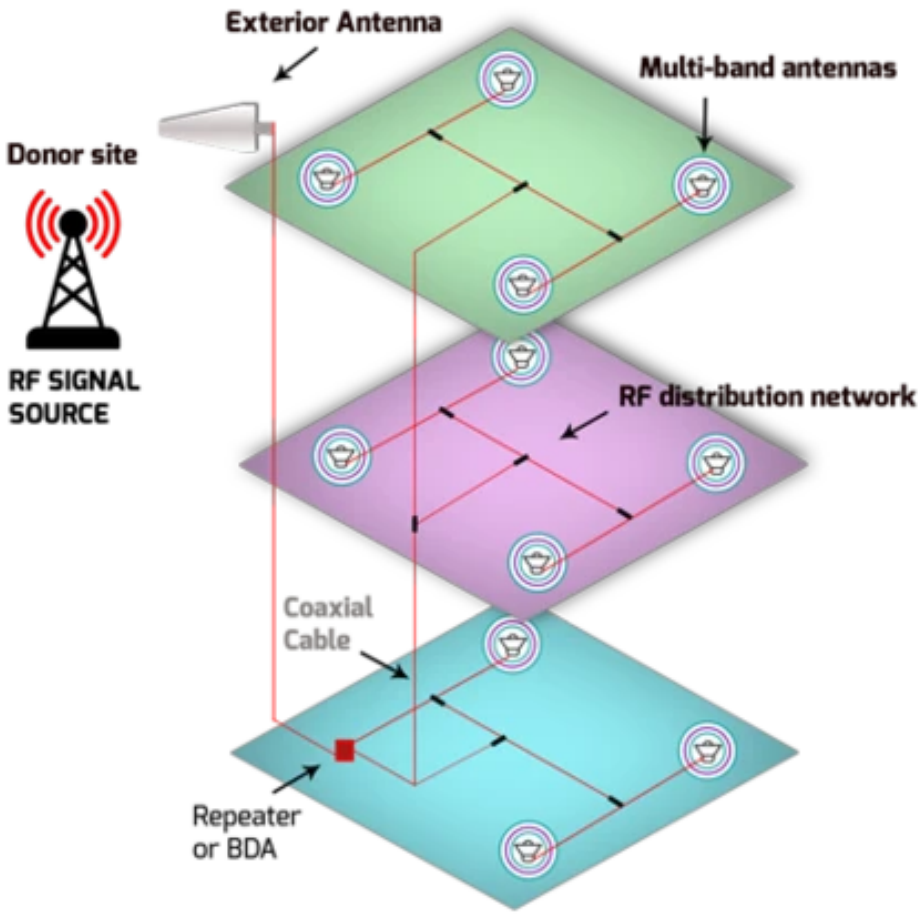


FIGURE 3.1: The diagram from the Passive Distributed Antenna Systems [10]

### 3.1.2 Exterior Antenna

The exterior antenna receives a cellular signal from the donor and transmits the signal into an amplifier, which then distributes the signal to the rest of the system.

### 3.1.3 Bi-Directional Amplifier

Bi-directional amplifiers or BDAs amplify the signal received by the exterior antenna from the donor site to the rest of the system's interior of distributed antennas.

### 3.1.4 Interior Antennas

Inside the building, it is needed to spread out antennas to cover the signal for the entire building complex. Careful planning is required not to transmit too much signal power where the signals would end up interfering with one another and drawing an unnecessary amount of power. On the other hand, you do not want to transmit too little power such that the signal is poor, or any additional changes to the interior will cause signal loss. This is one of the difficulties when deploying P-DAS systems. Since we require careful planning and placement, the system can suffer from changes or modifications made after the system was deployed. Even a small change, such as the change of ceiling mesh used, can have adverse effects on the coverage.

Two primary antennas types are commonly used as part of an indoor DAS solution. First, there is the omnidirectional antenna that emits the signal in all directions equally. On the other hand, on edges or corners, it is common to see the panel directional antenna. This type of antenna excels at transmitting the signal in the direction it is pointed. The other side of this antenna only acts as a back-plate.

### 3.1.5 Coaxial Cables

Coaxial cable are specialized cables used to transmit the signal by wired means until we need to go wireless. The cables are susceptible, which without the proper care during the installation, can cause the cables to wear out and require replacement quickly.

### 3.1.6 RF Combiners

RF combiners are devices that combine the signal from many different signal sources together. This allows the P-DAS to be installed in any location that it requires.

### 3.1.7 System Faults

One of the main advantages of using the P-DAS is that it is generally stable when it comes to faults in the system. The most common faults are usually from bad installation, antenna failure, and interior changes. P-DAS is difficult and expensive to extend should the capacity needs change throughout the lifetime of the system. The passive element of this system,

therefore, becomes a huge hurdle to the occasional maintenance requirements. Often more than not, the error is reported after complaints roll in, and coverage is lost.

## 3.2 The Internet of Things Components

Internet of things, commonly referred to as IoT, is a system of interconnected devices that communicate over the internet or other wireless means. IoT is used in many areas, from monitoring traffic and adjusting traffic flow, to the monitoring crops in agriculture. IoT is increasingly used over the years, with new applications popping up constantly.

We see an application of IoT is suitable for the problem of monitoring the P-DAS system. Below is a description of the prototypes we have developed for this problem.

While the IoT devices can be extremely different from one another, there are general guidelines and golden rules that make an IoT device usable in the industry. Starting with functionality, every IoT device has to be able to do some useful function that is demanded by the industry deploying it. The golden rule is that the more functions an IoT device needs to carry, the higher the cost and power consumption of the device. This means for any device, one must think carefully about how to be able to meet the requirements needed and still be economically viable for mass production. This is where we can leverage the second property of any IoT device, wireless communication capability. To keep costs down, we have to decide what functionality can be leveraged to other devices. We could, therefore, do heavy calculations on a nearby device such as a phone or PC. This is referred to as "edge computing." Otherwise, we can communicate with the cloud and do the calculations there. This is especially important when dealing with a battery-powered IoT device, which is not unusual to encounter. The industry standard for general-purpose sensors that only transmit data with minimal computation is four years without replacement. It Adds to the cost to replace the units or, if possible, replace the batteries of those units. Cost is a fundamental issue as if one is going to mass-produce the devices. The price should not be much greater than the current systems in place. However, this is evaluated on a case by case basis.

With the P-DAS usually to make sure one has good coverage throughout the building, it is common for many antennas to be placed throughout each floor. To monitor each endpoint of the antenna means that we would need a lot of IoT devices to cover them all. Since the antennas are located on the ceiling often away from any power outlets, we decided to go with battery-powered prototypes. To meet the demands of communication over a network, we had the choice between Bluetooth, Wi-Fi, or LoRa. We decided to stick with Bluetooth due to its availability and our familiarity with the technology. Lastly, we decided on which type of approaches to use in our prototypes that would be worth comparing. One of our prototypes is based on the mentality of keep it cheap keeps it simple while the other approach is pricier but delivers a lot more flexibility and functionality. These two approaches are dubbed the logarithmic power meter prototype and the GSM module prototype, respectively. We see these two opposite mentalities for the prototype as worthy to compare as they are far in between in terms of cost and power based on initial estimates.

### 3.2.1 Function

#### 3.2.1.1 RF Logarithmic Power Meter

The RF logarithmic Antenna is a simple device that uses an AD8318 RF Logarithmic Detector chip. It is a simple device that measures the radiation power of a signal. After it measures the signal's power, it sends an analog voltage as an output that ranges between 0.6 to 2.1 V. The voltage output represents the decibel-milliwatt (dBm) signal strength received. The decibel-milliwatt describes the power of the signal on a logarithmic ratio to 1 milliwatt. Using this chip digitally, one must sample the analog voltage using an analog to digital converter (ADC). Using 5 volts as a reference voltage and a 10-bit ADC the equation to turn the voltage into a dBm value is stated below:

$$f(x) = 19 - 19.53 \times 10^{-2}x \tag{3.1}$$

As you can see from the equation, the relationship is linear. However, it is only linear within the operating range of 2.1 to 0.6 V [11], after witch the conformance drops and the results become unstable. Individual differences in hardware may occur. This chip is incapable of doing any high order processing on its own to extract useful information from the signal it measures besides the power. Therefore we are limited in the data we can present, but it should still be a good indicator of errors and faults.

#### 3.2.1.2 GSM Module

The GSM module we are using is a full-on module that utilizes the SIM7600 chip. It features a sim card holder to attach a sim card and an audio jack that allows the sending and receiving of voice through a call. Furthermore, it has loads of functionality that may not be fully utilized for our purposes. Naturally, that makes the module a lot more expensive. The most important functionality that we will be using is the ability to issue attention commands or AT commands for short. These are commands that will allow us to do useful things with the chip such as: connecting to a desired cellular network, check for the signal strength, automatic reporting with configurable intervals and extracting information about the current network such as the ID of the provider with "AT+CPSI?" command [12]. The SIM7600 has a simple interface for very sophisticated hardware capable of producing the kinds of signal reports we desire. However, the compromises are made on cost and power consumption to achieve this level of performance. One of the reasons we chose this approach was that the idea that one could check every operator in the area to quickly tell if it was an incorrect configuration of the donor signal or problem with the operator. Unfortunately, collecting signal reports from all the requires a special sim-card requires a license that is very difficult and expensive to acquire. We were not able to produce the experiment we wanted. Do note even with a standard sim card. One can still see the other operators in the network even if we can't acquire a signal report for them. One could also do a rotation system to regularly switch out the operator and authenticate it with the different cellular networks.

### 3.2.2 Communication

Every IoT device requires some form of communication protocol to make data collection possible without the need for onboard storage solutions. The choice of communication protocol is a discussion that doesn't affect the main functions of the IoT device. However, it is vital for how the devices are installed. In the context of our devices, we require a lot of flexibility. This is because P-DAS is found in various environments. In the case of a regular building, the devices might be able to directly reach an access point if the building has Wi-Fi infrastructure in place. On the other hand, in a subway tunnel, we would be lucky to have cellular coverage across the entire section. This means it might be necessary to forward the wireless signal from one device to another until it reaches an area with Wi-Fi coverage. Alternatively, we could use LoRa or Bluetooth to access Wi-Fi through a gateway. Note, however, that it is not necessary to have the data accessible remotely, but storing it near the site could eliminate the need for a Wi-Fi gateway. The added benefit of Wi-Fi is that you would be able to access the data remotely from all around the world.

