UNIVERSIDAD DE CHILE
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
DEPARTAMENTO DE INGENIERÍA ELÉCTRICA

DESIGN AN IMPLEMENTATION OF A GAS SENSING DEVICE CAPABLE OF SENDING REAL TIME DATA VIA NARROW BAND - IOT

MEMORIA PARA OPTAR AL TÍTULO DE INGENIERA CIVIL ELÉCTRICA

ALMENDRA FERNANDA PIZARRO MUJICA

PROFESOR GUÍA:
CESAR AZURDIA MEZA

PROFESOR CO-GUIA:
EDUARDO CARRASCO GALDAME

MIEMBROS DE LA COMISIÓN:
FRANCISCO RIVERA SERRANO
JORGE SANDOVAL ARENAS

SANTIAGO DE CHILE
2024

RESUMEN DE LA MEMORIA PARA OPTAR
AL TÍTULO DE INGENIERA CIVIL ELÉCTRICA
POR: ALMENDRA FERNANDA PIZARRO MUJICA
FECHA: 2024
PROF. GUÍA: CESAR AZURDIA

DISEÑO DE DISPOSITIVO SENSOR DE GAS CON CAPACIDADES DE TRANSMISIÓN DE DATOS EN TIEMPO REAL A TRAVÉS DE TECNOLOGÍA DE BANDA ESTRECHA PARA INTERNET DE LAS COSAS (NB-IOT)

El monitoreo de la calidad del aire es crucial para la salud pública y la sostenibilidad ambiental. En las últimas décadas, se ha observado un deterioro de la calidad del aire en áreas urbanas, atribuido a mayores concentraciones de material particulado (PM) y partículas por millón (PPM) [1].

Sin embargo, el desarrollo de dispositivos para medir la calidad del aire suele ser costoso, especialmente los certificados por entidades como la Agencia de Protección Ambiental de los Estados Unidos [2].

Esta memoria investiga la viabilidad de usar tecnologías de sensores emergentes para crear soluciones económicas para el monitoreo en tiempo real de la calidad del aire. Motivada por la necesidad de soluciones accesibles, especialmente en regiones con limitaciones presupuestarias que restringen la implementación de sistemas de monitoreo tradicionales. La memoria se enfoca en los Kits de Inicio de Entel, desarrollados por RAK Wireless, que promueven dispositivos NB-IoT asequibles y sencillos.

Mediante una revisión de la literatura, avances tecnológicos y marcos regulatorios, se explora el uso de estos Kits para medir en tiempo real concentraciones de NO_2, NH_3 y CO. La metodología incluye diseño, prototipado y pruebas para evaluar la eficacia y confiabilidad de la solución propuesta.

Los hallazgos demuestran que las tecnologías NB-IoT pueden ofrecer soluciones asequibles para el monitoreo de calidad del aire, destacando la importancia de colaboración entre telecomunicaciones, organismos reguladores y agencias ambientales para mejorar la accesibilidad de estas tecnologías.

Esta memoria proporciona ideas sobre el desarrollo de dispositivos rentables para el monitoreo de la calidad del aire, con implicaciones para la salud pública, la política ambiental y la innovación tecnológica.

El objetivo del trabajo fue diseñar, implementar y validar un dispositivo inteligente para medir concentraciones de gases contaminantes y proporcionar estimaciones precisas de PPM. El dispositivo, que no requiere wifi y opera con datos en tiempo real, fue sometido a varias pruebas y calibraciones para garantizar su precisión. Además, se optimizó el código para mejorar la eficiencia energética y evitar el sobrecalentamiento.

Los resultados fueron positivos, cumpliendo los objetivos propuestos. No obstante, la gestión de la batería no fue óptima, sugiriendo que futuros trabajos podrían centrarse en mejorar la eficiencia energética del dispositivo.

RESUMEN DE LA MEMORIA PARA OPTAR
AL TÍTULO DE INGENIERA CIVIL ELÉCTRICA
POR: ALMENDRA FERNANDA PIZARRO MUJICA
FECHA: 2024
PROF. GUÍA: CESAR AZURDIA

DESIGN AN IMPLEMENTATION OF A GAS SENSING DEVICE CAPABLE OF SENDING REAL TIME DATA VIA NARROW BAND - IOT

Monitoring air quality is crucial for public health and environmental protection. In recent years, there has been a noticeable decline in air quality in urban regions worldwide, mainly due to increased levels of particulate matter (PM) and particles per million (PPM) [1]. However, developing devices that can measure air quality often involves significant costs, particularly those certified by organizations such as the US Environmental Protection Agency [2]. In response, this thesis investigates the use of new sensor technologies to design affordable real-time air quality monitoring systems. Driven by the need for economical and accessible air quality monitoring options, especially in areas restricted by financial resources, this study examines the use of Starter Kits by the telecommunications firm Entel. These Kits, powered by RAK Wireless technology, are designed to enhance the Internet of Things (IoT) ecosystem with their narrow-band IoT capabilities, offering simple and cost-effective solutions for various challenges. This research thoroughly reviews the existing literature, technological progress, and regulatory standards to explore the potential of these starter Kits to develop a device that can monitor air quality in real time for three specific gases: NO_2, NH_3, and CO. The methodology includes design, prototype development, and testing to assess the effectiveness and dependability of the proposed system. The results of this research add to the growing field of affordable air quality monitoring by showing how IoT technologies can be utilized to overcome the obstacles posed by expensive certified reference equipment. It also highlights the critical role of cooperation among telecommunications firms, regulatory agencies, and environmental bodies in enhancing the affordability and accessibility of air quality monitoring infrastructure. In general, this thesis offers valuable insights into the development of cost-effective air quality monitoring devices that impact public health, environmental policies, and technological advancement. The aim of this project is to design, implement and validate a smart device that measures the concentration of pollutant gases and accurately estimates the ppm values. In addition, the device must operate without Wi-Fi to conserve power and provide precise real-time data. To fulfill this aim, multiple prototypes of the device were developed, with ongoing calibrations to ensure the accuracy of the system. The software was also optimized to improve battery efficiency, prevent overheating, and protect sensitive components. The device successfully met its objectives with positive results. However, the battery management system did not perform as expected, suggesting that future efforts could focus on improving the energy efficiency of the device.

I wish I hadn't cried so much!
I shall be punished for it now, I suppose, by being drowned in my own tears!
That will be a queer thing, to be sure! However, everything is queer to-day.

If I had a world of my own, everything would be nonsense.
Nothing would be what it is, because everything would be what it isn't.
And contrary wise, what is, it wouldn't be. And what it wouldn't be, it would. You see?
-Alice in Wonderland

Acknowledgments

En primer lugar, quisiera agradecer a mi familia, a mi hermano René quien incentivó mi gusto por las matemáticas aun sin darse cuenta, que siempre me ha apoyado y ayudado en todo. A mi papá Ricardo, que siempre ha estado cuidándome y del que saco gran parte de mi personalidad extravagante y mi lado artista y matemático, te quiero mucho y agradezco lo que has hecho por mí durante estos años. A mi abuelita que me enseñó a caminar y que me cuidó cuando era pequeñita. A Juanjo, que siempre me ha apoyado en mis sueños y en mis metas, que nunca ha dudado de mí y que me ha tenido paciencia también todos estos años y me ha cuidado como a una hija más, te quiero mucho y lo agradezco de corazón. A mi hermanita Andrea, pasar la adolescencia contigo me abrió muchas cosas y te agradezco que siempre buscaste lo mejor para mí. Finalmente, a la persona más importante en mi vida, a mi mamá Alejandra, sin ti no sería la persona que soy ahora. Gracias por enseñarme lo que significa ser una persona honesta, amable y darme todos los valores importantes. Eres un pilar fundamental en mi vida y agradezco todo el cariño, paciencia y amor con el que me has cuidado todos estos años. No podría haber pedido una mejor mamá. Te amo.

Quería también dar las gracias a todos los amigos que me acompañaron en este camino, tanto a los del colegio como a los que hice en la universidad, gracias a toda la tropa neurodivergente por darme risas, peleas y chismes. Especiales agradecimientos al Gio, haberte conocido durante este último tiempo ha sido una de las mejores cosas, gracias por ser tan buen amigo. Gracias a Blanca, *My Melody*, que me ha ayudado y acompañado estos últimos años tanto en los juegos como en la universidad y que con la mayor amabilidad del mundo me presto su casa como sede para este proyecto.

De mis amiguitas del colegio les quiero dar las gracias a PL, me ayudaron a tener confianza y saber que siempre tengo un lugar donde ir. Mariana, estoy muy agradecida de haber podido convertirme en una amiga cercana a ti, gracias también por el apoyo que me has dado en mi vida y en todos mis proyectos. Finalmente, a Javiera, mi mejor amiga que me ha acompañado desde hace más de 10 años, gracias por protegerme en el colegio, gracias por cuidarme en mis momentos más difíciles y también por alegrarte conmigo en los mejores momentos, eres la persona que más me entiende y a quien siempre puedo recurrir, gracias por quererme, ser mi amiga y estar ahí para mí tanto para felicitarme como para guiarme cuando lo necesito.

Gracias también a Benjamín, que me acompañó en este último año de universidad y ahora mientras termino la memoria. Me has mostrado comprensión infinita en todos los sentidos y me has apoyado en los buenos y malos momentos. Gracias por aliviar mi día a día trayéndome felicidad y gracias por estar conmigo.

Finalmente, quiero agradecer a todos los profesores que me formaron y también a mi profesor guía Cesar Azurdia, que me acompañó durante todo este proceso, que fue comprensivo conmigo en mis momentos difíciles y que me ayudó de la mejor forma posible cada vez que lo necesité.

Table of content

Table index

Ilustration index

Chapter 1

Introduction

In recent times, with the increase and accelerated growth of the population, there has been an increase in traffic congestion and an uprising in the use of public and private transportation. This creates a negative impact on the quality of life of people and also on the environment [3]. Exposure to high levels of atmospheric pollutants such as nitrogen dioxide (NO_2), carbon monoxide (CO), and ammonia (NH_3) have detrimental effects on human health and contribute to climate change [4].
Recognizing this problem, it is imperative to develop efficient traffic and pollution monitoring systems that can provide real-time information on the level of contamination in urban areas. With this context in mind, Internet of Things technology has surfaced as a promising solution providing the ability to connect and communicate devices and sensors to a smart red for data communication.

This project pretends to explore the potential of a narrow-band Starter Kit, which from now on would be referred to as just Kit or Kits when talking about both devices; and to create, design and implement a device that can do an accurate detection of NO_2, CO, and $NH3$ in the environment, thus establishing a monitoring system of the change in the concentration of contamination in real time in certain urban areas. The Kit is characterized by its low energy consumption, high signal penetration, and large coverage, so it becomes an ideal starting point for the creation of the device in question, and also for implementing a network of these devices with the sensors and the cloud sending data in real time.

To archive the latter, a specific sensor will be used; this sensor is capable of measuring the concentration of the three gases mentioned above, the sensor will measure them, and then the Kits read this information, which would connect to the Narrow band network and give the information to a platform, in this case *AdafruitIO*, in which the data would be archived and displayed on a dashboard to allow visualization of the data and retrieval to later analyze its contents.
with the recollected information is expected to create an analysis of the contamination levels and concentrations at different hours of the day.
In summary, this work seeks to investigate and prove the viability of using this kit with the sensor combination to carry out the measurement of contamination on the environment in a more efficient way, both in monetary matters and in comfort for the user. This is because this device is expected to last for a long period of time without human intervention. Hopefully, the research of this investigation contributes to improving the diversity of equipment design to measure air quality and, with that, to better the quality of life of the population with regard to exposure to air pollutants, to foster sustainable urban planning and to promote the

incorporation of smart technologies to tackle current environmental challenges.

1.1. Motivation

As explained previously, the motivation for this project is to determine levels of pollution in the environment that affect the quality of life of the population. As time passes, it becomes more evident that environmental monitoring is necessary and that large amounts of contaminant gases produced by factories, mobile vehicles, and other sources cause detrimental damage to the health of the community where they are located [5]. Apart from this, most of the available devices in the market do not achieve an efficient and economical design; the device proposed accomplishes both and will provide the required data to the user and allow easy user manipulation and installation.

The purpose of this work is to design and implement a detection system of contaminating gases on real time, likewise is expected to to be able to accomplish an infrastructure of communication that allows the transmission of recollected data in a safe and efficient way. Its expected that this work contributes to the research of the air quality in urban areas and subsequently that it can be use to improve the air quality by providing precise and timely information about the levels in the air and the correlation to the public transportation vehicles and about the time and place when the concentration levels spike up or when they go down.

The idea is that in addition to creating and coding the device, all the data recollected is analyzed to find patterns and tendencies and with that being able to generate mitigation strategies for the contamination in the air in the context of public transportation.
The innovation aspect of this device is that it can be autonomous, meaning that it is portable, it does not need Wi-Fi connection for the setup of the device as it subscribes to the time topic from Adafruit to get the current time and date, and then it can completely work on its own sending the data via NB-IoT connection. The design of the device is calibrated both by hardware and by code, ensuring more accurate measurements; even tho the sensor is not designed to provide exact values since it is made to be a comparative sensor, it is still a reliable source for percentage changes on the device.
Also, since the sensor is not by the RAK company and does not use the pin header for the sensor connections of the RAK 19001 board, this project also presents a proof of concept on which its possible to demonstrate that external sensors can be used with this board, since there is almost no documentation about projects done with RAK Wireless boards that are not composed of all RAK made components.

For this project in particular, it is necessary to create two separate devices; they will be created equally so for the effects of this work, all the methodology and the process used will be concentrated on the creation of one device until the final data testing for which both devices are going to be used.

1.2. General objective

The main objective of this work can be described as follows:

Design and implement a NB-IoT device capable of automatically measuring gas concentrations, data transmission, and its analysis in urban scenarios.

1.3. Specific objectives

Inside the general objective there is also specific objectives which are described below:

- To implement and innovate the NB-IoT device provided by Entel.
- To develop a device that is low-cost and does not need constant calibration and operation.
- To adapt and calibrate a gas MOS sensor into the NB-IoT device.
- To ensure a reliable and stable connection between the NB-IoT device and the broker.
- To ensure a correct function of the device without the need for Wi-Fi
- To measure accurately different type of gas concentration in the air.
- To analyze the data and provide meaningful conclusions.

1.4. Thesis structure

The outline of this thesis is presented as follows. In the second chapter, the theoretical framework will be explored; this is to establish the preexisting foundation of this project on which it will be developed. This provides the technology used and the way gas detection works.
The third chapter will explore on the current state of the art of the project, this will provide some real-life examples on which this technology has already been used by other companies and countries as a whole and will provide a little resume on how they were deployed.
Chapter number four is the crucial chapter for this project, and here it exposes all the work done, from its conception till the implementation. It will also deepen the methodology used, the design, the materials used, and the final implementation of the project. Chapters five and six are about the results obtained from the created device and the analysis of these results. Finally, Chapter seven will focus on the conclusions of the project and possible future work directions will be provided.