We have chosen to deal with Bluetooth mesh in our prototype devices. This decision was based on the fact that we can leverage the benefits of mesh networking mentioned below while having an easy time accessing the data. During testing, we decided to use our smartphone devices as a portable interface with the devices. Furthermore, we were sufficiently close to our devices, where Bluetooth access is possible. As such, it was merely a convenient choice to make.

#### 3.2.2.1 Mesh Networking

To pass signals from one device to another, we could leverage a mesh network architecture. Mesh networks are flexible, self-optimizing, self-healing, extensible and configurable networks. The purpose of a mesh network is to extend coverage beyond the limits of a single access point. Every node in the mesh is aware of every other node within range. The data is passed from node to node based on the path that would provide the best throughput. This means that should one node go offline; the whole network will not go down. This level of flexibility is a desirable property when dealing with many devices. Thus we are increasing the points of failure. This is especially true in the after-mentioned subway, where the untimely loss of the device would be most impractical.

### 3.2.3 Power Consumption

As we have stated previously, the P-DAS antennas are often located in hard to reach areas. Thus, we can not ensure that there are reliable and readily accessible power outlets nearby. Therefore, we have opted for using battery-powered solutions instead. This means that the cost of installing our devices is minimal. However, further maintenance costs are induced. The best way to limit these costs is to make sure our devices can be up and running with minimal interaction needed. By lowering the power consumption of our devices, we can help increase the up-time of our battery-powered devices before the batteries need to be replaced. We will be investigating power consumption based on measurements in an experimental

setup and by referencing the data available in the data-sheets of our components. From other monitoring solutions, we see that the probes often last between 4-5 years before the need to replace them.

From our testing, it is shown that RF meter consumes more power than the GSM. At the same time, this might be confusing at first since the GSM is doing more things then the RF meter. Still, the module in use was stepping down a nine-volt battery to its operating voltage of 5 volts, comparing to the GSM that was stepping down 6 volts to 5 volts making the efficiency on the regulator much higher for the GSM.

### 3.2.4 Cost

The cost of each unit is an essential metric for assessing the potential gains (or losses) to deploying these devices in a real-world setting. If the costs exceed the potential savings in time from having the monitoring system in place at a P-DAS location, then it would be difficult to justify the adoption of this system despite the benefits in terms of up-time. The costs of the devices are estimated according to the price of their components. The data was aggregated from electronics distributors that supply parts to Sweden, and the cheapest supplier was selected as the data source. A price comparison service tool was used to simplify the process [13]. To make use of the price breaks at specific volumes and make the estimates more accurate, we report the price at an order of 1000 parts. Furthermore, the cost of resistors and capacitors were excluded as they amount to 0.1 SEK or less per part, so their impact on the final estimate is minimal.

TABLE 3.1: Cost estimate for the RF logarithmic power meter module based prototype

| Part | Distributor | Price Per Unit (SEK) | Quantity | Total Price (SEK) |
|---|---|---|---|---|
| AD8318ACPZREEL7 | Mouser Electronics UK | 64.7 | 1 | 64.7 |
| RN4871UVRM118 | Digi-KeySweden | 52.9 | 1 | 52.9 |
| ATMEGA328PBAU | Mouser Electronics UK | 11.0 | 1 | 11.0 |
| UA78M33CDCYR | Farnell element14 | 1.6 | 1 | 1.6 |
| 7A8000MAAET | Mouser Electronics UK | 2.8 | 1 | 2.8 |
| SSM103FSVPTR | Mouser Electronics UK | 7.4 | 2 | 14.8 |
| 54202T3003LF | Mouser Electronics UK | 1.3 | 1 | 1.3 |
| 593 | Mouser Electronics UK | 2.4 | 1 | 2.4 |
| 594 | Mouser Electronics UK | 2.6 | 1 | 2.6 |
| PCB Board | Seed Studio | 6.3 | 1 | 6.3 |
| **Total Cost** | **160.1** | | | |

TABLE 3.2: Cost estimate for the GSM module based prototype

| Part | Distributor | Price Per Unit (SEK) | Quantity | Total Price (SEK) |
|---|---|---|---|---|
| SIM7600EHS2107EQZ1W3S | Avnet Europe | 562.8 | 1 | 562.8 |
| RN4871UVRM118 | Digi-Key Sweden | 52.9 | 1 | 52.9 |
| ATMEGA328PBAU | Mouser Electronics UK | 11.0 | 1 | 11.0 |
| UA78M33CDCYR | Farnell element14 | 1.6 | 1 | 1.6 |
| 7A8000MAAET | Mouser Electronics UK | 2.8 | 1 | 2.8 |
| M207861546 | Farnell element14 UK | 6.2 | 1 | 6.2 |
| 54202T3003LF | Mouser Electronics UK | 1.3 | 1 | 1.3 |
| 593 | Mouser Electronics UK | 2.4 | 1 | 2.4 |
| 594 | Mouser Electronics UK | 2.6 | 1 | 2.6 |
| PCB Board | Seed Studio | 6.3 | 1 | 6.3 |
| **Total Cost** | **649.9** | | | |

## 3.3 Monitoring of Passive Distributed Antenna Systems

The word monitoring means to "observe and check the progress or quality of (something) over a period of time; keep under systematic review" [14]. In accordance, the purpose of our monitoring is to be able to extract some indication for the performance and well being of the P-DAS. The type of data we are dealing with from the system is cellular network data (See A) that is being transmitted electromagnetically through the air. The amount of power this electromagnetic (EM) signal contains is what we use to form what we call signal strength. Now, consider a transmitter with a simple antenna. When the antenna is connected, electricity flows through the antenna producing EM radiation. In other words, we can detect some level of signal strength at the transmission source. However, should we disconnect the antenna from the transmitter, we would discover that there is no EM radiation at the source; thus, very little or no signal strength will be detected.

Similarly, if we are to use signal strength as an indicator of performance, we are measuring if there is EM radiation present as we expect and how much of it is coming from the antennas. Thus we can assert that there is a physical malfunction in the system. The causes of such malfunction could be a damaged antenna (transmitting medium), a loose or damaged cable, or a power outage. Thus such a monitoring approach is limited to physical transmission errors only. However, we also know that the type of signals transmitted is modulated.

Meaning it carries binary information. Therefore, we could make use of this modulation to decipher the data that the EM signals are carrying. This technique would allow us to get not only information about the signal strength but also additional useful information such as the network provider id and cell id. Such an approach would detect even logical errors born of awry configuration or other logical faults.

The most popular method of monitoring P-DAS these days is not to monitor it at all. Rather when complaints start rolling in from disgruntled customers who can not get a good reception at a certain location in the building. That is when maintenance services are called to locate and eliminate the error source. The type of equipment used for diagnostics costs up to 100,000 SEK [15]. As such, it is not feasible to install such devices around the building. Furthermore, this method acts after the fact instead of as a preventative method. Therefore, downtime is not minimized. By focusing on the measurement of signal strength as an indicator of performance and placing multiple cheap probes at every antenna, we can take a more preventative approach to minimize system downtime and simultaneously localize the error by cross-referencing with every other probe in the system.

Now that we have determined what kind of interfaces we need to describe how we can assess our P-DAS's progression or quality. When a P-DAS system is installed in a building, initial measurements are taken, which describe the signal strength output present at different locations within the building. These measurements are termed the "operational values". This means that the values recorded are what the client and provider have agreed upon as an acceptable installation. This data is crucial for assessing the performance of the P-DAS system as it tells us that under normal conditions, we can expect the following signal strength levels to be present. Therefore to monitor is to assess if the signal strength currently detected is within the acceptable range of the signal strength that was present during installation. A map will be able to be created for each building by monitoring the output of every antenna. Tracking the antenna's production will be beneficial not only for knowing the status of each antenna but also the area. This will allow us to give an estimate of the problem. For example, even though one antenna is down, the entire floor has been going through a loss in signal output. Which could signify is not an antenna failure in a specific building but rather a cable fault. Thus reducing the amount of time searching for the problem and giving an early error report before the entire floor collapse.

## 3.4 Signal Strength

Signal strength in dBm or decibel-milliwatt is the standard metric by which we gauge the power of signals. The measurement is based on the decibel logarithmic scale, where we express the ratio of the power of the EM signal in reference to 1 milliwatt. For some power P we can express the signal strength x in dBm using the following equation:

$$x = 10 \log_{10} \frac{P}{1mW} \tag{3.2}$$

0 dBm means that the power currently being transmitted is exactly 1 milliwatt. In other words, every second 1 mJ or millijoule of energy is being expended. The typical operating

range for cellular network signal strengths is -30 dBm to -110 dBm [16]. This means around one microwatt to 1 picowatt of power. A usable signal is considered anything above -85 decibels. The power drops quite rapidly due to the nature of EM signals as the distance to the source increases. While this effect is easy to see over long distances, it is still detectable across small distances [17]. Therefore, it is possible to simulate the signal drop by changing the distance between the receiver and transmitting antenna without the need to move across large distances. However, water is a good alternative for greater attenuation over smaller distances [18].

## 3.5 Signal Damping with Water

Water has always been a significant problem when it comes to signal damping. Water itself absorbs an incredibly wide range of signals with very high attenuation. As such, a substantial factor in the terrible reception in forest landscapes is the water content inside tree trunks [19]. There are two main reasons why water is such a suitable attenuator. The dissolved ions and overall impurities present in water make for an excellent conductor. On the other hand, distilled water is an excellent insulator. Another reason is the stretching of the O-H vibrations in water molecules.[20] Since these vibrations occur at a high intensity and very short path lengths, it gives water an incredibly broad spectra absorption, which can be seen in figures in the appendix. It is a very complex calculation to find the exact amount of signal lost through the water at many factors into calculating theoretical RSS (Received Signal Strength). Since theoretical RSS is dependent not only on the power of signal but also on the frequency being used, the receiving antenna area, the type of water which is being tested and the minerals that reside in it, even the material waterproof box and the distance to edges can cause small scaling factors. [18] For example, you be hard press to get a signal on your phone past 20 cm of water. Yet, but while merely keeping everything the same, switching the mobile phone antenna to a much larger surface area, we still achieve a usable signal at depths of 37 cm.

## 3.6 Traditional Diagnostic Tools and Methods

Despite the relative simplicity of the P-DAS system, it is still complex in diagnosing errors that might arise during its lifespan. The use of passive components comes at the expense of convenient built-in diagnostic tools. Traditionally, it is uncommon for the industry to do regular check-ups to ensure that it is operational. This is partly due to the robustness and reliability of the P-DAS system. However, due to the changing times, with landlines becoming extinct, most companies rely on smartphones for communication. The loss of mobile networks can be very detrimental to industries and the public. Most deployed P-DAS systems in the industry are never checked-up or maintained [21]. On rare occasions, what is done is yearly or bi-annual sweeps in hopes of catching things early. The process consists of testing every BDA to see what kind of signals are coming in and out. Furthermore, one needs to do a walk/drive test to examine the signal strength levels to ensure they match design expectations. This process is often lengthy and costly and uses expensive tools such as the

S332E Site Master. As stated in the S332E Site Master Application Note [22], "An ounce of prevention is worth a pound of cure." Yet there is a lack of preventative action due to the high cost it incurs (traditionally) for a relatively stable system.

Tools like the S332E Site Master have been around for a while. They come with a vast number of features for diagnosing the condition of the cables, antennas, amplifiers, and other components that are part of the P-DAS. Some of the features include testing optic fiber cables for continuity to ensure that the signal reaches the destination point. In addition to continuity, it is capable of examining defects, cleanliness, and overall quality (end-to-end span loss and splice loss) with a scope camera. It is also capable of performing stress tests for checking micro-bends that could cause an unnecessary signal loss in the cables. Much like we are aiming for with our monitoring system, the S332E is capable of a Walk/Drive test to verify coverage (signal strength). However, many of the features in the site master requires at least two of them.

One other cost that must be considered that this is not a pick-up and plug test that anybody can do. These specialized devices that require highly skilled workers add to this method's cost as the worker would have to be trained to perform the testing procedures and analyze the results. On the other hand, the standard cost of bench-marking the performance of a deployed P-DAS for buildings under 20,000 $m^2$ is about 25,000 SEK [21]. To put things in perspective, the Malmö Live Konserthus is 90,000 $m^2$, so you can charge up to 57,500 SEK. This cost can surge for companies, especially if the P-DAS system located in places such as the subway, which requires traffic to stop running to do a full system check.

# Chapter 4

# Experiment Setup

## 4.1 Signal Strength

### 4.1.1 Approach

To gauge the performance of our devices and test out their measurement capabilities, we must be able to control the environment surrounding the devices to conclude their operation. Our devices should be able to report the signal strength level of the antenna they are assigned to monitor. Therefore, the dependent variable is signal strength in dBm. On the other hand, we had thought about changing the distance between the probe we built and the antenna we are monitoring. However, we believe that movement is not a good idea due to an effect known as fast-fading, which is caused by destructive interference. Therefore, we must manipulate the signal strength received without moving to minimize the impact. We considered the option, consequently would be to control the antenna signal output. However, we cannot do that as there is restricted access to the DAS infrastructure beyond the antennas themselves.

Furthermore, the antennas are often located in hard to reach areas which make it difficult to do any kind of manipulation to the antennas themselves. Therefore, our approach consists of using water as an attenuating medium for radio signals. The reason that a Faraday Cage wasn't used was due to we did not want to get a zero signal, which can be achieved by just removing the antenna on the IoT device. Building a signal damper box was a tricky affair if we wanted to be able to adjust how much the signal get dampen. Using water was a cheap and flexible way to change the signal dampening. The independent variable will be the water level sitting between the receiver of our probe and the transmitting antenna. With enough water between the two devices, we should be able to attenuate the signal enough as not to be interpreted by the probe. Thus by controlling the amount of water, we can maintain the amount of attenuation and evaluate if the device behaves according to expected results.

### 4.1.2 Establishing a base

For us to understand the numbers better, we utilized the approach described in the section above to attempt to isolate our devices from surrounding signals. Therefore, we attached our device to the bottom of a basin while vacuum sealed to be shielded from water. We then kept adding water until we lost cellular connection on our prototype GSM module. Once that happened, we measured the water depth at which the module was sitting. We also recorded

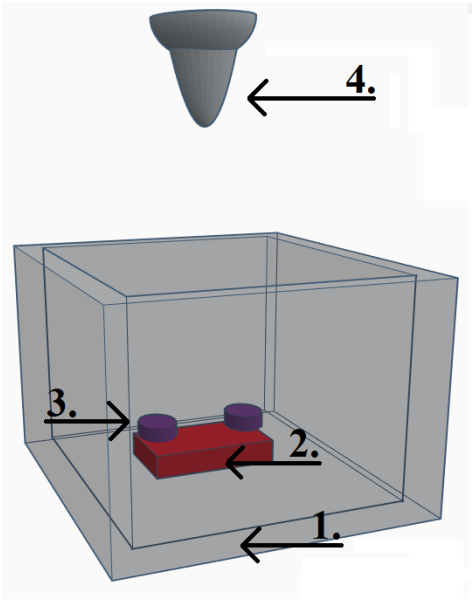


FIGURE 4.1: The diagram for the setup of the trail which was a box of water. 1. is the water filled in the basin 2. is where the device was placed. 3. Weight plates placed to keep the device from floating 4. Omidirectional Antenna

the response from the module for 30 seconds. If there are no significant changes in the overall readings, then we considered that our acceptable level of water depth where we can say that the module is "isolated." We then repeated the same procedure; however, we did that with our logarithmic power unit. In this case, we did not wait for a cellular connection drop but rather for the reading to decrease. From this procedure, we obtain an indicator of a large enough water depth level from which we can run our experiments.

### 4.1.3 Trail Experiment Setup

We thought it would be a good idea to test the measurements close to the transmitting devices. As such, we ran a trial at Malmö Live Konserthus in Malmö. We found an antenna transmitter and filled up a 48-litre basin of water 0.5 cm depth at a time right underneath the antenna, the prototype sitting at the bottom of the basin. We then took the average signal strength reading. This process was repeated until the water depth reached 27 cm.

### 4.1.4 Setup

For the main signal strength experiment, we used equipment initially intended for ultrasound imaging testing for the focal length biomedical department. The device consists of a large basin and a high precision vibration-free motor controller for manipulating the arm. Thus, we decided to allow the controlled movement of our devices to get consistent motion at every sampling interval. The sampling software transmitted data at 500 ms intervals, and the motor

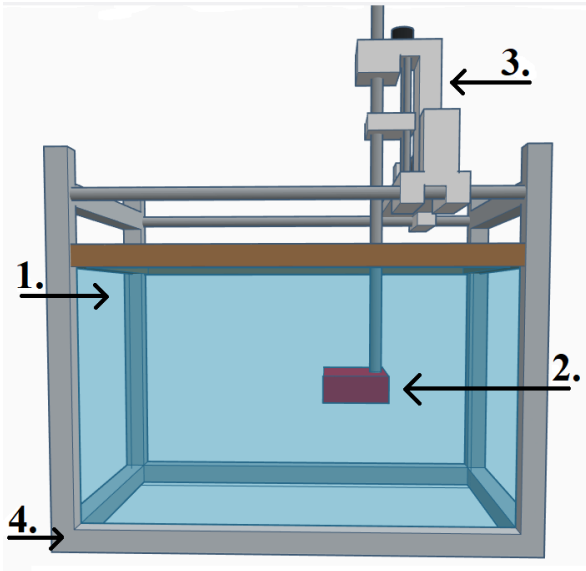


FIGURE 4.2: The diagram for the setup of the experiment. 1. is the water filled in the basin 2. is where the device was attached 3. is the stepping motor that is on the x, y, and z axis we are only using the z in this experiment. 4. Container holding the water.

was lowered 27 cm at a rate of 0.3 cm/second. The measurements were taken for 2 minutes at a time. The benefit of sacrificing the stationary approach to the controlled lowering is that we can more precisely calculate the depth. We can take a lot more data that would otherwise have to be done in an agonizing and less effective method. In the span of 27 cm, we should still notice an effect that is not the result of interference only, depending on the results of our section above. Unfortunately, compared to the trail set up, the antenna was not closed by which meant the values were much lower than the trail testing.

## 4.2 Power Consumption

To conclude the power consumption of our devices, we resorted to measuring the current drawn straight from our 9 V battery in different situations. By knowing the current and the voltage, we can calculate the power as by the formula below:

$$P = V \times I \tag{4.1}$$

The procedure we followed was the same for all of our different components. We started by measuring the current draw of our micro-controller without any other components attached. To get the current, we connected a Uni-T Ut131B multi-meter in series between the 9 V battery's positive terminal and the voltage input of the PCB. This formed our base current draw as we could easily attach the other modules to our PCB. Once we had a base current draw from the board alone, we simply subtracted that value from the additional current draw incurred by our newly connected module. At each step, we waited at least 30

seconds to make sure the value stabilized before we kept it in our records. We tested different operation modes for our components as most of them supported some operation mode intended for when the module was not needed or to save power by simply disabling some functionality. We then organized two profiles we call "active mode," which is when we are fully operational with all functions and "passive mode" when we do not intend to read or transmit values.

### 4.2.1 AD8318 RF Logarithmic Power Meter

We measured the current draw of our system with the AD8318 connected to the board without additional components. Two operating modes were tested as specified by the manufacturer: Power-On mode where the enable pin is given 5 V and Power-Down mode where the allow pin is given 0 V. Additionally, we measured when the RF Meter was disconnected entirely from the system. As a comparison point, we went through the AD8318 chip datasheet [11].

### 4.2.2 SIM7600 GSM Module

This time we attached the SIM7600 GSM Module to the board with every other component disconnected. We tested two operating modes. The first operating mode was with the module connected to the cellular network and requesting data. The second operating mode was with the module in "minimum-functionality mode," which was set through the AT command "AT+CFUN=0". In this mode, the module still accepts AT commands (required for wake-up), which works for our PCB design without a reset circuit. As a comparison, we went through the SIM7600 hardware specifications [12]

### 4.2.3 Bluetooth RN-41

As we are using Bluetooth communication, we needed to also account for the power draw of that module. We tested again using the RN-41 and the board with no other components in two states: standby and connected. While in standby mode, the Bluetooth module is still discoverable and able to pair with other devices. There is an additional state called "deep sleep," which was not tested due to requiring a reset circuit [23]. However, we still include the data as part of our comparison point when we discuss optimizations.

# Chapter 5

# Results and discussion

## 5.1 Results

### 5.1.1 Signal Strength Readings

From our main experiment for signal strength with the controlled rate of motion, We see that the GSM module prototype exhibits a steep decline of signal strength as the depth increases. The readings tend to be more stable due to the CSQ scale used internally, which only allows changes of 2 dBm at a time to be reported (Fig. 5.1).