Chapter 2

Theoretical framework

This section provides a review of the literature of the items needed to contextualize and comprehend this project. Understanding the fundamentals will allow a better understanding of the implications and possible applications of this type of developments.

2.1. Internet of Things - IoT

The Internet of Things, or IoT, is a network of interrelated physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and connectivity, which allows these objects to connect and exchange data [6]. Data exchange can be between other IoT devices or with cloud servers.
This technology contains a mix of computer science, electronics, and communication engineering for its function; the main advantage of this is that IoT devices do not need to be connected to a public internet to communicate, they just need to be on the same network and be individually addressable.
The therm *smart device* appears as early as 1982, but the concept of the *"Internet of things"* and the term itself first appeared in a speech by Peter T. Lewis, to the Congressional Black Caucus Foundation in Washington, D.C., published in September 1985. According to Lewis, *'The Internet of Things, or IoT, is the integration of people, processes, and technology with connectable devices and sensors to enable remote monitoring, status, manipulation, and evaluation of trends of such devices,'*.
The term *'Internet of Things'* (IoT) was coined by Kevin Ashton in a presentation to Proctor & Gamble in 1999 [7]. He is one of the founders of the Massachusetts Institute of Technology's Automatic Recognition Lab. He considered radio-frequency identification (RFID) as a fundamental component of the Internet of Things, a system that would empower computers to oversee the management of individual items. The core idea of the Internet of Things revolves around the incorporation of short-range mobile transceivers into diverse gadgets and daily essentials. This integration enables innovative forms of communication among people and objects, as well as between objects themselves [8] [9].
Currently, the main goal of IoT is to create a smart and interconnected ecosystem where devices can seamlessly interact and make intelligent decisions with little to no human intervention [10]. With the decreasing cost of integrating computing power into small objects, it is now possible to add connectivity through many devices. For example, the voice service capabilities of Alexa to microcontrollers (MCUs) uses less than 1 MB of integrated RAM, as

seen in the case of light switches.
An entire sector emerged with the goal of filling homes, businesses, and offices with IoT devices. These smart objects can automatically transmit data over and over the Internet. All these invisible computing devices and the associated technology are collectively called the Internet of Things.
As a result of reduced device costs, improved cloud storage computing, increased speed, and decreased delivery expenses, numerous companies and research institutions have articulated diverse projections regarding the potential influence of the Internet of Things (IoT) on the internet and on the economy in the coming decade. Huawei envisions a total of 100 billion IoT connections by 2025. Meanwhile, Manyika et al. estimate the prospective economic impact of the Internet of Things to range from $3 to $11 trillion dollars annually by 2025 [11].
IoT revolutionizes both personal and professional spheres, improving lifestyles and optimizing business operations. Consumers use IoT-embedded devices, such as smartwatches, cars, and thermostats, to streamline daily activities. For instance, upon arriving home, a person's car can seamlessly communicate with the garage, triggering the door to open. Simultaneously, the thermostat adjusts to a pre-set temperature, and the lighting dims to a lower intensity and specific color.
Beyond its impact on personal convenience, IoT also plays a crucial role in the business landscape. It provides organizations with real-time insights into operational efficiency, covering machine performance, supply chain management, and logistics operations. This comprehensive view empowers businesses to make informed decisions and improve overall productivity. Furthermore, the IoT facilitates automation, allowing machines to perform repetitive tasks autonomously. This not only reduces labor costs, but also minimizes waste and improves service delivery. By optimizing manufacturing and delivery processes, IoT contributes to cost effectiveness while ensuring transparency in customer transactions.
Recognized as one of the most crucial technologies today, IoT continues to evolve, and businesses increasingly recognize the potential of connected devices to maintain competitiveness [12]. As companies embrace IoT solutions, technology remains a driving force in shaping a smarter, more efficient future.

2.2. Narrow Band - IoT

Narrow Band IoT or NB-IoT, is a Low-Power Wide-Area network (LPWAN) technology standardized by 3GPP in 2016 in the 3GPP release 13 (LTE Advanced Pro) [13], its main focus is to acquire data from smart applications that demand a low transmission rate. The most important characteristic of this technology is that it allows massive connection at a low energetic cost, offering at the same time high bidirectional coverage, both for signaling and for the data plane. Furthermore, the fact that its deployment is in the 4G LTE architecture considerably reduces the implementation costs of this technology, and this is also enhanced by the low cost of the devices used to operate with this technology.
NB-IoT is designed specifically for the use of IoT applications, providing efficient communication along with low data rate, long battery duration, and wider coverage.
The communication by Narrow Band as its name expressed uses the guard band between the broad band to transmit data, these guard bands are known as narrow bands, they use OFDM modulation to operate for downlink communication and SC-FDMA for uplink communications, and have a bandwidth of 180 kHz. This type of technology operates inside the

spectrum of licensed bands, ensuring reliable and interference-free communication.

This kind of band, as mentioned above, has extensive coverage, allowing devices to communicate and connect even if the cell phone signals are weak [14]. This network can penetrate buildings and subterranean structures more effectively compared to traditional cell phone networks. It also works with a low data rate; this is because NB-IoT is optimized for applications that send small amounts of data with low frequency. It can hold up to 250 Kilo bits per second (kbps), which is adequate for purposes such as environmental monitoring, smart samples intake, and asset tracking.
In general, this type of technology is adopted by industries like agriculture, smart cities or houses, logistics, public services, etc. [15]. The narrow band IoT can provide space for the implementation of IoT networks on a large scale, with thousands or even millions of devices, facilitating the recollection and efficient data analysis for various applications [16].
NB-IoT has been adopted by telecommunications operators all around the world, a large number of countries have implemented this types of network commercially because of that the connectivity of IoT devices on a bigger scale has been possible.

The architecture of this technology simplifies the EPC technology present in LTE networks, with the objective of complying with the traffic requirements stipulated in the 13 release. The MME, SWG, and PGW functions are enclosed in a dedicated core network called C-SGN, as shown in Figure 2.2.

The S1-MME interface is maintained and the S1-Lite interface is optimized for control messages; the structure of these interfaces is shown also in Figure2.2. In addition, the S1-U interface is no longer required in this structure [17]. Finally, the overall structure of the NB-IoT is represented in Figure 2.1 below:

To ensure that the battery of these devices can be active for years without intervention is necessary to reduce the energetic consume to the minimum, For that reason, the NB-IoT network integrates a temporal connection system that allows the device to be disconnected for long periods of time.
Telecommunication operators have made relevant investments to implement these structures. There have been deployments of these networks, pilot tests, and infrastructure actualization to provide coverage and connectivity to NB-IoT on almost all of the territory, providing a wide coverage range.

2.3. Narrow Band IoT and other technologies.

There are other existing technologies that support massive IoT deployments; there is category M1 (Cat-M1), LoRa and LTE-M. Although these can be used for the same purpose, they address different types of cases and have distinctive characteristics that separate them from each other.

Cat-M1, also standardized by 3GPP, functions within a 1.4 megahertz (MHz) bandwidth. It entails increased device complexity and costs compared to NB-IoT. However, due to its broader bandwidth, Cat-M1 can achieve reduced latency, support data rates of up to 1 megabit per second (Mbps), and offer enhanced device positioning accuracy [19].

LTE-M is also 3GPP standardized, and LTE machine-type communications (LTE-MTC) operate within a 1.4 MHz bandwidth, achieving data rates peaking at 1 Mbps. LTE-M offers

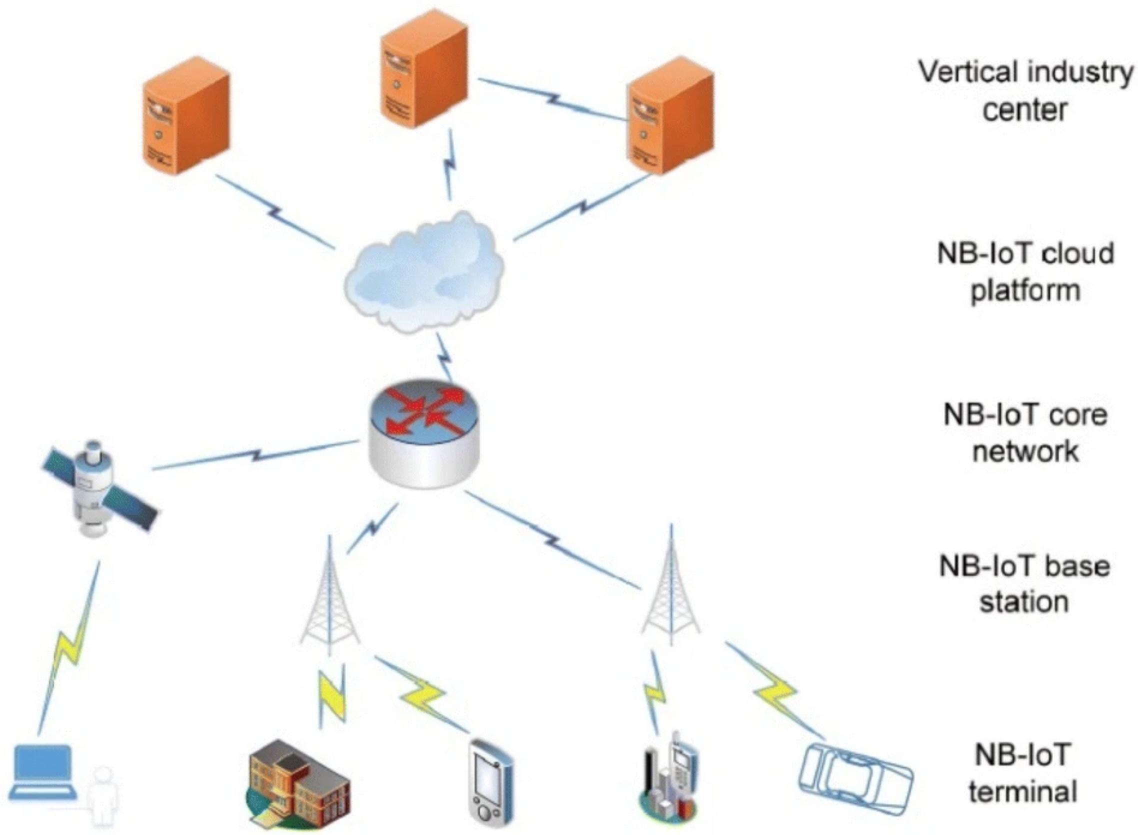


Figure 2.1: NB-IoT architecture, extracted from NB-IoT: applications and future prospects in perspective of Bangladesh [18].

simplified device complexity, low power consumption, high connection density, and minimal latency, extending coverage, and enabling the reuse of existing LTE infrastructure. Deployment options include integration within a standard LTE carrier or standalone deployment in dedicated spectrum, using LTE spread spectrum technology. Compared to NB-IoT, it operates across multiple generations of cellular networks and eliminates the need for a gateway, offering enhanced indoor coverage, support for numerous low-throughput devices, low latency sensitivity, minimal device power consumption, optimized network architecture, and cost-effectiveness. However, LTE-M is relatively pricier due to patents held by major carriers, necessitating royalties for intellectual property usage by LTE-M users [19].

Finally, Long Range or LoRa is employed as a Wide Area Network (WAN) technology, and represents a non-cellular modulation approach within LoRaWAN, the standard protocol for WAN communications. Developed by the LoRa Alliance, a nonprofit organization focused on standardizing Low Power Wide Area Network (LPWAN) technologies, LoRa enables energy-efficient, long-distance wireless communication for Internet of Things (IoT) devices. LoRa serves as the modulation technology for LoRaWAN, an LPWAN specification aimed at facilitating extensive communications. Both LoRa and NB-IoT operate within the LPWAN domain. While NB-IoT and LoRa target low-power devices, NB-IoT boasts lower latency compared to LoRa, thanks to its higher device output power, enabling faster data rates. NB-IoT typically operates in licensed spectrum but can also be deployed alongside standard

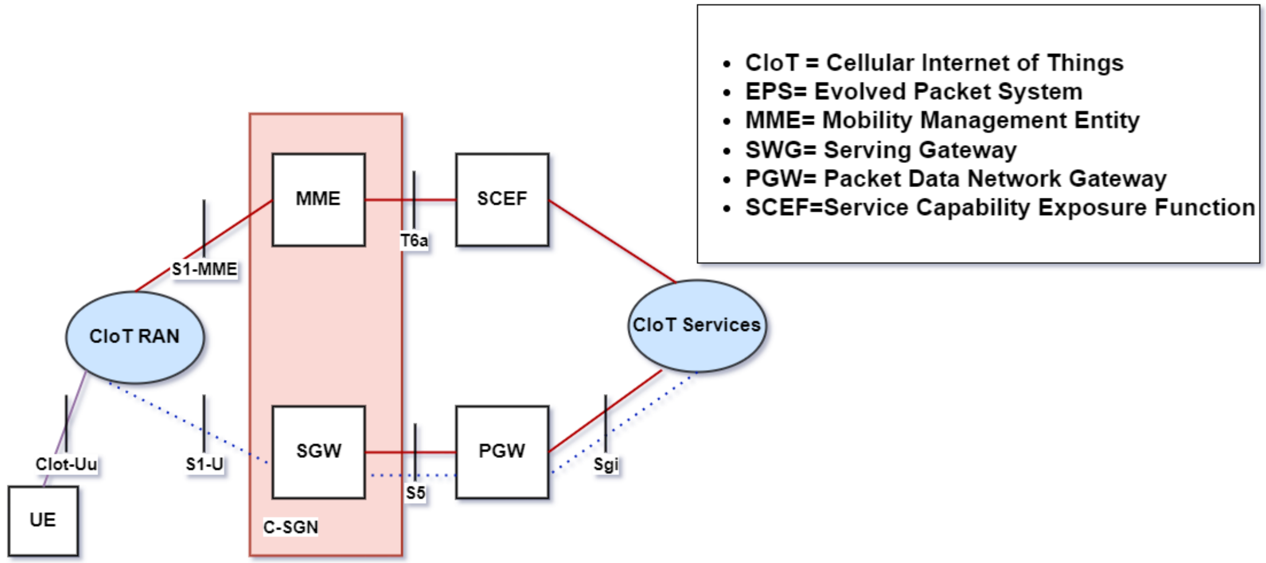


Figure 2.2: Data transmission and reception architecture for NB-IoT network.

LTE carriers or in standalone dedicated spectrum. Its narrow channel width allows for integration within larger LTE channels, replacing GSM channels, or occupying guard channels of regular LTE signals. On the contrary, LoRaWAN utilizes spread spectrum modulation to enable communication between low-power devices and IoT applications. Operating in unlicensed frequencies worldwide, LoRaWAN spans radio frequency bands from 433 to 923 MHz, with a maximum data rate of 50 Kbps per channel and bandwidth choices of 125, 250, and 500 kHz [19].