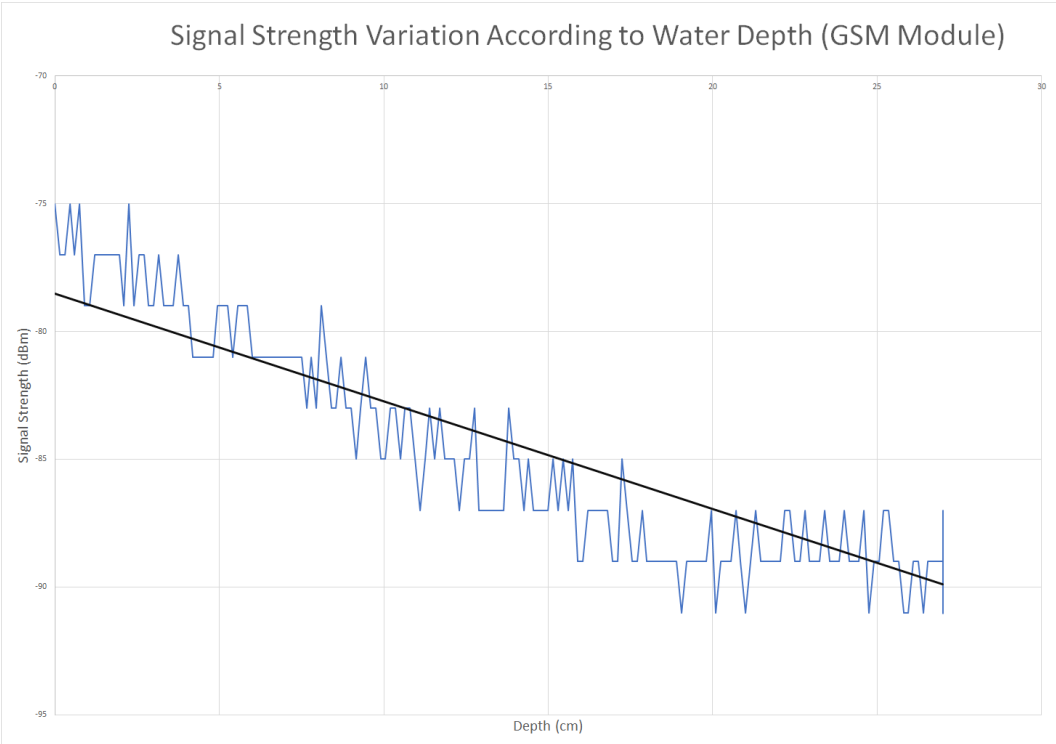


FIGURE 5.1: The signal strength reported from the GSM prototype as it descends slowly down the water basin. Black line is simply a linear trend line added for clarity.

On the other hand, our logarithmic prototype did not do as well. The signal drop was minuscule for the same distance compared with the GSM module. The signal seems to be close to the rated performance of this module at -65 dBm; only a significant drop is seen around 22.5 cm mark (Fig. 5.2).

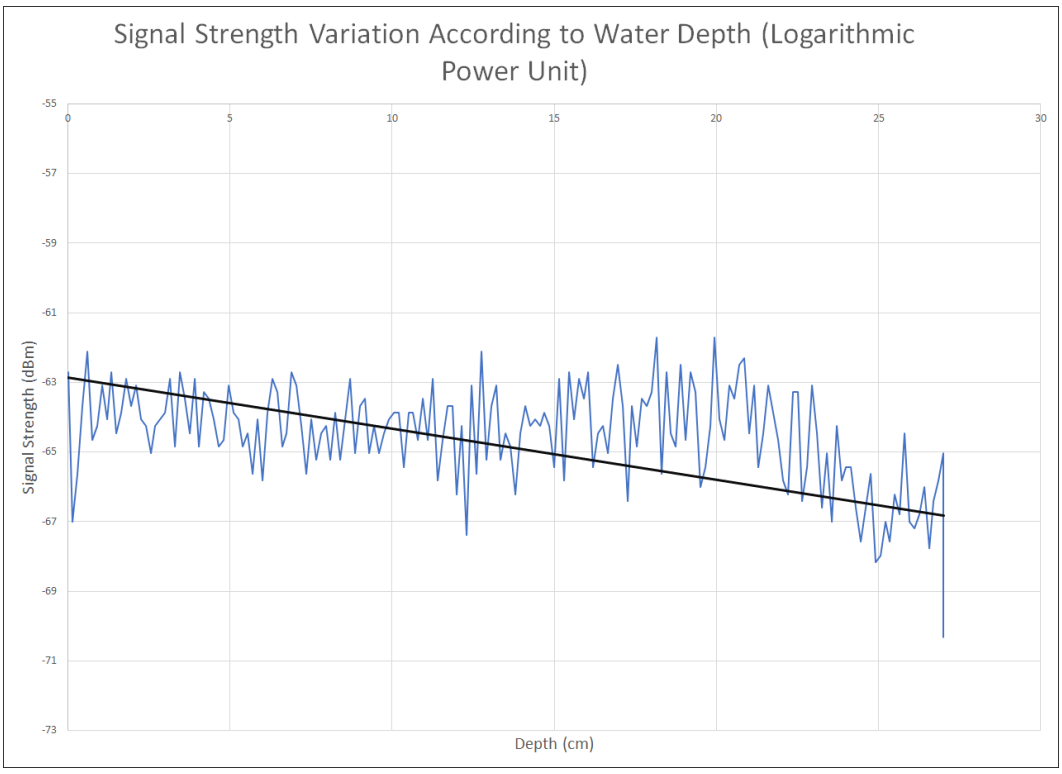


FIGURE 5.2: The signal strength reported from the logarithmic prototype as it descends slowly down the water basin. Black line is simply a linear trend line added for clarity.

Meanwhile, the data from the logarithmic performance underneath a DAS antenna at the Malmö Live Konserthus shows that a substantial signal drop per cm is detected when operating at a higher ambient signal strength (Fig. 5.3).

Lastly, our baseline values for when we have deep water submersion at 28 cm, which turned out to be a good depth (Fig 5.4, 5.5), the signal strength from the GSM module prototype value is this time reported as a CSQ value. The reason is that we are unable to connect to the network. As such, the GSM module fails to produce any report in dBm.

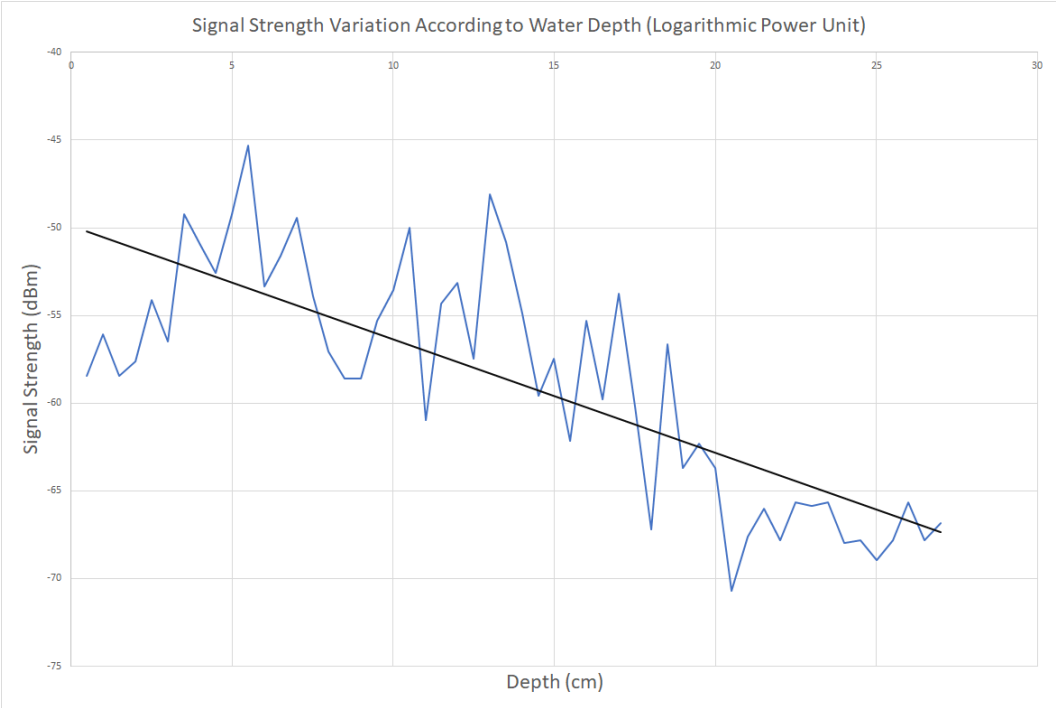


FIGURE 5.3: The signal strength reported from the log prototype as we increase the water level manually. Black line is simply a linear trend line added for clarity.

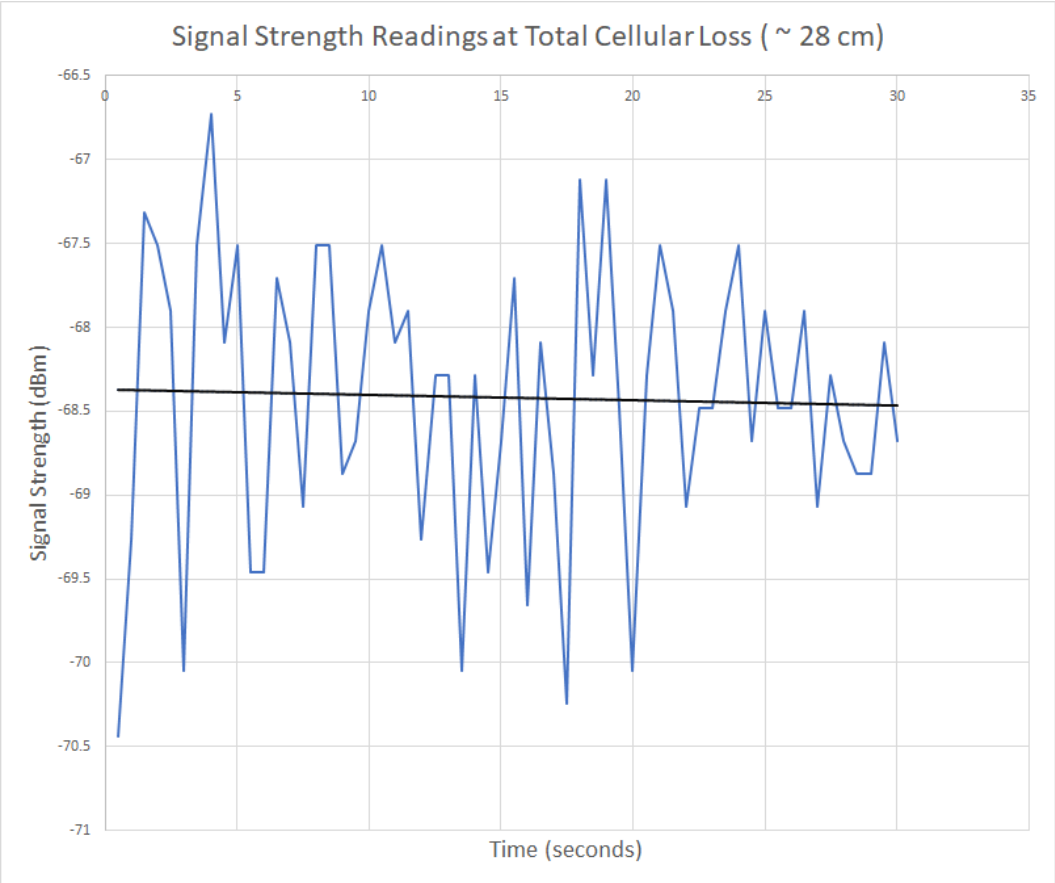


FIGURE 5.4: The signal strength reported from the log prototype as we recorded the data for 30 seconds while it sits at the bottom of the water basin. Black line is simply a linear trend line added for clarity.