These differences are condensed in Figure 2.3, with all these considerations NB-IoT was the technology selected, since its standardized is more secure than LoRa and is less likely to get interference from other signals, it is more affordable than other technologies, and since devices are expected to be stationary, it does not need extreme mobility management. Besides, the latency provided by the network is sufficient, the rate and quantity of the measurements does not require more than the network provides, and since data are only transmitted in text format it does not need voice support.

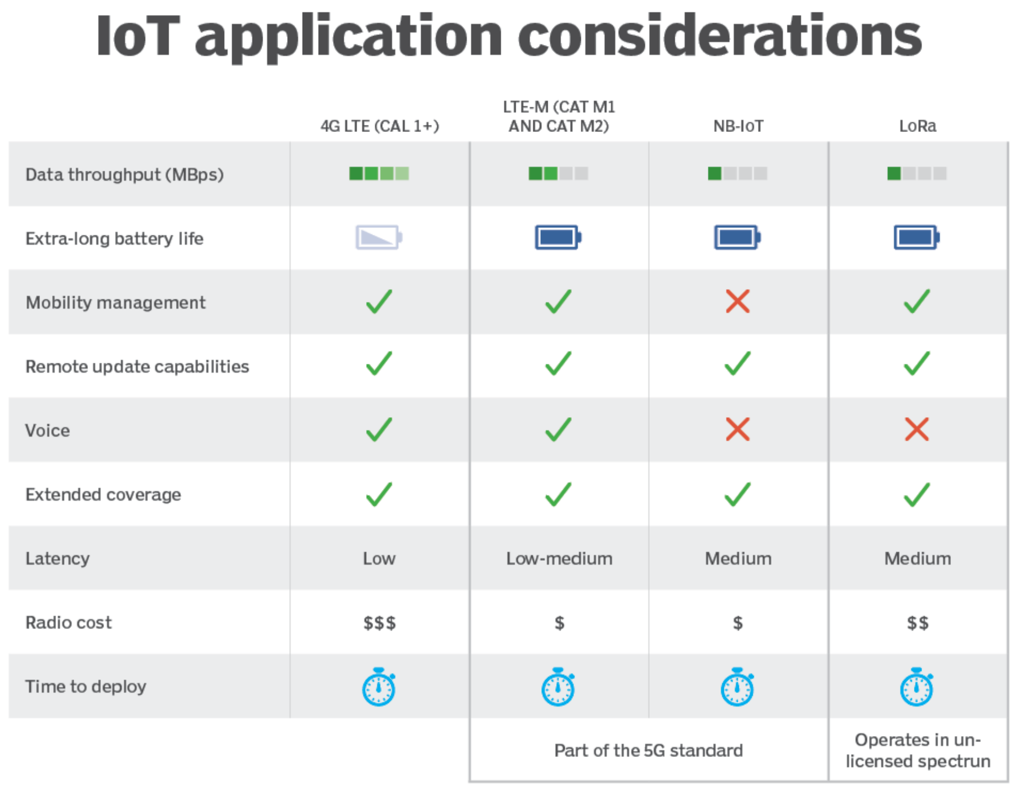


Figure 2.3: Comparison versus NB-IoT and similar technologies.

2.4. NB- IoT on Chile

On Chile, this technology is not yet fully developed; however, some companies are researching and developing this technology. The big telecommunications business is working towards the full implementation of NB-IOT and some already provide services of this technology. Below is a brief timeline of its development on Chile:

- The first company to take the initiative was Telefonica in 2017, and it was the first project successfully deployed that used real client data and NB-IOT technology. They implemented a system which allowed monitoring of residential water meters, the implementation allowed the customers and the company to be able to check diary consumption and its associated costs, providing a faster way to detect potential water leaks or abnormal situations [20].

- Following that, Claro Chile started working on this technology around 2019. The company launched a device for real-time tracking of pets in July 2019, in conjunction with the municipality of Las Condes, partnering and providing tracking devices to people who adopted pets from the local animal shelter [21]. The devices worked via referenced GPS and a mobile application on which the owners could look for the pets location, and also received notifications and warnings if the pet was far away from its designated area.

- In August 2020, Claro Argentina announced a specific network that would provide specific connectivity for IoT, and as of today in Chile, Claro already offers a diverse variety of NB-IoT solutions for enterprises such as *smart fleet, smart office, smart board, smart building, smart security, smart tank,*, etc. [22].

- On the other hand, Entel has recently released NB-IoT commercially and its operating in almost all of their infrastructure around the Chilean territory. They also have a website [23] about their NB-IoT plans, and it shows information about what NB-IoT is and the future applications of this technology.

2.4.1. Gas detection

The urban atmosphere is composed of various gases such as N_2, O_2, Ar, and gaseous pollutants such as CO, CH_4, H_2, NH_3, NO_2, among others. These are present in concentrations ranging from parts per trillion (ppt) to parts per million (ppm).
Detecting gas concentrations can be done by a series of tests, ranging from chemiluminescence and differential optical absorption spectrometry with in situ calibration to nondispersive infrared photometry and liquid gas/solid chromatography.

Interest in the selected gases NO_2, CO, and NH_3 comes from their detrimental effects on human health. NO_2 causes harm to the respiratory system, cardiovascular health, and overall well-being. Exposure to NO2 can cause a range of respiratory problems, particularly in vulnerable populations such as children and individuals with pre-existing respiratory conditions such as asthma. In addition, NO2 can exacerbate allergies, increase susceptibility to respiratory infections, and contribute to the development of cardiovascular problems such as heart attacks and strokes. Prolonged exposure to NO2 has been associated with decreased lung function, adverse developmental effects during pregnancy, and even higher mortality rates due to respiratory and cardiovascular causes. Furthermore, NO2 plays a role in the formation of smog, further deteriorating air quality and exacerbating respiratory problems.
Menawhile CO, is a highly toxic gas that poses significant health risks to humans. Exposure to CO occurs primarily by inhaling exhaust fumes from vehicles, gas appliances, and heating systems. CO binds to hemoglobin in the bloodstream, reducing the blood's ability to carry oxygen to vital organs and tissues. This can lead to a variety of adverse health effects, including headaches, dizziness, nausea, and confusion. In severe cases, CO poisoning can result in loss of consciousness, coma, and even death. Pregnant women, babies, and people with cardiovascular diseases are particularly vulnerable to the effects of CO. Furthermore, long-term exposure to low levels of CO has been associated with cardiovascular problems and neurological impairment.
Lastly, NH_3 or ammonia is commonly found in household cleaning products, fertilizers, and industrial processes. It poses various health risks to humans, primarily through inhalation or contact with skin and eyes. Inhalation of ammonia vapor can irritate the respiratory system, leading to coughing, throat irritation, and difficulty breathing, particularly at high concentrations. Prolonged or severe exposure to ammonia can cause damage to the respiratory tract and lungs, resulting in pulmonary edema and respiratory failure. In addition, ammonia can irritate the skin and eyes, causing burns, redness, and itching upon contact.
Acceptance levels for these gases vary depending of the gas; according to the World Healt Organization or WHO, the acceptance levels for CO exposure can go up to 25 ppm and still

be at the safe level if this exposure occurs within 8 hours [24]. For NO_2, it becomes dangerous to parse the threshold of approximately 1 ppm. Lastly, for ammonia, on average, it is below the recommended concentration of 1 ppm. The odor threshold for ammonia in humans is 1 - 5 mg/m^3 (= 0.16-0.84 ppm) [25].

2.4.2. Air quality MOS sensors

MOS stands for Metal-Oxide-Semiconductor, and an MOS sensor is a type of gas sensor that detects the presence of certain gases, especially volatile organic compounds (VOCs) and various other gases. These sensors are widely used in environmental monitoring, industrial settings, and consumer applications.
MOS sensors are typically made up of a thin film of metal oxide, often tin dioxide (SnO2), titanium dioxide (TiO2), or other metal oxide material. This film is deposited on a semiconductor substrate.

When certain gases come into contact with the metal oxide film, they cause changes in the electrical conductivity of the film. The interaction is specific to the type of gas, allowing MOS sensors to be selective in detecting particular gases [26].
The presence of gases induces a change in the electrical resistance or conductivity of the metal oxide film. This change is then measured to determine the concentration of the target gas.

These sensors are known for their advantages, such as compact size, low cost, and low power consumption. They are especially useful for detecting gases in real-time and are commonly employed in applications such as air quality monitoring, industrial safety, and even in some consumer products like gas detectors and air quality monitors.
Although these sensors work well, they are not very precise, and thus they have a better use as a comparative type of sensor than an exact measurement device. With calibration, better results can be archived, but they cannot guarantee a 100 % accuracy.

Chapter 3

State of the art

During recent years, there have been more frequent implementations of NB-IoT devices in various scopes, both inside homes and in urban areas. By 2019 the global association of mobile network providers was able to identify 141 operators in 69 countries that were investing in NB-IoT, and 90 of those operators had already deployed their network in 51 countries.

3.1. Narrow Band - IoT implementations related to the work

- Remote measurement of residential weather meters: On February 2017, Telefonica, Huawei, and Kamstrup launched their first NB-IoT trial in clients with real data using NB-IoT technology successfully [20]. One of the leading businesses in the offer of water supply services in Chile was able to test the connectivity of a remote sampling of residential water meters.
  Remote utility would allow clients to know their dairy consumption, facilitating real billing costs to avoid unwanted charges, detecting water leaks and abnormal situations. In addition, this provides to the operational devices of the companies with the information of the state of the water supply of the end customers.

- Help Flash IoT: During 2021 Vodafone Spain established an alliance with Netun Solutions, an Spanish company that created emergency lights called *"Help Flash"*, this was done with the intention of being the first IoT luminescent device to replace the emergency triangle on the road [27]. *"Help Flash"* It is a luminescent beacon that integrates NB-IoT technology and that in case of emergency it automatically connects to traffic control centers thanks to the global network of Vodafone Spain.

- The SMairT project aimed to develop and implement a low-cost sensor pilot launched in 2017 for real-time monitoring of key environmental variables in the vicinity of the cultural axis of the Guadalajara City Hall by CI3 [28]. To achieve this, three low-cost sensors-equipped fixed monitoring stations were installed, allowing the measurement of pollutants such as $SO2$, $NO2$, CO, and $O3$. This provides citizens with real-time information on the air quality they are breathing when accessing their website "www.smairt.es" however its not accessible by the website anymore.

Chapter 4

Design and implementation

The design and implementation are fundamental parts of the project. The objective is to create a device that is reliable, inexpensive, and that does not need to be calibrated or operated constantly. Furthermore, it needs to be able to send data in real time without the use of Wi-Fi connections to ensure high rates of power savings.
When looking at a new project, the first thing to do to understand what an IoT project is, and to look at the six different aspects for characterizing an IoT project, this are:

- Communications
- Processor
- Storage
- Power Consumption
- Functionality
- Cost

These edges will be explored in the following sections as well as in the methodology used to facilitate the development of the device.

4.1. Methodology

The line of work followed to complete this project was, first of all, to establish the main goal and divide the project into various steps, ranging from immediate to long-term goals, the steps taken are also shown in Figure 4.1.

- Determinate and analyze the capacities and limitations of material already in possession; this involves doing extensive research on the board and the components already available for the board.
- First of all, it is necessary to determine which sensor it is going to be used, the board itself, it is made to be attachable with sensors made from the same company, however, for this project, since our principal focus is to determine in some capacity the variability of certain gases in the air, it was needed to come up with other options for this device.

The board also has pins to connect other devices manually, so it was also essential to be able to identify the available ports of this board, since not all of the input pins are unoccupied by the board because the board uses them for internal purposes.

- For the assembly, as explained above, some adjustments had to be made to create the desired device. As will be explained later, the chosen sensor was not only not *"ready to use"*, but also required 5V to function properly, and the maximum output of the board was 3.3V, because of this a boost converter was installed. Additionally, the sensor manufacturer also recommended that the best outcome for the sensor would be if all pins in charge of measuring the data were fed half the voltage used to feed the entire sensor, so the use of additional resistance was also implemented.

- The creation of the code involves all the functions determined to be crucial for this project. The key functions determined when the device was going to sleep, wake up, measure, etc., and finally, be able to transmit the data recollected via the NB-IoT network to a cloud where the information would be stored and represented on a dashboard.

- The goal is to collect data with the device for determined periods of time and in different places. One device would be located in the eastern zone of Santiago and another device would be placed on the center zone of Santiago, these devices will measure the different gas concentrations at certain times of the day for ten days.

- With the recollected data, the main objective is to be able to identify patterns, tendencies, and relevant correlations between the concentration of the gases and the time of the day when they were taken.

4.2. Design and version one of the device

When contemplating about the design, they were many considerations, as explained before, not all the pins for the RAK19001 were available to use, and most of them are digital inputs, and as such, they are not capable of measuring the analog input delivered by the sensor. With this in mind, the prototype was developed.
For the first development of the sensor the use of the temperature and humidity sensor was not considered, this version only consisted of the sensor being used by itself and the design was simple as shown on the block diagram of Figure 4.2, basically the sensor was connected to the pins and the readings were made directly by the input pins.

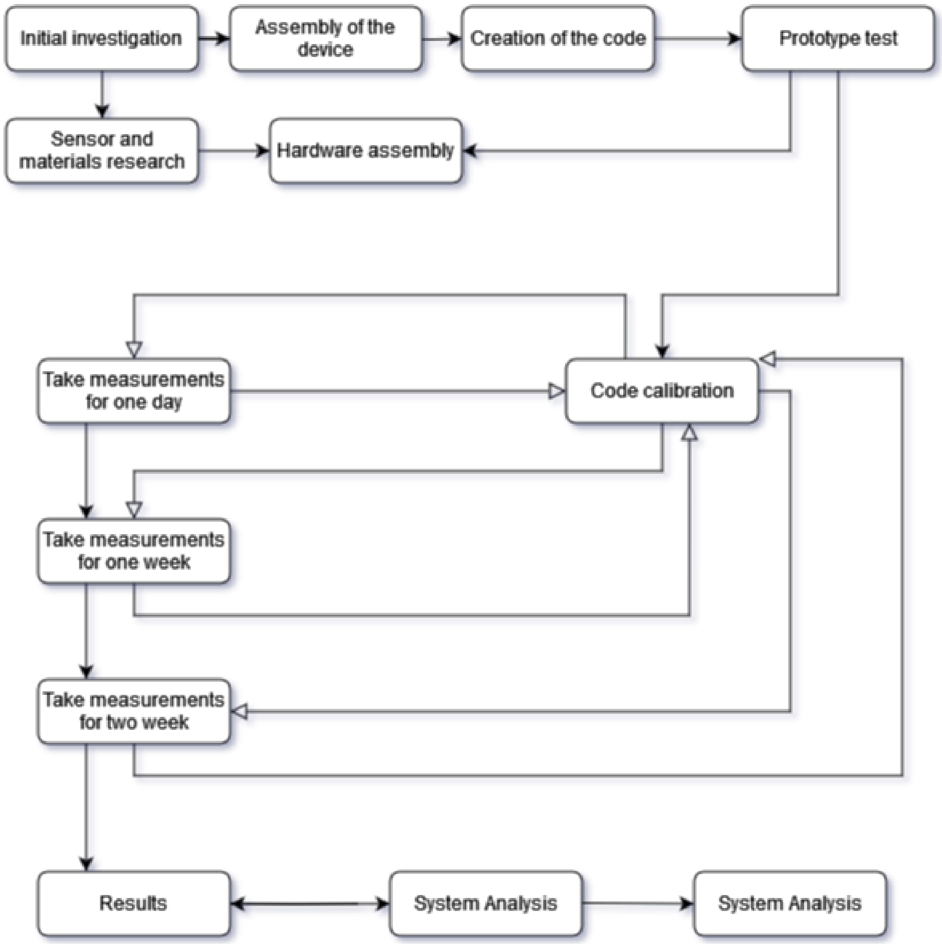


Figure 4.1: Methodology breakdown.

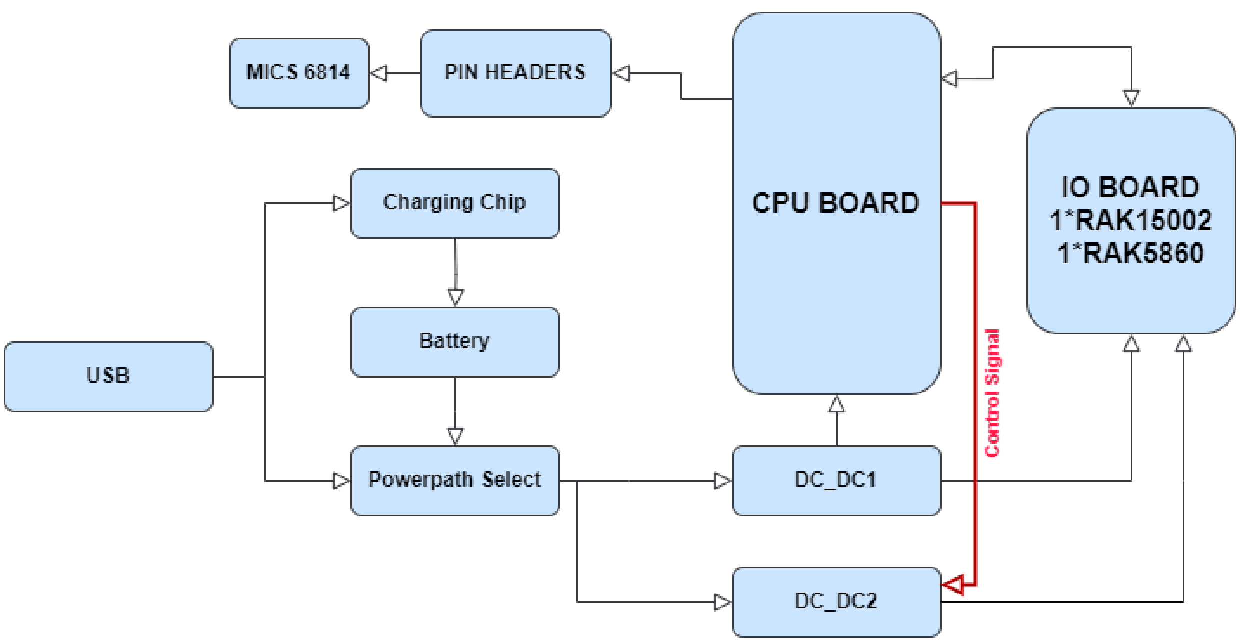


Figure 4.2: Block diagram of the first version of the Kit.

Although this implementation worked and gave readings, those were inconsistent and fluctuated significantly in between readings, even if the readings were only seconds apart. The objective was to create a reliable sensor, so the first attempt did not show the expected results; later this design was discarded, and the final version was adopted.

4.3. Hardware - final version

For the final version, the intention was to improve the quality of the readings and obtain more consistent and reliable measurements. Although the RAK19001 has ADC conversion with a resolution of 12 bits, this is of low quality. Since the sensor does not communicate through an I2C channel, the solution to make its output more trustworthy was to use an external ADC converter, thus implementing the use of the ADS1115 on which the sensor would be attached with NH_3 going to A0, CO in A1 and NO_2 in A2, leaving only A3 without use. With this in mind, the block diagram for the final device was implemented as seen in Figure 4.3.

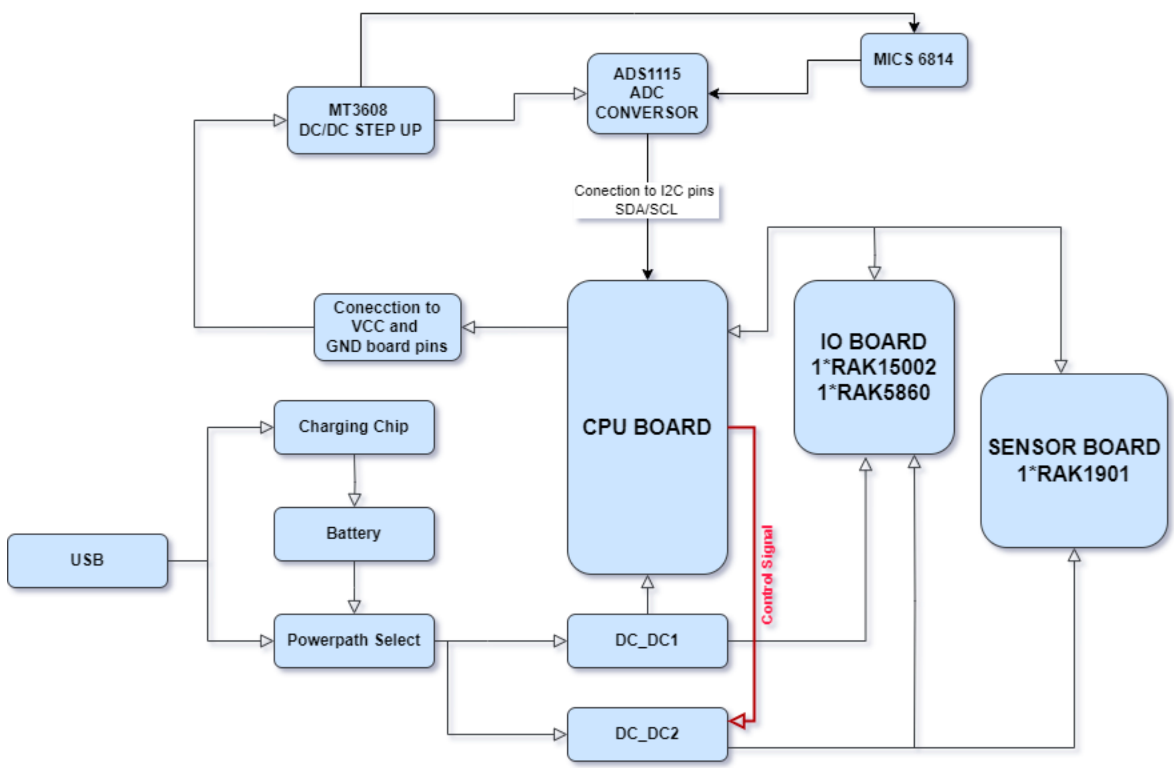


Figure 4.3: Block diagram for the final device.

Although this seems like a straightforward solution, some adjustments are also necessary, as the manufacturer suggests in Figure 4.4, depending on the application and precision of the A/D converter, a single load resistor of 56 k [Ohms] may be sufficient. Rload must be 820 [Ohms] at the lowest value in order not to damage the sensitive layer. Using the resistors in series they create a voltage divider for the circuit, ensuring that the voltage received will not also damage the sensor itself. The maximum voltage allowed for each channel should never exceed 3.5 [V], as it could damage the sensor and render the readings useless.
To avoid this issue, the device contains 3 resistors in series with a potentiometer, since manual

calibration is advised, trim-pot potentiometers provide a feasible solution making it easier to manually adjust the amount of voltage received by the devices and to set the desired starting value, since 2.5 [V] finds itself at the mid range of 5 [V] each of the potentiometers were calibrated to adjust to this output voltage as shown in Figure 4.5.
In addition to this, the sensor diagram is presented in Figure 4.6.

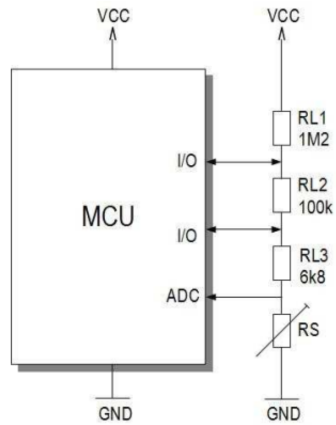


Figure 4.4: MICS sensor suggested use by Manufacturer.

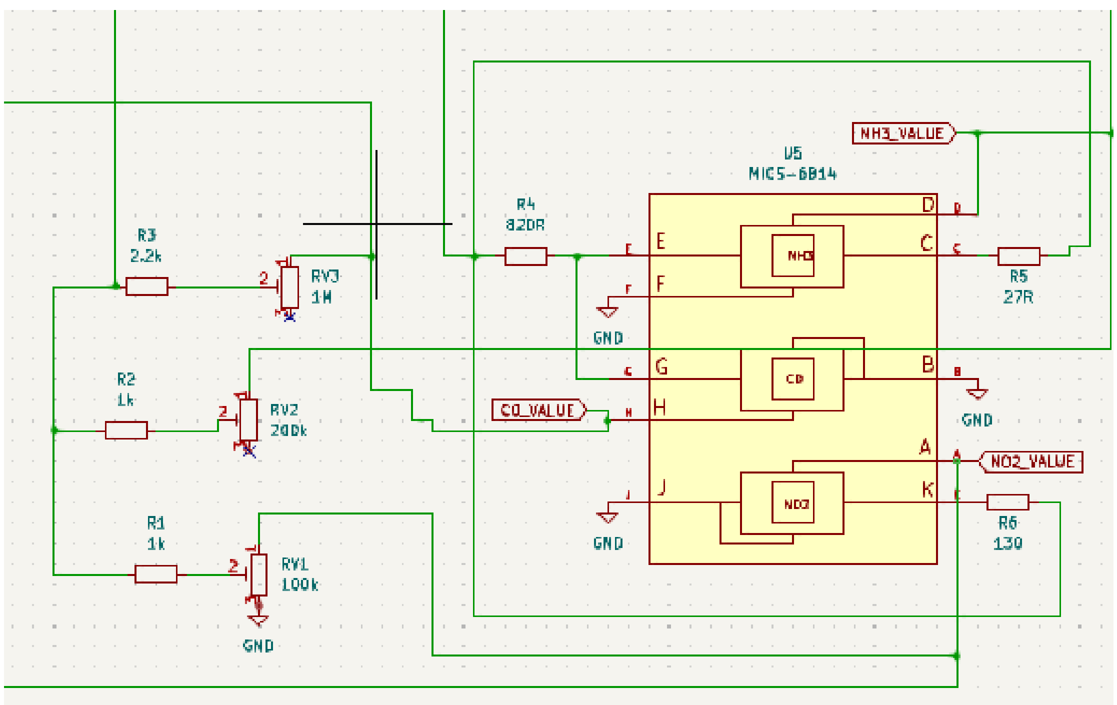


Figure 4.5: Circuit diagram for MICS sensor.

The sensor is then connected to the ADS1115 ADC converter, and the signal passes through until it reaches the board and starts reading the data. Finally, the complete schematics for this project are shown in Figure 4.7.

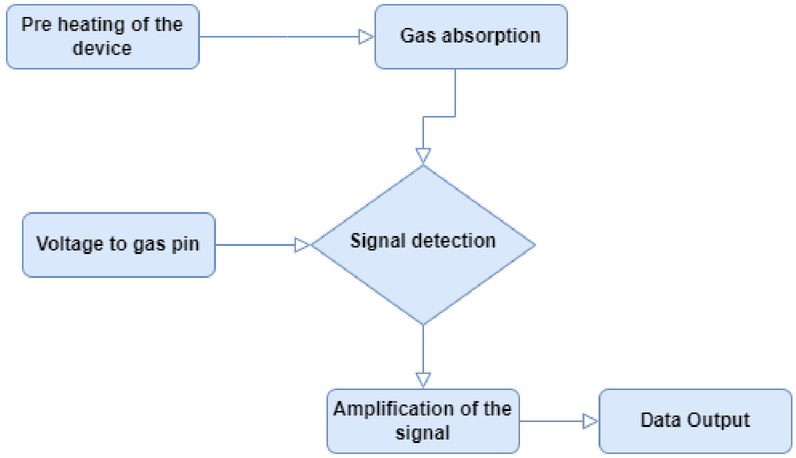


Figure 4.6: Block diagram of the sensor operation.