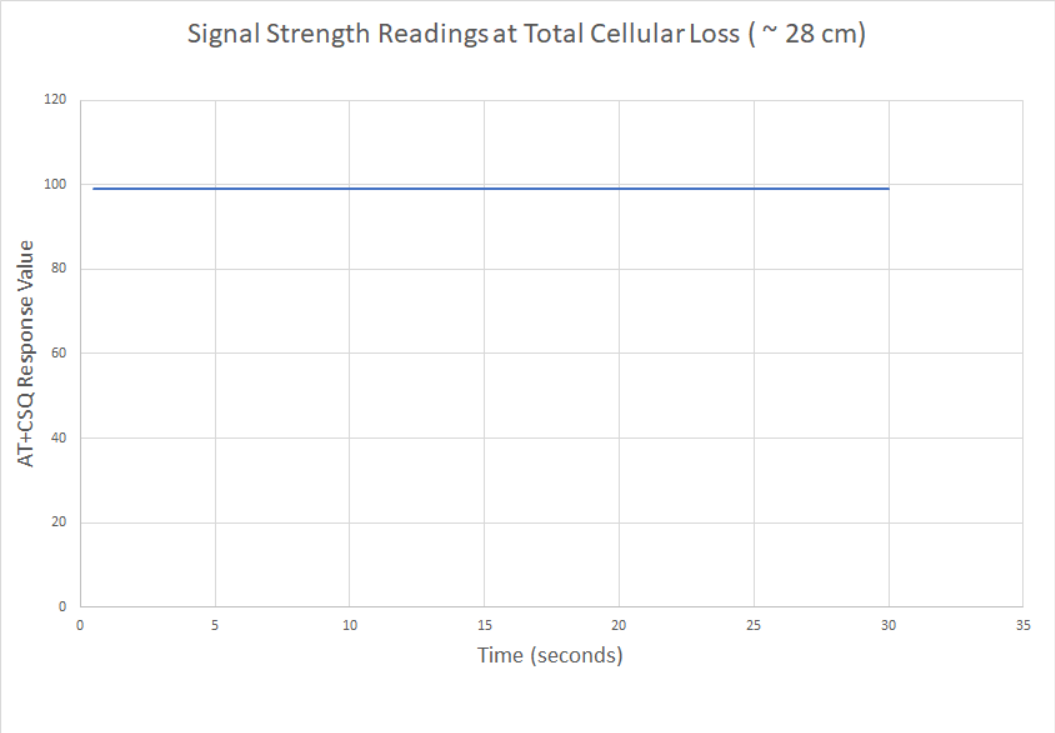


FIGURE 5.5: The CSQ value reported from the gsm prototype as we recorded the data for 30 seconds while it sits at the bottom of the water basin. Black line is simply a linear trend line added for clarity..

### 5.1.2 Power Consumption

Starting with the RF Logarithmic Power Meter in our "active mode" profile, we have the board (atmega328p) in regular operation with the RN-41 powered on and connected, and lastly, our RF Module powered on (Fig. 5.7). The measured current draw amounts to 115 mA compared to a data sheet specified 105 mA. Using equation 4.1 and with the voltage level of 9 V, we calculate the measured power consumption to be 1.035 Watt. With the RF Logarithmic Power Meter in our "passive mode" profile, we have the board (atmega328p) in idle state with the RN-41 sleeping, and lastly, our RF Module powered-off (Fig. 5.6). The measured current draw amounts to 7 mA compared to a data sheet specified 4.46 mA. Using equation 4.1 and with the voltage level of 9 V, we calculate the measured power consumption to be 0.063 Watt.

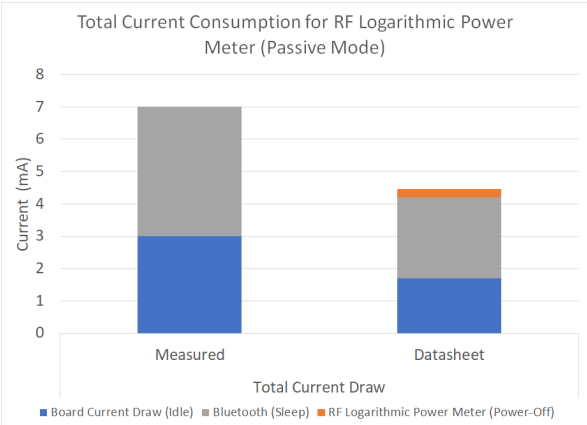


FIGURE 5.6: The current draw from the 9 V battery measured as opposed to data sheet specifications of the whole system in a passive state broken down by module.

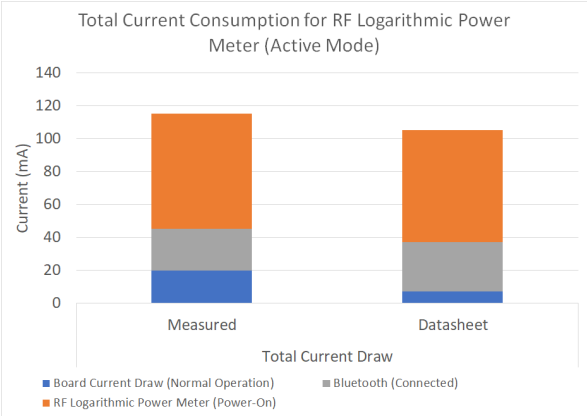


FIGURE 5.7: The current draw from the 9 V battery measured as opposed to data sheet specifications of the whole system in active state broken down by module.

Next to the measurements from the GSM module in our "active mode" profile, we have the board (atmega328p) in regular operation with the RN-41 powered on and connected, and lastly, our GSM module active (Fig. 5.9). The measured current draw amounts to 85 mA. Notice that there is no data-sheet value specified for the GSM module, as the only mention was "depends on the network state." Using equation 4.1 and with the voltage level of 6 V, we calculate the measured power consumption to be 0.51 Watt. With the GSM module in our "passive mode" profile, we have the board (atmega328p) in idle state with the RN-41 sleeping, and lastly, our GSM module idle (Fig. 5.8). The measured current draw amounts to 27 mA compared to a data sheet specified 21.7 mA. Using equation 4.1 and with the voltage level of 6 V, we calculate the measured power consumption to be 0.13 Watt.

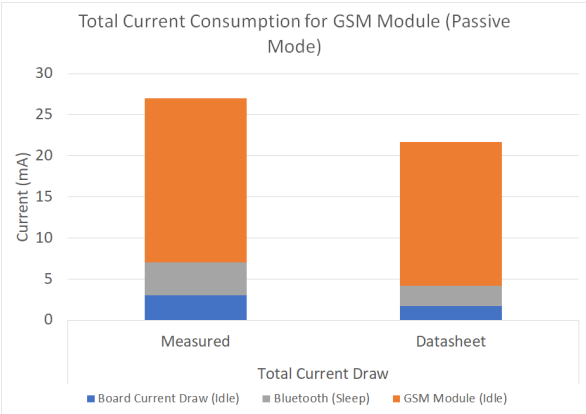


FIGURE 5.8: The current draw from the 6 V battery measured as opposed to data sheet specifications of the whole system in passive state broken down by module.

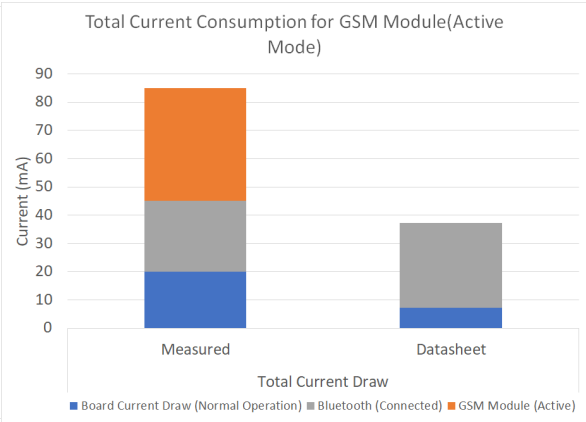


FIGURE 5.9: The current draw from the 6 V battery measured as opposed to data sheet specifications of the whole system in active state broken down by module.

## 5.2 Discussion

### 5.2.1 Signal Strength

#### 5.2.1.1 Water Depth and Attenuation

From our results represented in figure 5.4, we see that a water depth of roughly 28 cm provides enough attenuation to reduce the signals to the lowest possible reading. In this case, the noise strength across the 1 MHz - 8 GHz spectrum amounted to an average power of -68.6 dBm. We must take into consideration that the AD8318 chip has log conformance down to -65 dBm that being the smallest value within the recommended operating range. Therefore, we saw no benefits going beyond 28 cm for our experiment. Using the same water depth with the GSM Module, our results in figure 5.5 indicate that that water level is suitable for the other module as well. The GSM Module's SIM7600 modem has a signal report feature that uses different strength codes to indicate the signal strength level. By getting a value of 99, the module says it is unable to obtain a signal strength reading due to its disconnecting from the network. Therefore, we can conclude that the signal attenuation was enough to completely block the signals at the frequencies used for cellular communication. It is important to note that this is the water depth that was considered enough for our experiment environment where the signal strength reached -45 to -50 dBm, as shown in figure 5.3. When examining the signal strength variations in this figure concerning the data provided in figure 5.2, we see that the base signal strength in that location was -63 dBm, which is a weaker signal by default. Thus while we did use a depth of 28 cm, we see that you would need less depth to attenuate a signal from -63 dBm to -65 dBm than -50 dBm to -65 dBm. The weird signal behavior in figure 5.2 between the 20 cm to 25 cm mark is believed to be a result of attenuating the signal to a level that lies outside the recommended operating range for the AD8318 chip thus the readings became unstable.