4.4. Calibration

For device calibration, two approaches were used, first to calibrate via hardware and then to calibrate via code.
For hardware, the calibration used was made to achieve the best range for the measurement of gases, the input voltage as explained before was set for all gasses to be 2.5 [V] at the base level so it could have the best range for detecting variations.
For the code calibration, the base code used was inspired by the Grove Multichannel Gas Sensor calibration code [29], where they used the same MICS 6814 sensor and calibrated their code by performing experimental measurements.
In addition, it was calibrated following the values given on the National Air Quality Information System website [30], until it reached values similar to those reflected on its website. The values on the page are in $[\frac{ug}{m^3}]$ as shown in Figure 4.8, so it was necessary to transform them to ppm for this project. The calibration could be done more precisely because the values provided by the page change each 24 hours and are not updated on real time or revised by a professional, so the values can also contain corrupted data. The code works by securing a stable reading and setting that as the base value for the gasses, then when calculating, it makes a comparison between the read value and the base radio. Taking into account that the maximum number of steps the ADC converter is capable of reading equals 65536, the calculation for the ratio goes as shown in Equation 4.1. Each comparison is powered to two to get more variation with the change of resistance.

$$ratio = (\frac{Resistance}{BaseResistance})^2 * (\frac{65536 - baseResistance}{65536 - resistance})^2 \tag{4.1}$$

To obtain the ppm value of the code, the values were adjusted according to the groove sensor formula using as a reference the values given by the National Air Quality Information System [30]. With this in mind, the final equations for each gas ppm, CO, NO_2 and NH_3 resulted in the respective equations 4.2, 4.3 and 4.4

$$ppm_{CO} = (ratio^{-1.179}) * 0.4385 \tag{4.2}$$

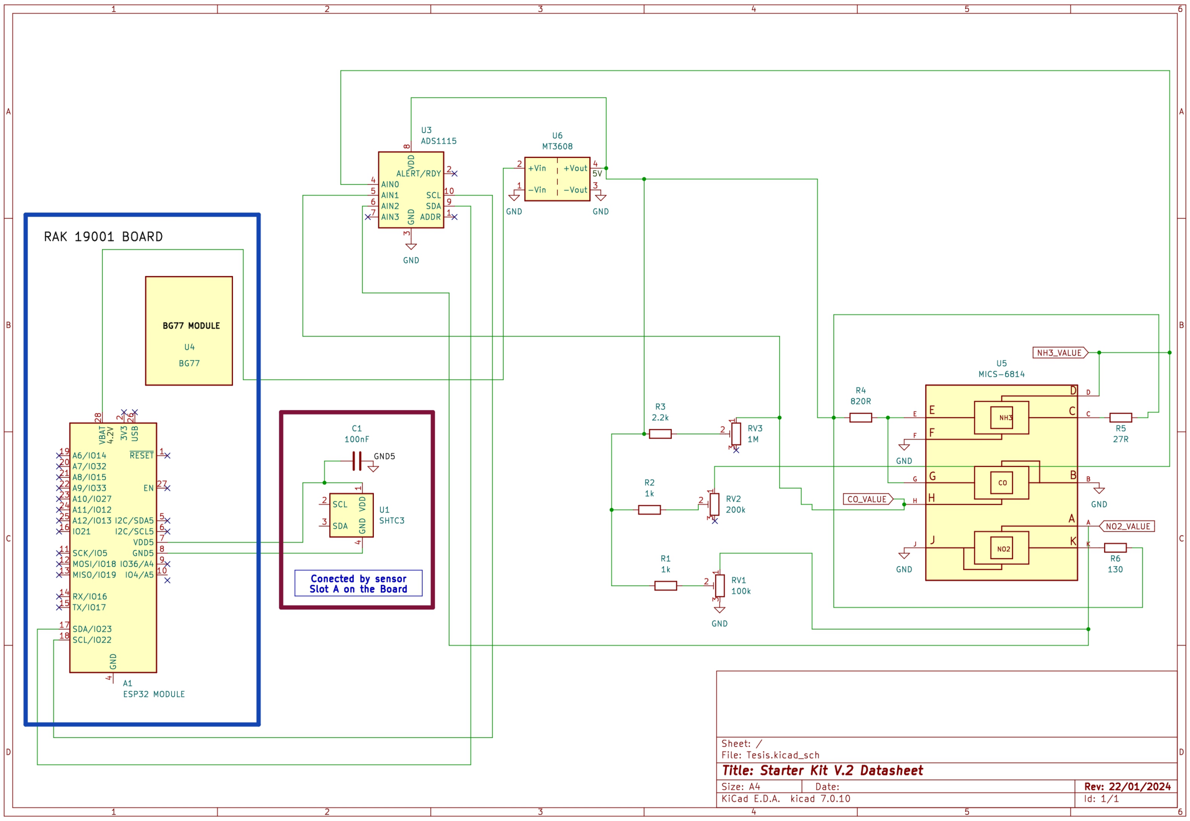


Figure 4.7: Schematics connections for the Kit

$$ppm_{NO_2} = \frac{(ratio^{1.007})}{68.55} \tag{4.3}$$

$$ppm_{NH_3} = \frac{(ratio^{-1.670})}{14.70} \tag{4.4}$$

4.5. Algorithm

For the development of the algorithm, resources from different libraries available on GitHub were used. Although there is already a good amount of research, there are few projects that integrate the RAK technology with the devices made; thus, it was necessary to adjust several parameters as explained before. The breakdown of the code is explained below along with its block diagram presented in Figure 4.9.

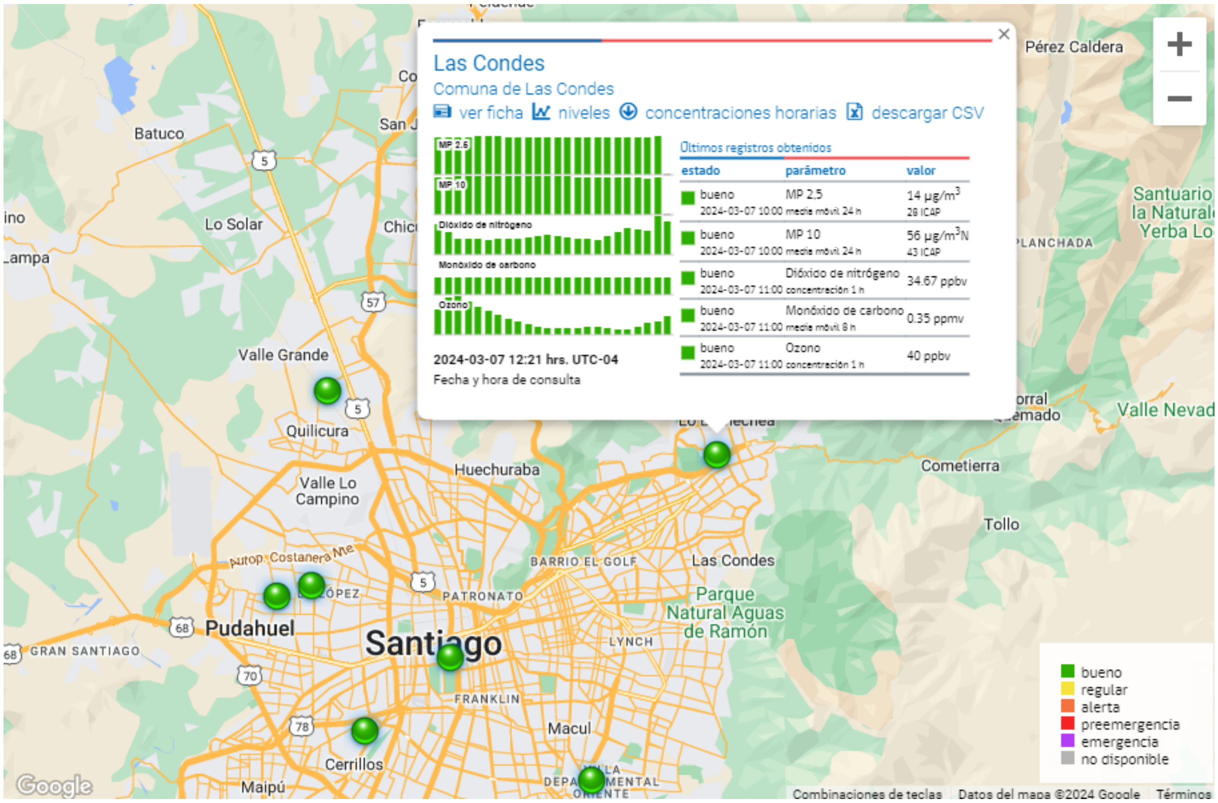


Figure 4.8: Web display for gases concentrations by the Ministry of Environment, extracted from the Air quality information system of Chile [30].

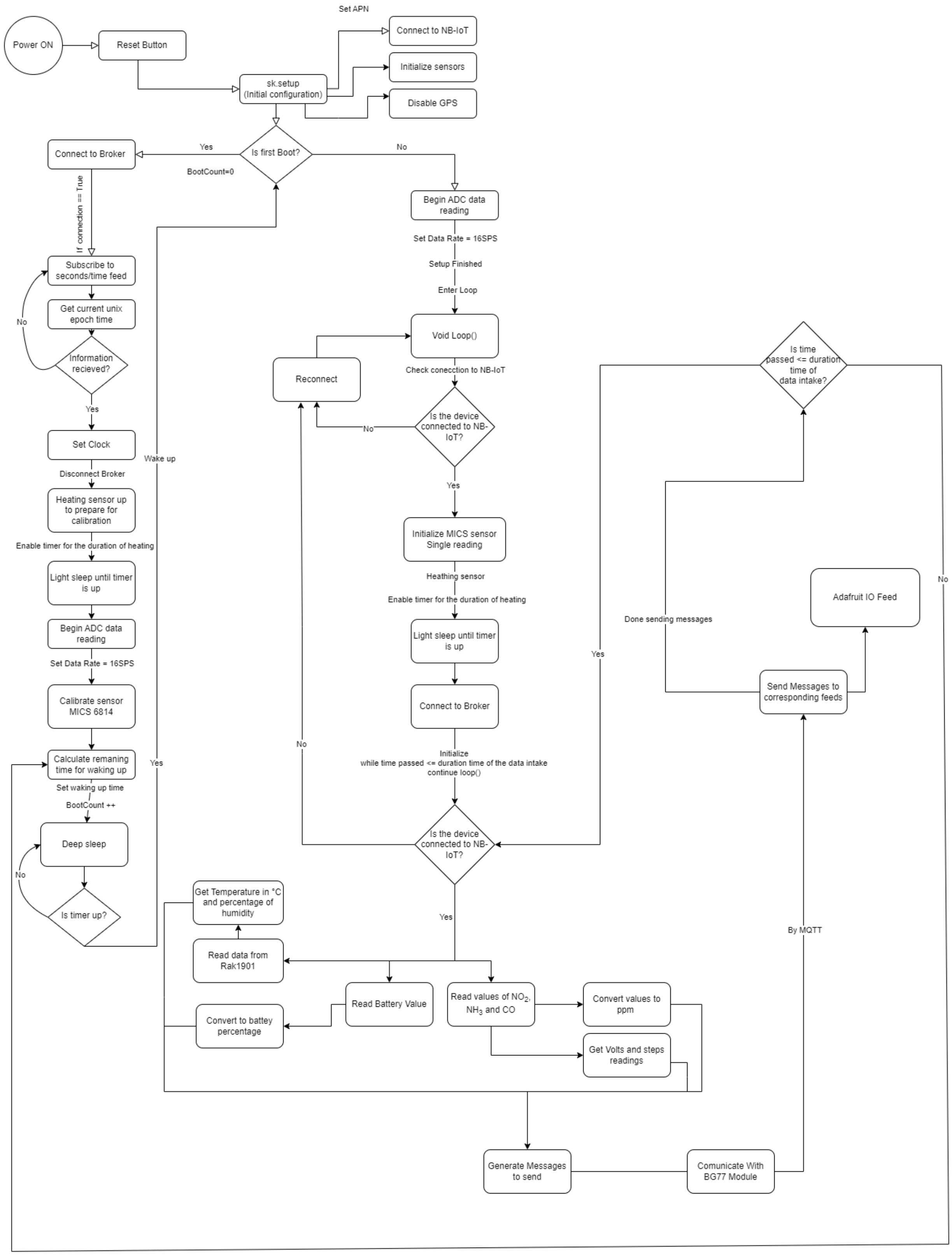


Figure 4.9: Block diagram of the code implemented.

The goal of the project is to read sensor data from a wireless communication link. The RAK11200 uses the Arduino interface to be programmed. Based on it and understanding how it works, the code was developed to archive the device's purpose, which is for the device to be able to function without human intervention. To ensure this, it is important to configure the device accordingly, as seen in Figure 4.10. When the device is first booted up, it is necessary to set all the initial parameters of the device, more exactly on the BG77 module via AT commands; this setup allows the device to connect to the NB-IoT network, the initialization of the sensors, and it also disables the GPS functionality to ensure more power saving.

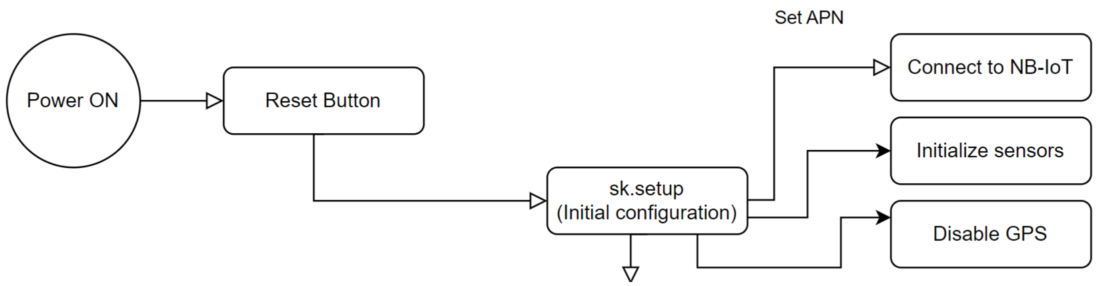


Figure 4.10: Startup of the code.

Then the code asks if its the first time being booted up, since the device doesn't need human intervention, the BG77 module by itself is able to get the time by subscribing to a specific feed which delivers the epoch time in seconds. Although it is not the same as getting the NPT time from the web, its still very accurate and the time sets well, so no lag is evident as the time passes. When this method is used, the device saves more battery life since the Wi-Fi function of the ESP32 consumes a lot of power.
The device then takes the time from subscribing via MQTT to the Adafruit time feed, and it gets the epoch time in seconds, then sets the clock in the correct time zone, in this case UTC -3 for the summer time on Santiago, and stores it in the RTC memory of the ESP32. After that, the device can run smoothly for as long as it wants, as long as it is powered and not turned off, so after setting the clock, the device disconnects from the broker as shown in Figure 4.11.

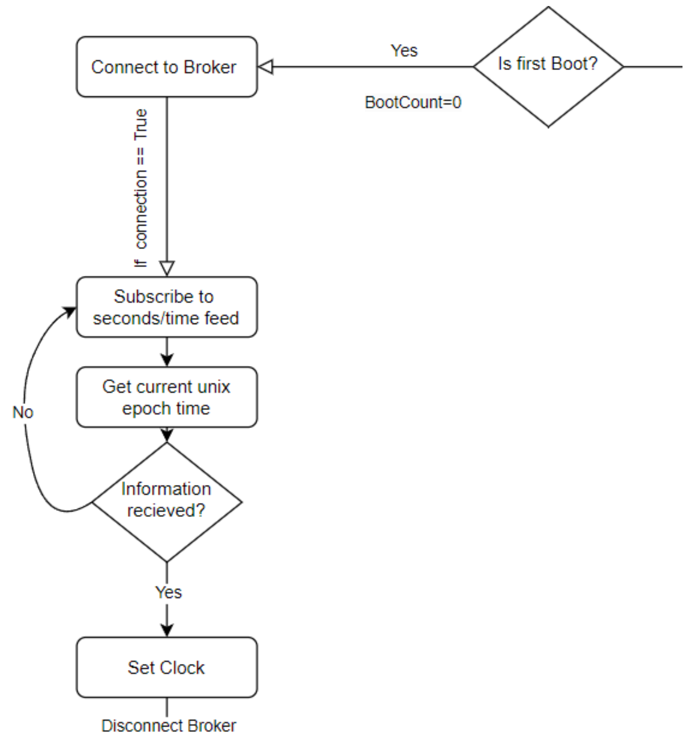


Figure 4.11: Enabling and disabling of the Wi-Fi and setting clock.

Then the calibration for the sensors is started, the sensor takes about one hour to be properly heated, and after that time the calibration is initialized. The calibration works by getting readings for a set amount of time, in this case 5 seconds, and if the variation of the mean of the last 5 readings is less than 30 as explained before, then it sets the base value for the next of the readings; its important to remember that since this type of sensor works better as a comparative sensor the calibration should only be done when it starts to be able to accurately measure the variation. Once the base value for each of the gases is set, calibration is performed; this process is contained on the part of the code shown in Figure 4.12.

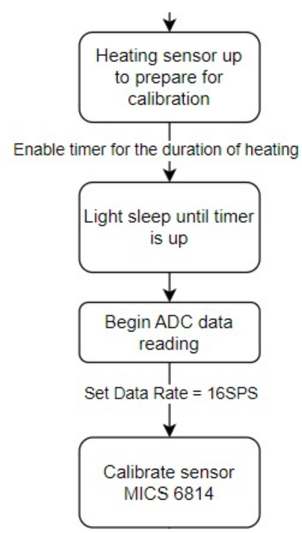


Figure 4.12: Calibration of the sensor.

After the calibration is done, the remaining time to wake up is calculated and the device goes into deep sleep until that time is reached, as shown in Figure 4.13. The type of sleep used is deep sleep via the ESP32, and deep sleep was not implemented on the NB-IoT module. The device goes to deep sleep because there could be many hours before it needs to start taking measurements, and keeping the device running all the time apart from impacting the battery life can also shorten the life of the device itself by exposing the components to heat for such long periods.
When the time is reached, the device wakes up again and runs the Setup () section of the code a second time. Since the device never shuts down, in its RTC memory the event is registered as boot number two, so it skips the sequence of having to subscribe to the feed and is able to retain the previous set time.

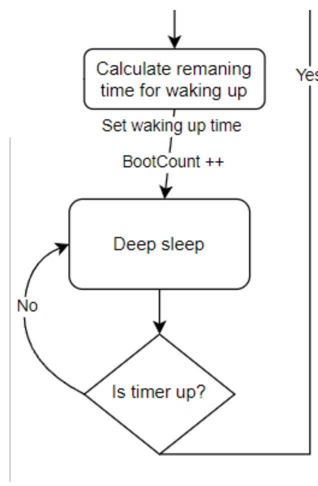


Figure 4.13: Setting timer to wake up from deep sleep.

When the device detects that it is not the first time being booted up, it continues with the code and begins to read the ADC data, it sets the rate for data intake to 16 data points a second, and with that the setup part of the code is done and enters the loop() section.
The first part of the loop consists of checking if the NB-IoT connection is not lost, if its not connected to the network, the device tries to reconnect. Once it detects connection it activates the single reading of the MICS sensor as its seen on Figure 4.14

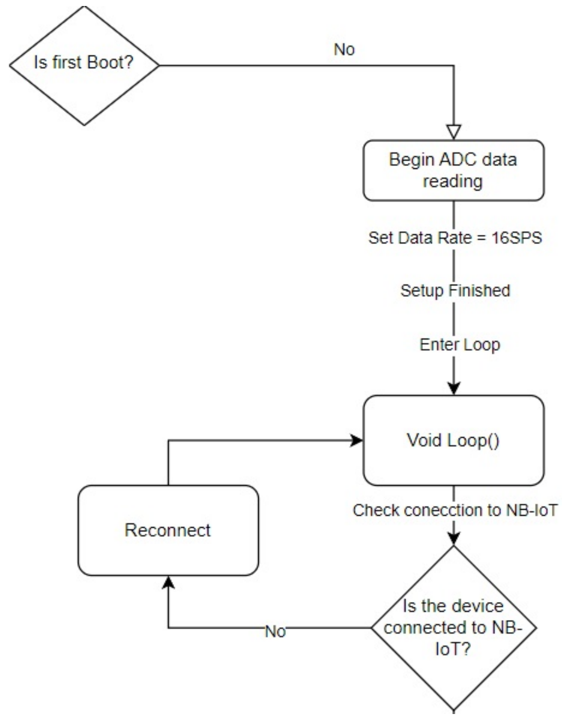


Figure 4.14: Entering loop() void, checking for NB-IoT connection and initialization of the Sensor.

After initializing the sensor, this begins the heating time; for MICS6814 it takes about an hour to be properly heated, so the time is set for an hour of heating to ensure optimal functionality, and in the meantime the device activates light sleep function to not waste more power while the sensor is heating. When the timer is up, the device connects to the broker, by this it means connecting to the cloud that would receive the data that the device is sending. Once this is done, the sensor initializes another timer that exists to set the duration of the data intake. Finally, it checks once again if its connected to the NB-IoT network. This is visible in Figure 4.15.

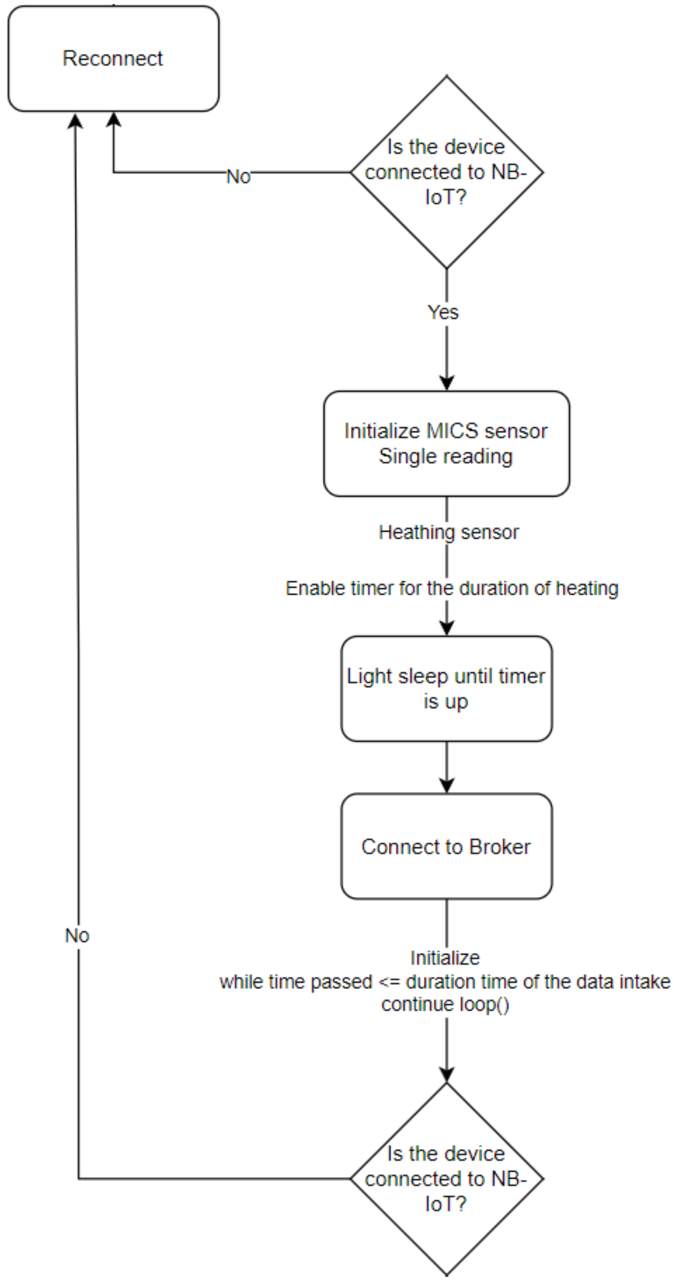


Figure 4.15: Connecting to broker.

When the above is ready and it ensures that it is connected to the Narrow band network, the device starts taking and storing the values of the different data inputs. Since the dashboard used to store the data only allows a maximum of 10 feeds each value, the feeds set for each device were to set the transform of input value in ppm for each gas, so three feeds are used on the value data; then also the battery percentage is sent and finally a general message is send containing the voltage measurement of each gas, the temperature and humidity read by the SHTC3 sensor and the number of analog steps reached by each of the gases, bear in mind that the maximum number for analog steps for 16 bits is equal to $2^6 = 65536$ which is between 0 and 10[V], this is important when managing the data since the normal Arduino Uno board contains only 10 bits, which equates to 1024 analog steps at a maximum of 5[V]. Then the device after generating these messages, communicates with the Module containing the BG77, and it sends them to their corresponding feed one by one. Its not possible to send all at the same time, Figure 4.16 represents the reading of the values and the message generation.

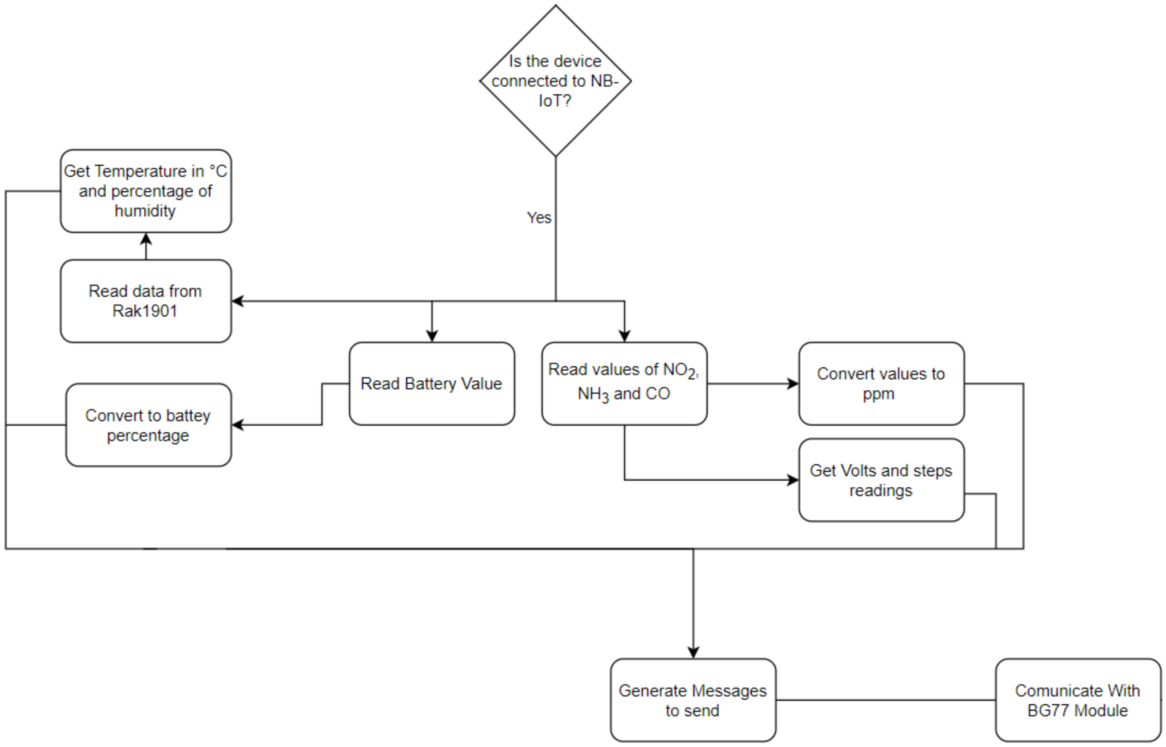


Figure 4.16: Reading values and communication with BG77.

The final part of the code is represented in Figure 4.17.The BG77 module sends these messages through MQTT to the platform feeds until the next message is sent, then asks itself if the time it has been running is still lower than the time settled for the duration of the code. If the time has passed, then it goes back to calculate the remaining time until its the hour to take measurements again and starts deep sleep until then. If the time passes still below the set duration, it runs the loop again, taking data, storing the messages, and sending them via MQTT to the platform selected.

4.6. Materials

In this section, the materials used for this project are explained in detail. The materials needed to assemble the device consist of two types, modules made by RAK Wireless and generic components made by various manufacturers.

4.6.1. RAK Wireless components

The main component of the device is the RAK19001 board, as shown in Figure 4.18, this main board acts as a printed circuit board (PCB) with all the integrated circuits and basic connections pre-frabricated using the standard sensors and modules of the company. The ecosystem is well implemented and the results are easy to get used to.

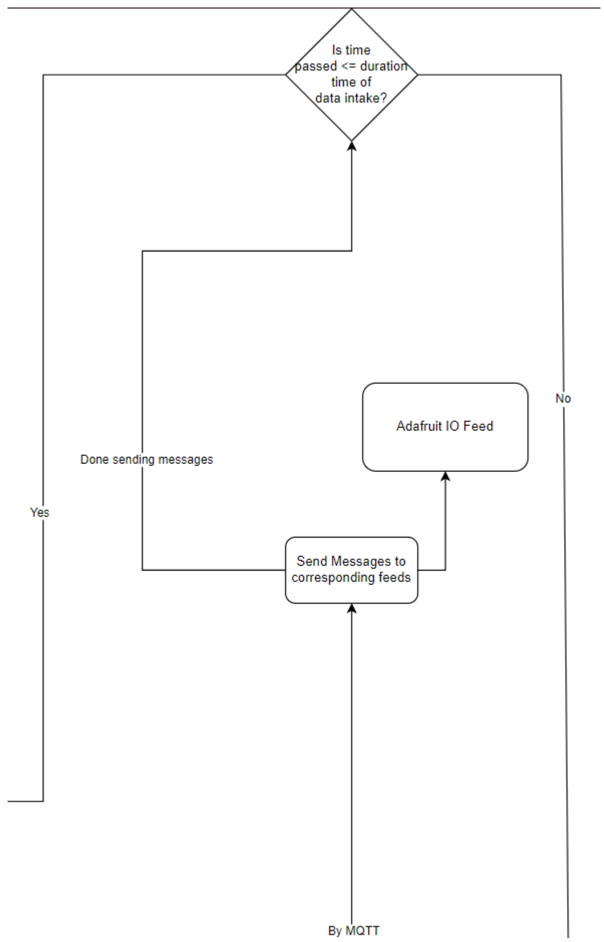


Figure 4.17: Sending messages and connecting to the feed finalizing the loop if necessary