Similarly, we see this effect in the GSM Module's SIM7600 signal report shown in figure 5.1. The signal strength doesn't seem to change much at the 20 cm to 25 cm water depth mark. This could indicate that much like the RF Module, the GSM Module is being driven to signal levels at the edge of what it is capable of measuring. Thus, we do not get as stable as a reading. Furthermore, when nearing the edge, the GSM Module will receive a command from cellular tower to increase its transmission power to combat the reduced signal strength, which could explain why the signal does not get lost entirely at those depths. Therefore, if this experiment were done again, it would be essential to run both the water depth experiment and signal variation experiments in the same environment so that the depth is suitable. In our case, the depth we chose was deeper than necessary.

#### 5.2.1.2 Signal Reports and Variation

By figure 5.2, we see that the RF meter reports an ambient signal strength of -63 dBm, which decreases slowly down to -66 dBm across the depth of 27 cm. On the other hand, our GSM module (figure 5.1) reports an ambient signal of -75 dBm down to -90 dBm across the depth of 27 cm. This difference can be explained in two parts. We must first understand that

while the GSM Module uses the SIM7600 modem, which has demodulation and frequency filtration capabilities, the RF Module's AD8318 is simply a Logarithmic power meter that reads the average strength on a range of 1 MHz - 8 MHz. This means that the GSM Module for cellular networks produces a much more accurate signal strength report as it operates directly on the cellular network. With such a vast range, the RF Module's AD8318 is picking up signals from all kinds of sources, which could contribute to the higher signal strength reading.

Furthermore, the AD8318, as previously stated, has a minimum recommended operating range of -65 dBm; therefore, signals weaker than that will not be reported as reliably. Considering that the cellular signal went as low as -90 dBm according to the GSM Module, this value lies way outside the RF Module's operating range AD8318. This reflects a bad choice of Logarithmic power meter from our part, which is an actual product that should use a much more sensitive chip with a much narrower detection band. In an ideal scenario where we have a much higher ambient signal, as seen in figure 5.3, we can see that the RF Module's AD8318 performs much better. Therefore, the approach of using a logarithmic power meter in general, we believe, is still a valid strategy provided you choose the right one.

While our devices will not phase out such tools, the device will become a motoring tool. That instead of doing expensive and full system sweeps that cheap IoT devices are used instead. In case of system failure which these people come in blind and search for the problem, with the history of our IoT devices on each output of the antenna can help the find the fault at a faster rate.

### 5.2.2 Features

Another aspect that is important to discuss is the different features that each approach provides. The RF Module is the simplest of the three, only measuring the radiation output of the antenna in the range of the frequencies it can pick up. The GSM module being more advanced provides more accurate signal reports because the module is similar to that found inside a phone. This makes it more useful as when the module signal is low or lost connection, most likely, and the phone would have the signal has lost the connection as well. It also comes with more sensitive equipment allowing it to detect lower signals than the RF meter. It has more features since it connects to the cellular network and can scan and see different service providers operating. As well as connect to them. Comparing these two devices to the S332E, both devices only cover a fraction of the features, yet those features are essential for monitoring the P-DAS system. We, therefore, think that the IoT devices should be able to take over the S332E monitoring job as a permanent in place solution, but it doesn't have the tools to do a true troubleshoot as the expensive S332E provides. By working in conjunction with the S332E and traditional diagnostic tools, the IoT devices can be a significant time saver when it comes to finding the error source in the P-DAS system.

### 5.2.3 Predictive Maintenance

The ability to collect signal strength reports on a daily bases which our prototypes provide combined with the ability store that data on a nearby device with higher processing power

or the cloud opens up the possibilities for a lot of advanced data analysis that can provide a lot of insight to the status and health of the P-DAS system. The data can be analyzed for trends that could warn of a steady decline in signal strength output or even estimate forecasts of signal behavior based on statistical regression models. The degree of sophistication of the analysis varies depending on the available data sets. To obtain meaningful data, one could install this monitoring solution and simply collect the data over time. Error encountered and resolved over that time-span the data collected and labeled to model the state of the system and armed with that knowledge a data set can be created to train neural network algorithms to pick up these trends and predict their occurrence in the future. There is currently no such data available; however, thus only through adopting monitoring solutions and collecting data can that possibly be explored further.

### 5.2.4 Power Consumption Maintenance Cost

#### 5.2.4.1 RF Module

In our active state, we get a current draw of 115 mA (figure 5.7. The largest contributor being the RF Module itself, which draws 70 mA. In comparison with the datasheet records, we should be drawing 105 mA; however, the difference is negligible as differences are expected due to losses incurred in the voltage regulator and onboard LEDs. With our current setup which uses a 9V alkaline Duracell battery which has a rated capacity of 580 mAh [24] we can expect it to last roughly 5 hours with a power draw of 1.035 W. We, therefore, resort to having the device in a passive state profile when it is not being used (figure 5.6. In this state, we draw 7 mA by utilizing energy-friendly profiles on our different modules, drawing roughly 17x less current and bringing down our power to 0.063 W. With the same battery on full capacity, we can run for roughly 83 hours. Our literature study shows the goal as five years to compete with the current devices; this means our devices should survive 43,800 hours. In passive mode, we would still need a 306,072 mAh capacity to keep our device operational. This is a huge cost. Even by cycling through passive and active mode, we are far from the target. We must, therefore, do further optimizations to our design to reach a better power consumption. For battery-powered devices, the batteries themselves (being non-rechargeable) are the main source of the maintenance cost, and power consumption directly affects that. Using an equivalent 9 V Duracell battery with price of 17.7 SEK each [25] and our estimate of 100 - 150 antennas in a 20,000 $m^2$ office space. We require 1,770 - 2,655 SEK per interval of 83 hours at best, which amounts to 186,809 - 280,214 SEK annually in pure battery swapping expenses. This further emphasizes the need for better power consumption.

#### 5.2.4.2 GSM Module

In the active state, we have a current draw of 85 mA (figure 5.9) with the GSM accounting for 40 mA. That is less than the RF module's draw of 70 mA. However, we see that in its passive state (figure 5.8), the GSM module still draws 20 mA compared to the RF module's 0 mA. This difference is significant as it is the cause for worse passive mode performance. The limitation is imposed by design as we could technically enter what the manufacturer

calls "deep sleep," but that requires changes to the PCB to support a reset circuit for the GSM module. The datasheet states that in "deep sleep," the module would consume less current than when in regular operation, leaving it vague exactly how much we can save [12]. With our current setup which uses a 6 V battery pack which holds 4x AA alkaline batteries for a total capacity of 11,400 mAh. Thus we get an "active state" performance that lasts 134 hours.

On the other hand, in our "passive state" (figure 5.9), we have a current draw of 27 mA giving us 422 hours before we need to switch batteries. Once again aiming for 5 years or 43,800 hours, we would need a 1,183,222 mAh battery, which is a ridiculously huge amount. In passive mode, which is where the device will mostly remain, the maintenance cost for a building of about 20,000 $m^2$ with 100 - 150 antennas can become large. The cost born out of battery replacements amounts to 15.6 SEK per interval of 422 hours [26] for 100 - 150 antennas; it will be 32,383 - 48,574 SEK annually. Cheaper than the maintenance costs for the RF but still pretty huge.

The old method of hiring people for a diagnostic would place no maintenance burden on the company that has a faulty P-DAS. Due to the nature of the service where you would rent out the equipment and the staff until the diagnostic is over.

### 5.2.5 Cost

We estimated the cost of our RF Module to 164 SEK (table 3.1) and GSM Module to 654 SEK (table 3.2). Which is much lower than the price of a single S332E reaching up to 100,000 SEK [15]. You could say we are doing well in terms of cost. However, there are some things to put in perspective. Our monitoring system would need one unit per antenna. Thus the price could easily reach tens of thousands. But we see the potential cuts in time spent locating the errors to be advantageous. The infamous case of Nya Karolinska, where the indoors P-DAS system failed, and indoor coverage was compromised [27]. It took several months and two manual sweeps of the giant complex to locate and fix the problem.

On the other hand, when it comes to benchmarking costs, we stated that the cost of benchmarking a P-DAS in a roughly 20,000 $m^2$ building is about 25,000 SEK such a facility could have anywhere from 100 - 150 antennas. Thus, you could say the price per antenna is 166 - 250 SEK. With such a figure, we can see that our RF Module is sitting in that range, but it lacks the functionality to do a full benchmarking (it can only do coverage, not download/upload speeds). On the other hand, the GSM Module device sits way out of range but is capable of full benchmarking. It might seem like these devices are too expensive. Still, we are only talking about benchmarking costs and not including the added benefits of the tools built for monitoring purposes.

## 5.3 Conclusion

In this dissertation, through conducted experiments and analysis, we have attempted to answer two questions. The first one is about assessing the performance, cost, and maintenance

cost of implementing an IoT based monitoring system for passive distributed antenna systems. Secondly, we wanted to know how the same measured metrics of said IoT system is compared with traditional methods, mostly involving a post-fault diagnostic. The goal of answering these two questions is to assess the potential benefits that might come from having a monitoring system in place. We indicate it could improve up-time as it allows for preventative actions and saves costs through helping better identify the problematic area in a massive network. When it comes to performance, we see that our two prototypes cannot examine the internals of the system. It appears that the devices used in diagnostics such as the S332E can investigate the cables themselves and not just the end-point transmission. This means that the data we can provide on the health of the system is based on its result performance in terms of signal strength (coverage) and data transmission rates (GSM module only). These are the metrics that are visible to the end-user as directly affect their experience. Thus they are well suited for the task of monitoring with the GSM module-based approach offering more than the RF meter, albeit at a higher cost. Speaking of cost, as we had hypothesized previously, the GSM module did end up costing a lot more sitting at almost 650 SEK per unit compared to the RF module's 160 SEK per unit. These prices are even not including any markup, just pure estimated production costs. In comparison to the more traditional approach, we found that a benchmarking of the system would cost about 25,000 SEK for a 20,000 $m^2$, which could house anywhere between 100 - 150 passive DAS antennas. To compete with that, our devices would need to sit in the range of 166 - 250 SEK. This means our GSM module is sitting way outside the range. However, we are suggesting a more permanent in place solution that would monitor over the years as opposed to a one time service. Therefore, these devices end up making up for the costs over time. However, as we have discussed prior, we see considerable room for improvement if we factor in the maintenance costs. Traditional methods incur no maintenance costs as they are a service by nature. On the other hand, the price for batteries was estimated for a 20,000 $m^2$ building housing 100 - 150 antennas at 32,383 - 48,574 SEK for the GSM module and 186,809 - 280,214 SEK annually for the RF meter prototype. It is highly unlikely that such costs are justifiable based on the fact that the systems are generally reliable. Even if a faulty installation does happen, it is safe to assume that you are less likely to encounter further problems once the problem is amended. Thus, a key to making these devices more palatable would be to improve their design. Starting by fully integrating the different modules we have selected for our system, thus eliminating a lot of the power regulators and choosing more suitable chips like a separate logarithmic power meter than the AD8318.