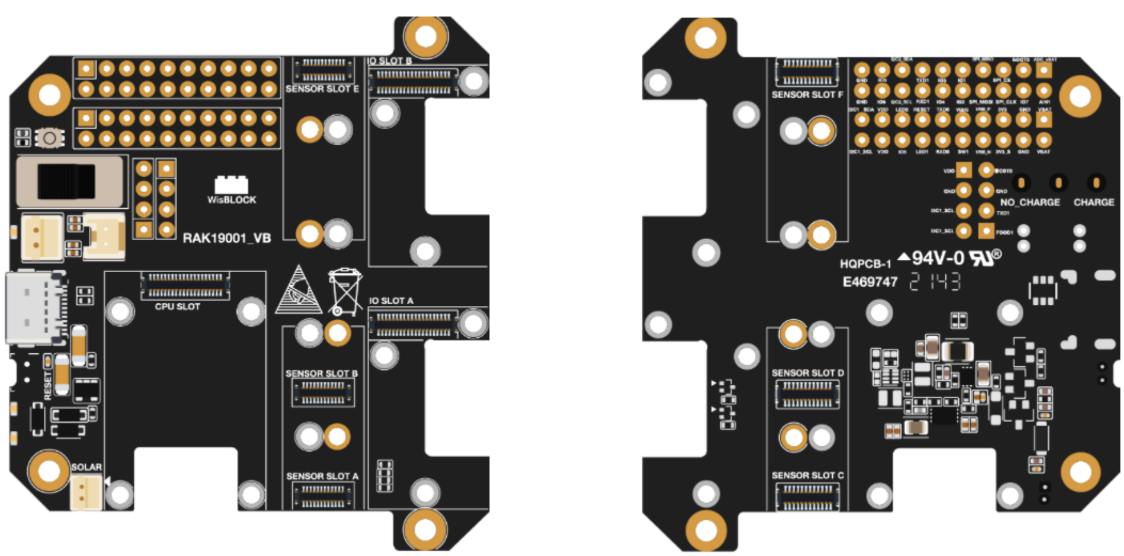
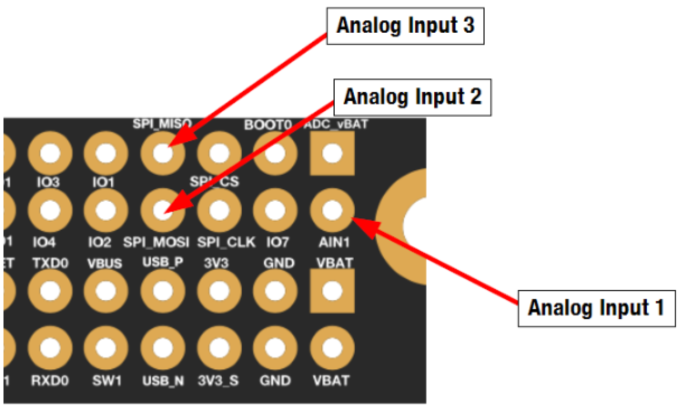


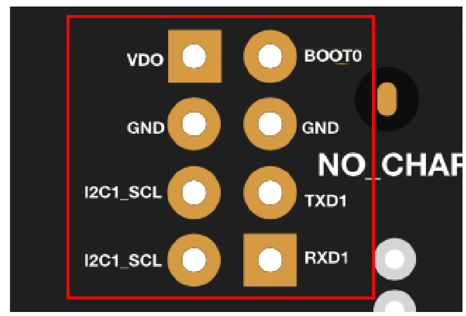
Figure 4.18: RAK19001 board, extracted from RAKWireless [31].

This board has several pins for external use, but, as explained before, not all of these

pins are for free use since some components such as the modules and sensor slot already occupy it; for the initial design, the pins used were the analog input 1 or A1, SPI_MISO and SPI_MOSI as show in Figure 4.19.a. Those pins when not using the SPI functionality can serve as both input or output, regardless of whether they do not provide any sort of pull-up mode implemented, so its necessarily necessary to use pull-up resistors to get them to work properly. As will be explained later, the use of those pins provided low-quality readings, for which they were discarded.
Instead, it was chosen for the use of the I2C channels (SDA and SCL) of the board presented in Figure 4.19.b, these ADC inputs provide a much more stable quality of the readings, also ensuring more accurate data.



(a) Analog inputs for first design.



(b) I2C pins for final design.

Figure 4.19: Pin headers for RAK19001, extracted from RAKWireless [31].

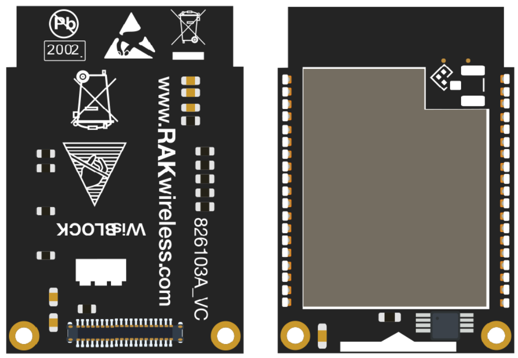
The board also needs a microprocessor to work; The ESP32 provides a high rate processing data and allows one to control all the components; it also provides Wi-Fi connection but this is not used since the device is able to get the current time via MQTT request using NB-IoT, and all of the other functions of the device do not require Wi-Fi to work. The lack of Wi-Fi usage helps save battery life, as Wi-Fi consumes a lot of power. The module occupied is the RAK11200, which is shown in Figure 4.20. It can be seen how the module is mounted on the board.

To connect to the NB-IoT network, the device used a BG77 that provides the NB-IoT LTE connection, this board is named RAK5860 in Figure4.21 in addition to mounting, it is observable in the 3D image that it has a slot for a sim card, this is important because not every sim works with this type of technology. The module also provides a connector for the antenna and a GPS module.

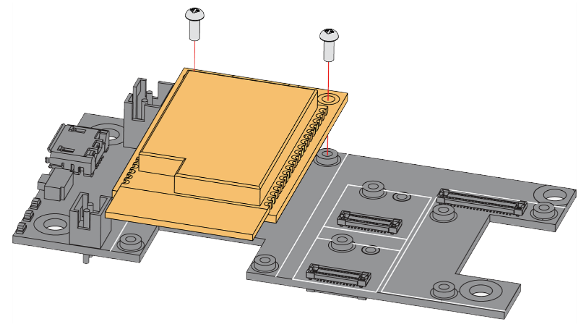
Finally, the last three components that came with the kit were the RAK1901, as shown in Figure 4.22.a and its mounting on Figure 4.22.b. That is, a temperature and humidity sensor, a portable 2500 [Mah] with 3.7 [V] battery, as shown in Figure 4.22.d, and an antenna, as shown in Figure 4.22.c.

4.6.2. Generic electrical components used

Although RAK possessed a diverse variety of sensors and components, none of these sensors had the ability to read the NO_2 signal, for this reason in particular it was decided to use another sensor, in this case the CJMCU-MICS6814 presented in Figure 4.23, this is

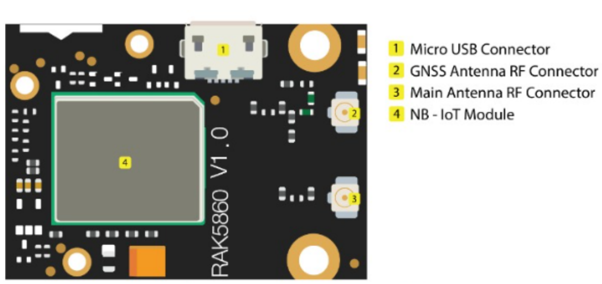


(a) RAK11200.

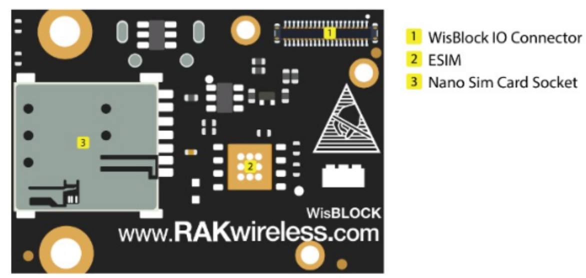


(b) Mounting of RAK11200 on RAK19001.

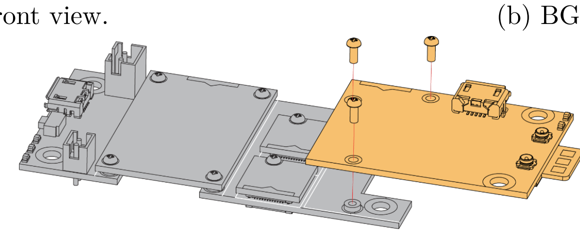
Figure 4.20: RAK19001, extracted from RAKwireless [32].



(a) BG77 front view.



(b) BG77 Backview.

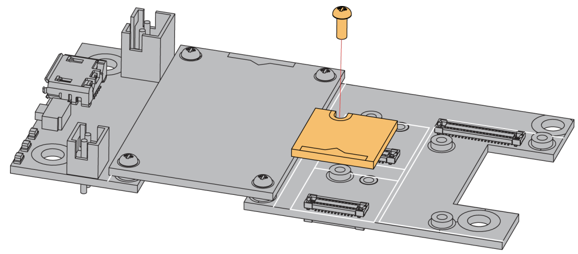


(c) Mounting of RAK5860 on RAK19001.

Figure 4.21: RAK5860 BG77 Module, extracted from RAKWireless [33].

an MOS sensor with three fully independent sensing elements that can measure NO_2, NH_3 and CO.

(a) RAK1901, extracted from RAKWireless [34].



(b) RAK1901 Mounting on RAK19001, extracted from RAKWireless [34].

(c) LTE antenna.

(d) Battery.

Figure 4.22: Components.

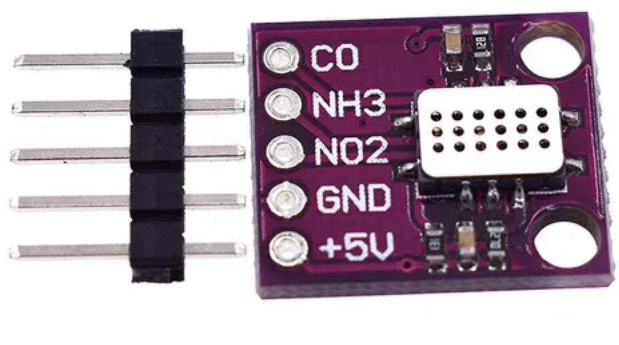
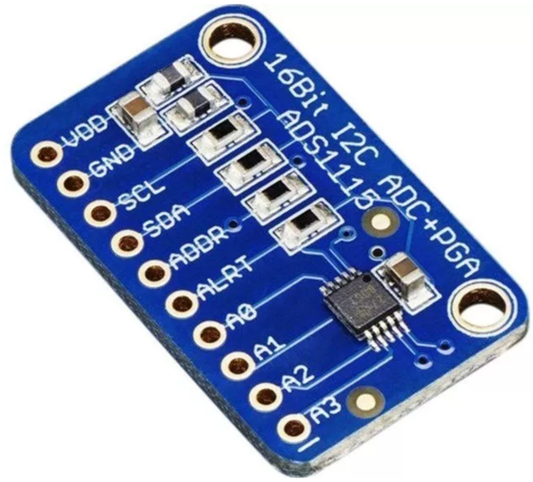


Figure 4.23: MICS-6814, extracted from Shopee [35].

Since the RAK19001 can only supply power in the amounts of 4.2 [V] and 3.3 [V] a step-up DC/DC converter was used. The converter in question is the Mt3608 shown in Figure 4.24.a with a minimum input of 2 [V] and a maximum output of 24 [V] DC. Also, since the need for more accurate measures was in place, along with the change of pins used, it was necessary to adapt the MICS6814 to make it possible for the sensor to communicate via I2C, for this the ADC converter ADS1115 shown in Figure 4.24.b was used as a medium for communication, this device converts the analog input to digital output, and it has a resolution of 16 bits in comparison with the 12 bits of the ESP32.

Apart from the components mentioned above, resistance were used along with trimpots of different values.

(a) Mt3608 Step Up.



(b) ADS1115 ADC converter.

Figure 4.24: Step up and ADC converter images.

The components used are listed in Table 4.1

Table 4.1: Components used to assembly one Kit

Component	Quantity	Component	Quantity
RAK19001	1	Battery 2500Mah	1
RAK11200	1	MICS6814	1
RAK1901	1	ADS1115 ADC 16-bit	1
RAK5860	1	Mt3608 Step up DC/DC	1
Antenna LTE	1	Trimpot 200k	1
Trimpot 100k	1	Resistor 1K[Ohm]	2
Trimpot 1M	1	Resistor 2.2K[Ohm]	1

4.7. Implementation

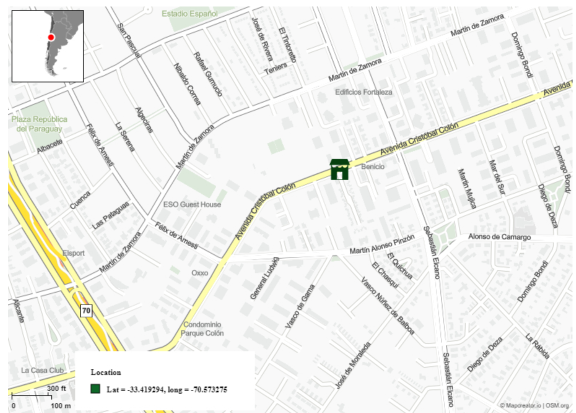
As it was first mentioned, the project consisted of making two devices, until now its only been talk about one since the devices are identical to ensure a fair comparison between them. The first assembled kit was placed on Santiago, near the “Autopista Central” driveway, the location was on the second floor on a balcony, this to ensure exposure to the environment. The ideal location for this device would have been lowered since as shown in Table 4.2 the optimal height to ensure a good reading for these specific gases is about 1 meter and 50 centimeters of height[36], this was not possible because since it needed monitoring to ensure that no one tempered with the project outside, so the safest option was to leave it in a nearby house.

For the device located in Las Condes, it was set up in a house near Cristobal Colon Street. The map for each location of the devices is presented in Figure 4.25.a for the Santiago Kit, referred to as Kit 1, and in Figure 4.25.b for the one in Las Condes, referred to as Kit 2

Table 4.2: Table containing various gases and the recommended mounting height of sensors for its detection, data extracted from [37].