Furthermore, with some adjustment to the circuitry which can allow for a reset circuit and external timers to be attached we would be able to reduce the power consumption drastically and thus save on battery expenses. Alternatively, one could opt for an outlet based model, but we do not recommend that. All in all, it would be too presumptuous to disregard IoT monitoring solutions for passive DAS without more data, and we do recommend further study of this topic. With the amendments to the design we have described, we believe that IoT monitoring solutions could become an industry-standard going forward as a cornerstone that allows for a more reliable and robust passive distributed antenna system.

# Chapter 6

# Social and Ethical Aspects and Future Work

## 6.1 Social and Ethical Aspects

This device has many social aspects and befits, as we have implicated in our thesis. With the increased amount of installation of the P-DAS systems and mobile networks being the norm of communications nowadays. Having access to cellular networks is not only important socially but also a matter of safety. This aligns with our goals to meet the greater performance demands and keep the system up and running by providing a cheap monitoring system that can reduce time and cost incurred by downtime. This benefits companies by paying for expensive troubleshooting and for the company providing the troubleshooting by allowing them to focus their efforts in the troubled area. These devices were developed with the mentality of being safe for people with low transmission power in the area and are easy to install. This device only measures the antennas' signal strength, so it does not infringe on public privacy.

## 6.2 Future Work

As by our limitations and conclusions, we see there are several possibilities to take this research further. Out of all the possibilities, the most notable one would be an evaluation of these devices in a controlled and experimental setup. We were limited in our approach by not being able to adjust the P-DAS system parameters to check different failure scenarios and assess the response of our devices to that. Therefore, if all restrictions are lifted and we can artificially introduce damage either by faulty installations or just outright cutting, twisting and bending things out of place, what kind of responses would we get. This would allow us to understand the robustness of our two different devices fully. As well as how much of the help it would have in conjunction with more traditional methods. Such experiments make for a much more complex and more profound analysis that could further push the potential of smart monitoring solutions. Other exciting topics include building better prototypes based on the things we have learned so far. Such for example, building a hardware filter for the RF module, which would give us more accurate results. We know that we should decrease our power consumption and choose more suitable modules for the job. Therefore, making

revisions and analyzing the performance after those adjustments are made would make for an excellent future study. Finally, an exciting future work that could potentially be done once more data is available from monitoring P-DAS would be to take all that data and analyze it to see if any useful neural network can be trained to pick up the type of errors the system is facing, perhaps even predict its occurrence in the near future as a prevention tool. However, further experiments should be prioritized to assess if the monitoring system can respond well to the different errors and failures that a P-DAS system goes through.

# Appendix A

# Supplement

## A.1 Cellular Networks: History & Overview

The story of mobile telephony services dates back as early as the late 1940s. The second world war had sparked numerous developments in radio communication technology which formed the basis of the first commercially available mobile telephony services. The technology implied that unlike the landline systems one could reach a mobile device without the need for a direct wired connection, thus this service can be adopted by a much greater number of people and over a much greater area. However, the early services suffered several impediments to mass adoption. There were too few channels which meant that only three customers in any city can call simultaneously. Furthermore the equipment was expensive, power hungry and heavy [28].

The earliest description at a cellular network did not come about until 1947 when in his memo Bell Labs engineer Douglas H. Ring proposed the development of a cellular telephone system [29].

However, at the time the technology that would allow such a system to be built had not yet manifested. Furthermore, there were two key issues that needed to be solved in order for the cellular network to work as intended. The first issue had to do with frequency reuse which would require minimal interference from each tower and the other being "hand-off", or the ability to change the tower that is servicing the call as one moves between the regions without cutting-off.

Modern cellular phone services, at least in a recognizable form did not come about until the early 1970s. The advancements made in MOSFET, cellular networking and large-scale integration technology allowed such services to be affordable [30].

And at last on April 3rd, 1973 the first truly mobile handheld call was made by Martin Cooper to his then rival Dr. Joel S. Engel who worked at Bell Labs [31]. Within the same year Martin Cooper filed for a patent describing the Radio Telephone System. A portable duplex radio telephone system which includes some familiar elements of today's modern telephone system such as a base station transmitter and radio tower [32].

### A.1.1 The Main Components

Paul Bedell defines 5 main components to the cellular network: The phone, the cell base station, the back-haul network, the mobile switching center (MSC) and lastly a connection to the public switched telephone network (PSTN) and Internet. In this section an overview will be given of the roles of these different components in shaping the way the network operates today [33].

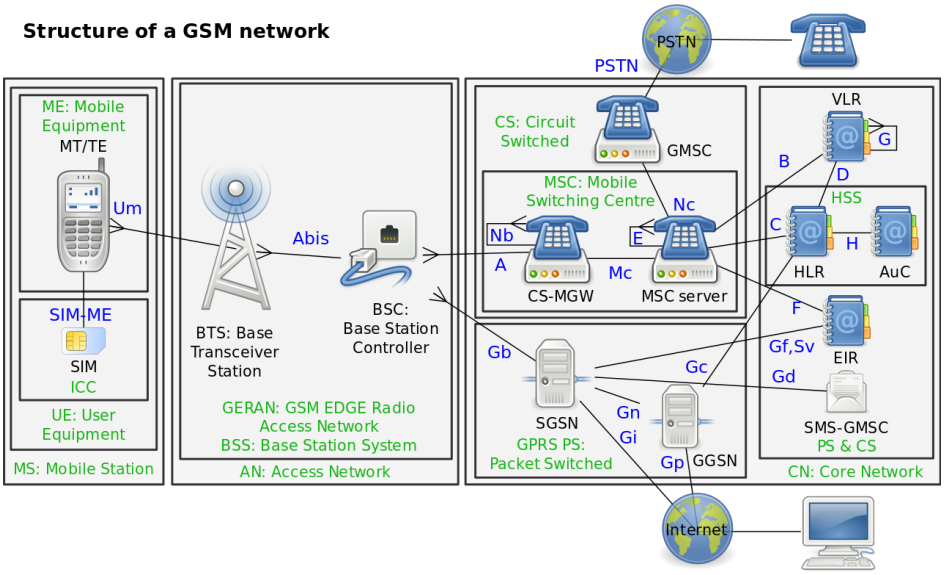


FIGURE A.1: Structure of a GSM network that showcases the common components of a cellular network.
©Wikimedia Commons

The modern smartphone typically supports many different mobile networks including the two most popular GSM and CDMA. Its role is to act as a transceiver for sending and receiving data across the air interface to and from a radio tower that houses the base transceiver station (BTS).

The BTS is the first component of what is known as the base station system (BSS). The BTS houses several equipment whose purpose is to transmit and receive radio signals. Examples of technology that could be found inside a BTS are: Transceivers with TX and RX feeds, comparators that allow the selection of the best signal and a data line that allows the transmission of data to other systems such as the MSC; Combiners which act as RF multiplexers this means we do not require a separate antenna for every channel; Duplexer which allows the TX and RX to be done on the same antenna lowering costs; Linear amplifiers that help amplify the signal after the power costly combination operations and other vital equipment. One can think of BTS as unintelligent access points. They do not have the capability to do any network management on their own. That is why several BTS are connected together to a base station controller (BSC).

The purpose of the BSC is to do some lighter management such as call setup and call hand-off for seamless switching when the user device is moving (inside a train, car). The BSC offloads some of the work in order to allow the MSC to focus on other tasks which will be discussed shortly. In some implementations the BSC is refereed to as a radio network controller (RNC).

The MSC is the centerpiece of any cellular network. It acts as the center of operations and houses a lot of vital processes as well as adjunct processes. Some of the vital roles of the MSC include: Monitoring the health of all the BTS and in case of error and reporting to the network operations center (NOC); Paging which is the means in which one can locate the requested mobile; Internet connectivity which allow cellphone users access to the world wide web; PSTN connection and least-cost routing; Billing and validation processes which allow for features like roaming through databases which include the home location register (HLR) and visitor location register (VLR). There are further authentication processes that serve to stop fraudulent users from using the network. In essence the MSC houses the core functionality of the cellular network.

Depending on the implementation CDMA vs GSM vs others these details will differ slightly. However, this summarizes an overview of cellular networks and their key components.

### A.1.2 Revisions

Over the years, the cellular network architecture has evolved tremendously. The amount of network traffic on the cellular network is expected to more than triple within the next 5 years [34]. As such spectral efficiency and advanced modulation schemes become of upmost important and the architecture is constantly evolving to meet these demands. As of today, the cellular network has gone through four generations with a fifth generation being rolled out soon. Although, a general overview of the network components was given in the previous section. There are some key changes in the life of mobile networks that are worth bringing up. Mobile networks went from analog systems to digital which marked what is now referred to as 2G. After that General Packet Radio Services (GPRS) extended the 2G architecture with a packet switched architecture capable of interfacing with the world wide web (WWW). The next biggest transformation came about with the 4G architecture which was the first to get rid of all circuit switched elements and have a completely packet switched network [35].

### A.1.3 GSM/GPRS Interface and Modulation

As stated in the previous section GPRS was an improvement by adding packet switching architecture to the circuit switched GSM thus allowing for mobile internet traffic. GPRS uses a frequency division duplex (FDD) based interface that makes use of time division multiple access transmission protocol (TDMA). This means that

the transmitter and receiver are operating at different frequencies separated by either 90 MHz or 45 MHz. The TDMA technique however, allows several users to be connected on the same channel by giving each user a pre-defined time slot. In case we have full-rate communication the user will get one time slot every frame while half-rate communication indicates that the user gets one time slot every two frames. Thus GPRS can support 8 users (full-rate) or 16 (half-rate) however, one time slot is always reserved for the broadcast control channel (BCCH). These time-slots can carry either voice data that will go through the circuit-switched network or packet-data that will go through the packet-switched network.

When it comes to the modulation of the signal GPRS uses what is called Gaussian minimum shift keying (GMSK). GMSK is a modulation technique where phase of the carrier signal is varied by the modulation signal. A Gaussian Filter is used before the modulation stage hence it differs from regular MSK. The impulse response is described as followed where B is the half-power bandwidth [36].

$$k_1 = \frac{\pi}{\sqrt{2\ln 2}} \tag{A.1}$$

$$h(t) = \frac{k_1 B}{\sqrt{\pi}} e^{K_1^2 B^2 t^2} \tag{A.2}$$

GMSK modulation is mostly based on MSK. MSK modulation operates very similarly to offset quadrature shift keying (OQPSK). This means that two signals are in quadrature (separated by 90 degrees in phase) such as a sine and cosine signal are summed together. By varying their amplitudes one can produce much more complex modulations in phase, frequency and amplitude. The function that changes the amplitude of the cosine is called the I function by convention and similarly the function that changes the amplitude of the sine function is called the Q function. However, as implied by the name this modulation scheme focuses on interpreting the changes in phase as representations of binary data. The key difference is that OQPSK uses square pulse signals as I and Q signals. However, MSK uses half-sine signals to reduce distortions. An overview of the process can be seen in the figures below (Fig. A.2, A.3).

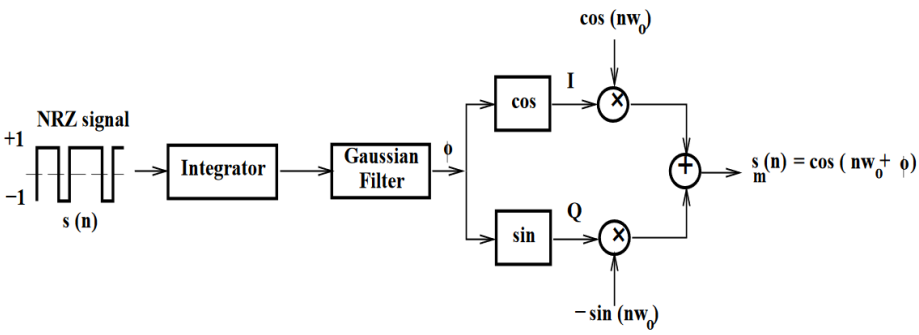


FIGURE A.2: Modulation of GMSK using quadrature signals.

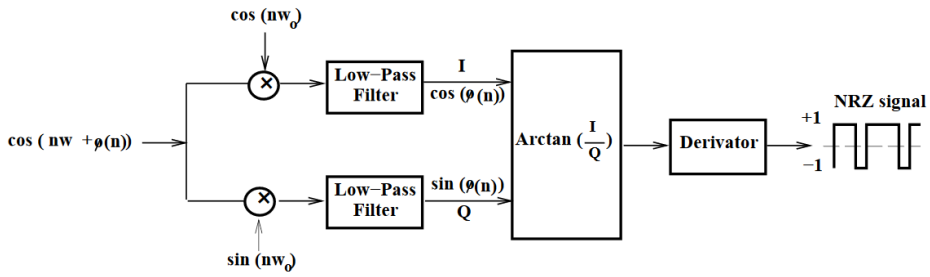


FIGURE A.3: Demodulation of GMSK using quadrature signals.

As shown in the figures above you start GMSK encoding by having a binary signal that is integrated and convoluted with a Gaussian filter. A Gaussian filter reduces the out-of-band interference which allows for more narrow phase angles. We then compute the I and Q signals to represent the binary signal data which we intend to transmit and combine the quadrature signals to be transmitted. At the reception site this process is inverted to restore the binary data.

## A.2 IoT devices

The two IoT devices are meant to be mounted right next to a DAS antenna thus they are small light probe devices which are battery powered and can be mounted with a simple two-sided tape.

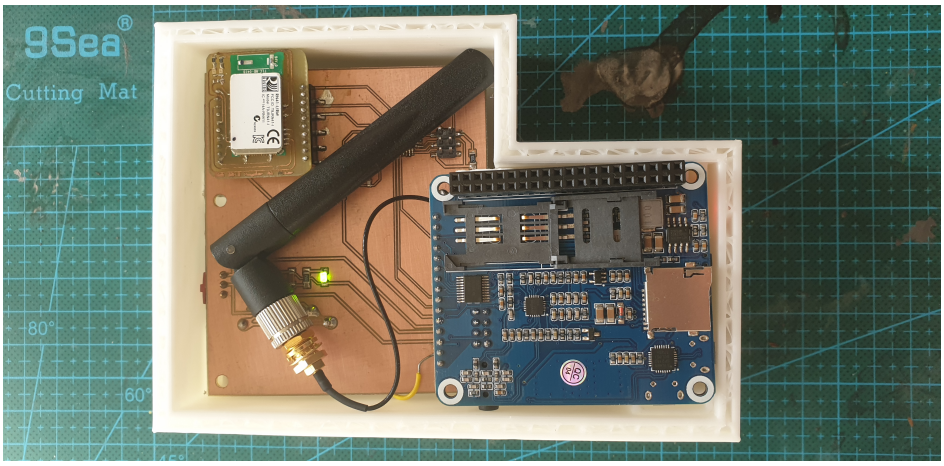


FIGURE A.4: Picture of the GSM device

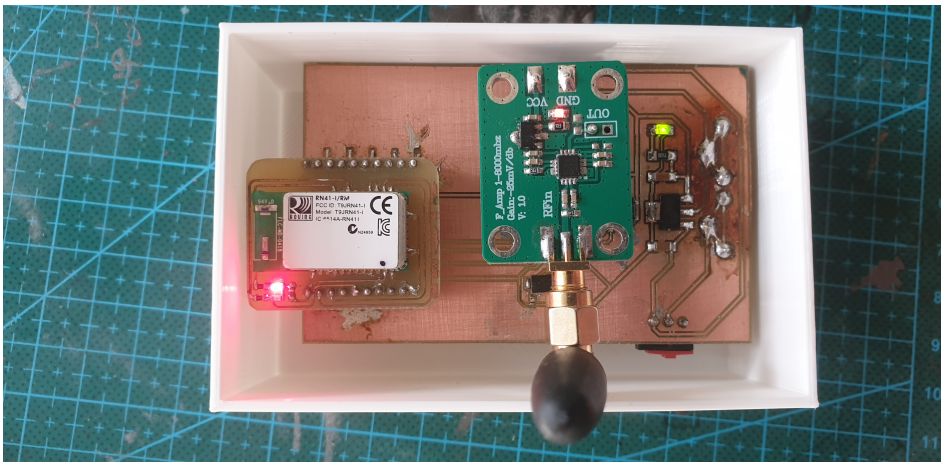


FIGURE A.5: Picture of the RF device

## A.3 Extra

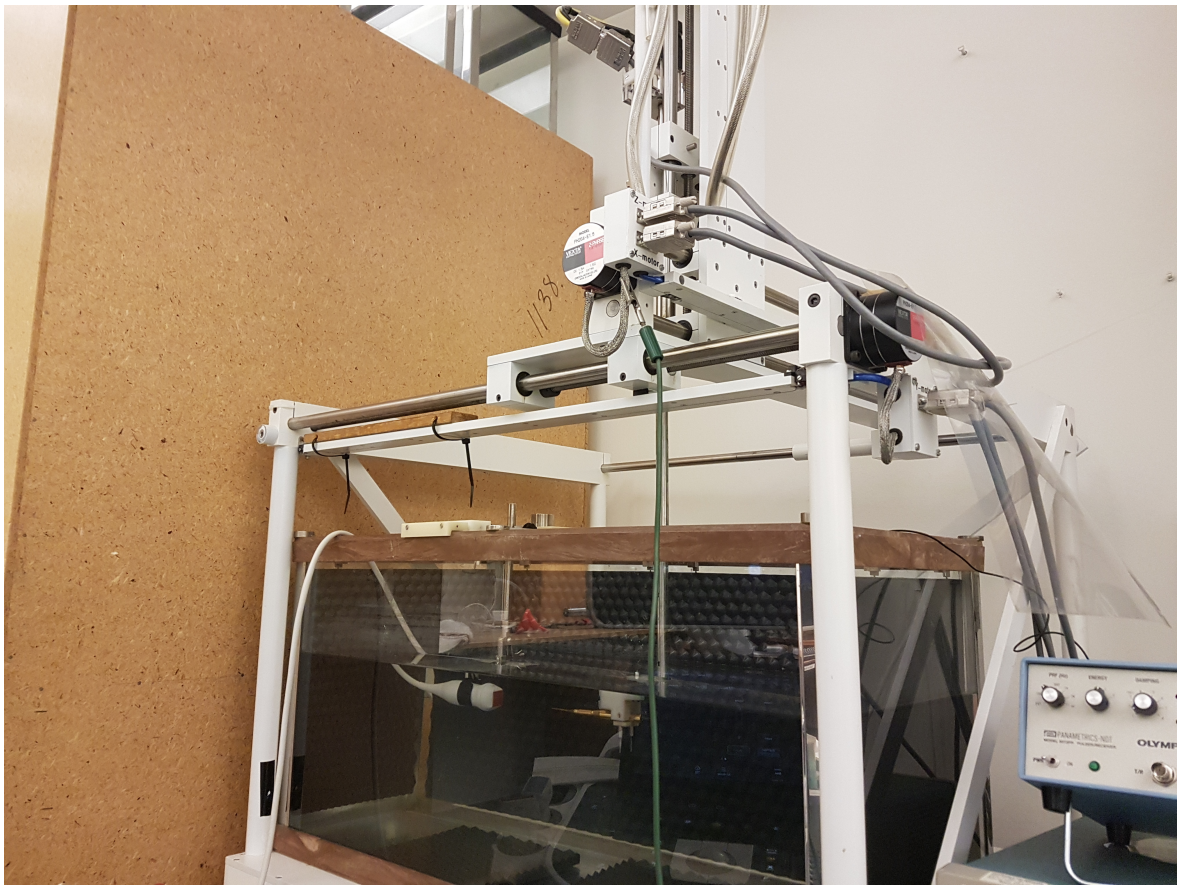

FIGURE A.6: Picture of the Ultrasound focal point tester

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