Gas	Chemical Symbol	Color	Smell	Molecular Weight	Vapor Density (kg/m3)	% in Atmosphere	Risks	LEL %	UEL %	Recommended Detector Mounting Height
Acetylene	C2H2	Colorless	Odorless	26	1,092	NA	Flammable	2,5	100	Breathing Level (4-6 ft)
Ambient Air	-	Colorless	Odorless	29	1,205	100 %	NA	NA	NA	NA
Ammonia	NH3	Colorless	Pungent Odor	17	0,6	NA	Toxic	15	28	Roughly 12" from ceiling
Argon	Ar	Colorless	Odorless	39,95	1,661	0,934 %	Asphyxiant	NA	NA	Breathing Level (4-6 ft)
Butane	C4H10	Colorless	Odorless	58,12	2,5436	NA	Flammable	1,8	8,4	Roughly 12" from floor
Carbon Dioxide	CO2	Colorless	Odorless	44,01	1,842	0,0310 %	Asphyxiant/Toxic	NA	NA	Roughly 12" from floor
Carbon Monoxide	CO	Colorless	Tasteless / No Smell	28,0101	1,14	NA	Toxic/Poisonous	12,5	74	Breathing Level (4-6 ft)
Chlorine	CI2	Green/Yellow	Pungent Odor	35,453	2,898	NA	Toxic/Oxidizer	NA	NA	Roughly 12" from floor
Chlorine Dioxide	CIO2	Green/Yellow	Pungent Odor	67,452	9,99	NA	Oxidizer	NA	NA	Roughly 12" from floor
Ethanol	C2H6O	Colorless	Pungent Taste	46,1	1,59	NA	Flammable	3,3	19	Roughly 12" from floor
Helium	HE	Colorless	Odorless	4,02	0,0664	0,00050 %	Asphyxiant	NA	NA	Breathing Level (4-6 ft)
Hydrogen	H2	Colorless	Odorless	2	0,0899	0,000000 %	Flammable	4	75	Roughly 12" from ceiling
Hydrogen Sulfide	H2S	Colorless	Pungent Odor	34,081	1,53	NA	Toxic	4	44	Roughly 12" from floor
Methane	CH4	Colorless	Odorless	16	0,55	0,0002 %	Flammable	5	15	Roughly 12" from ceiling
Nitrogen	N2	Colorless	Odorless	28,02	1,165	78,084 %	Asphyxiant	NA	NA	Breathing Level (4-6 ft)
Nitrogen Dioxide	NO2	Red/Orange	Pungent Odor	46,006	3,66	NA	Toxic/Poisonous	NA	NA	Breathing Level (4-6 ft)
Oxygen	O2	Colorless	Odorless	32	1,331	20,948 %	Oxidizer	NA	NA	Breathing Level (4-6 ft)
Ozone	O3	Colorless/blue	Pungent Odor	47,9982	2,14	0,000006	Toxic/Oxidizer	NA	NA	Roughly 12" from floor
Propane	C3H8	Colorless	Odorless	44,1	1,882	NA	Flammable	2,1	9,5	Roughly 12" from floor
Refrigerent R-22	CHCLF2	Colorless	Faint Ethereal Odor	86,45	3,66	NA	Asphyxiant	NA	NA	Roughly 12" from floor
Refrigerent R-134A	CH2FCF3	Colorless	Faint Ethereal Odor	102	1206	NA	Asphyxiant	NA	NA	Roughly 12" from floor
Refrigerant R410A	CH2F2	Colorless	Faint Ethereal Odor	72,58	3	NA	Asphyxiant	NA	NA	Roughly 12" from floor
Sulfur Dioxide	SO2	Colorless	Pungent Odor	64,1	2,26	NA	Toxic	NA	NA	Roughly 12" from floor

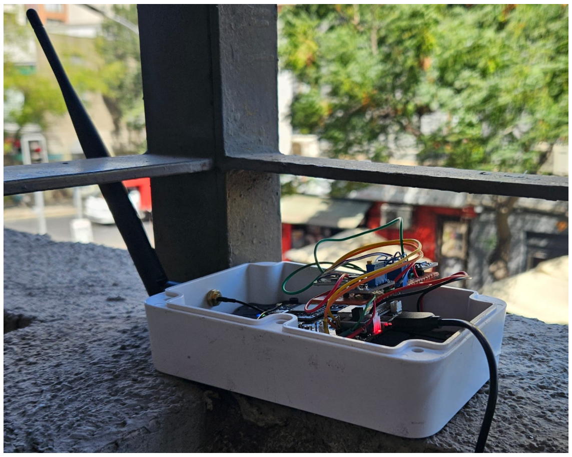
(a) KIT 1 located on Santiago.
Latitude = -33.453524, longitude = -70.661951.



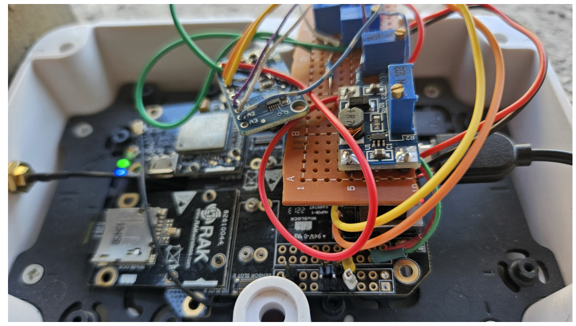
(b) KIT2 location Las Condes.
Latitude = -33.419294, longitude = -70.573275.

Figure 4.25: Locations of the Kits

Pictures of the real setup are visible in figures 4.26.a, 4.26.b, 4.27.a and 4.27.b for KIT1 in Santiago, and in figures 4.28.a and 4.28.b for KIT2 on Las Condes.

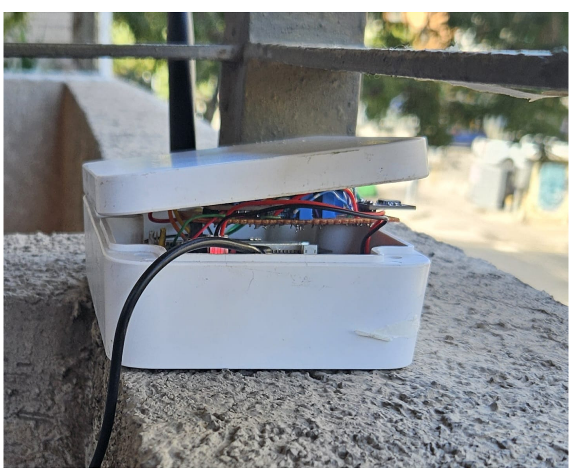


(a) KIT1 located in Santiago, side view.



(b) KIT1 located in Santiago, inner view.

Figure 4.26: Locations of KITs in Santiago.

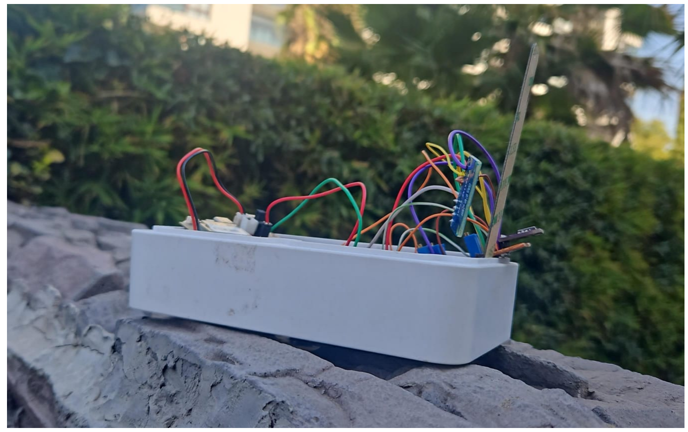


(a) KIT1 located in Santiago, final set, with cover.

(b) KIT1 located in Santiago, upper view with cover.

Figure 4.27: Locations of the KIT in Santiago already covered.

(a) KIT2 located in Las Condes, final set and front view.



(b) KIT2 located in Las Condes, side view.

Figure 4.28: Locations of KITs in Las Condes.

Chapter 5

System Evaluation and Analysis

To evaluate the system, the metrics used were if the device achieved the edges defined in the design section. The general implementation of the system follows the diagram in Figure 5.1. The results obtained with the development of the device are shown in the following section.

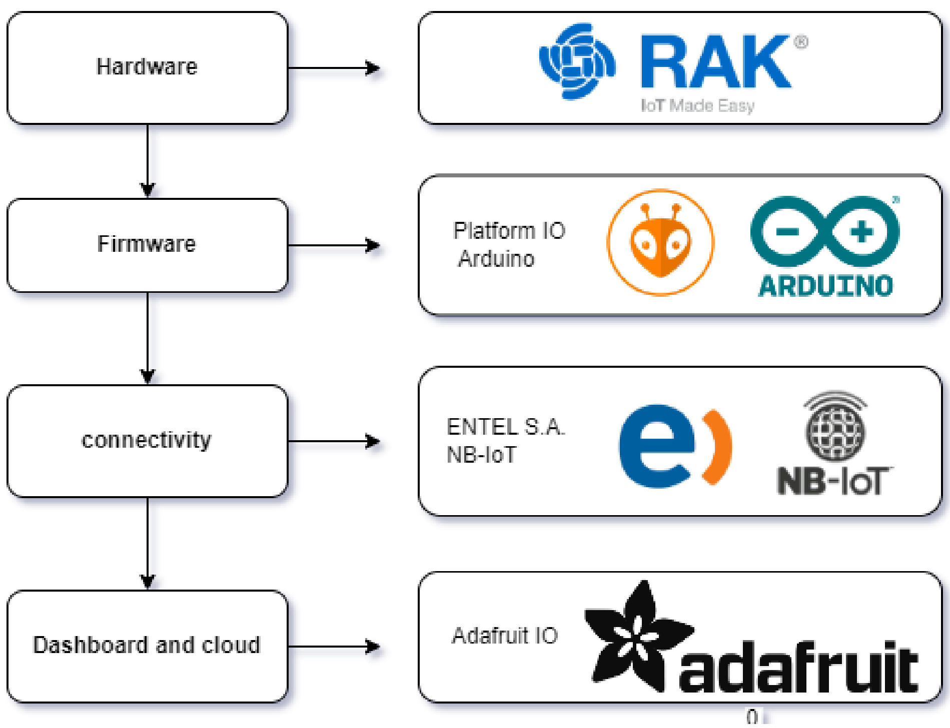


Figure 5.1: Overall implementation of the device.

5.1. Results and evaluation

It was archived that the device would be able to function without human intervention in addition to establishing it at the location where it would take action.

The calibration of the device was tested several times until an optimal configuration was archived that provided stable readings of the gases and their input into the board, as shown in Figure 5.2, and the internal calibration made with the code was also provided by a manufacturer that tested the gases in a neutral environment. The device was able to calibrate the sensor, generate the message, send the messages via MQTT and publish them on the dashboard; as of today, both devices are still running and updating the data. Three dashboards with the information were created, two with more precise data of the devices and a main one showing the comparison between the data gathered by the devices as shown in the figures 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8.

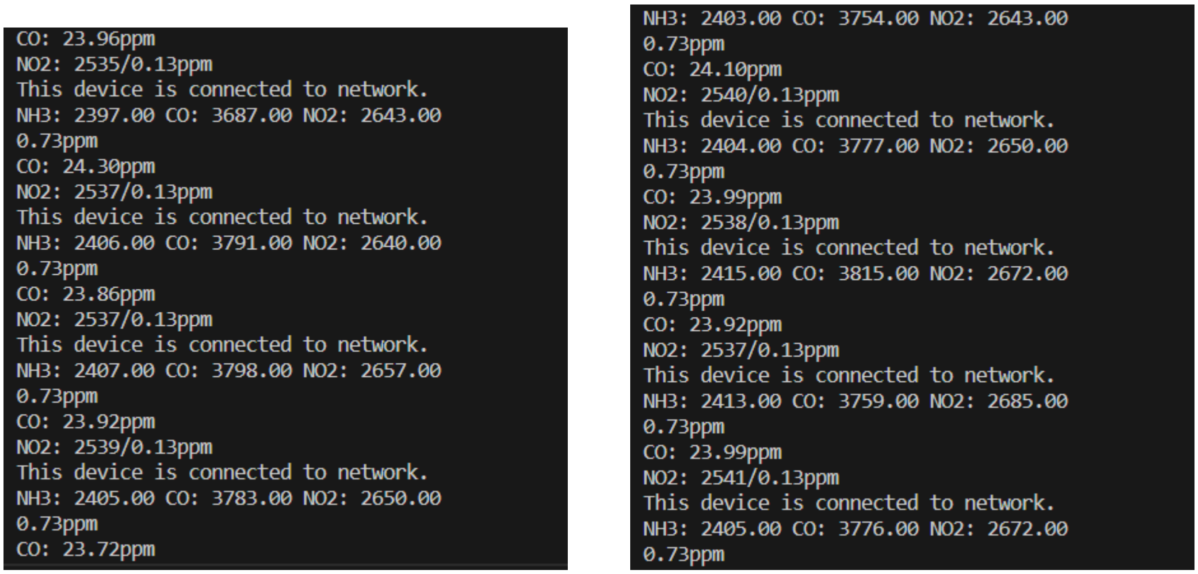


Figure 5.2: Display on a serial monitor of the calibrated data.

For the calibration, it was expected to read consistent values and that those were in between the expected guidelines values. The calibration was done in both the main code and by itself to see how its behavior would change, expecting that the values had little variation between both.

Figure 5.3: Main Dashboard.

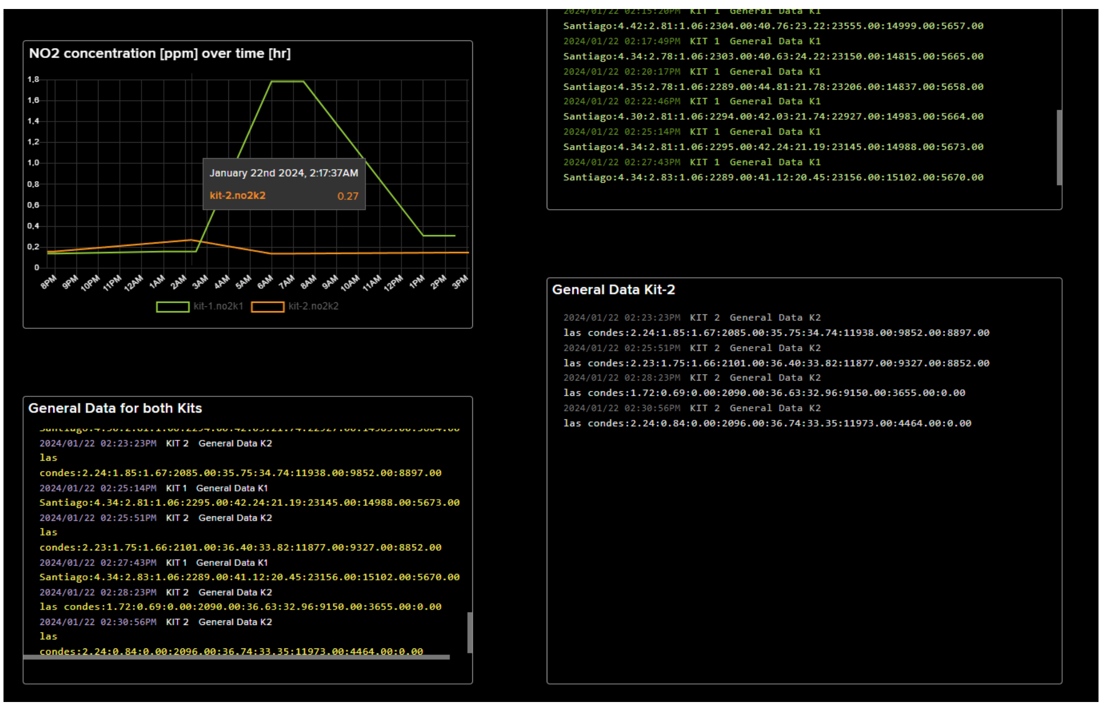


Figure 5.4: Main Dashboard part 2.

On the main dashboard created, its possible to see real time data of the sensors and the comparison between KIT1 from Santiago and KIT2 from Las Condes at the same time. There is graph comparisons for each of the three gases, battery life remaining for each KIT and the

General data input with the rest of the values for both of the KITs.

Figure 5.5: Dashboard for Kit one on Santiago.

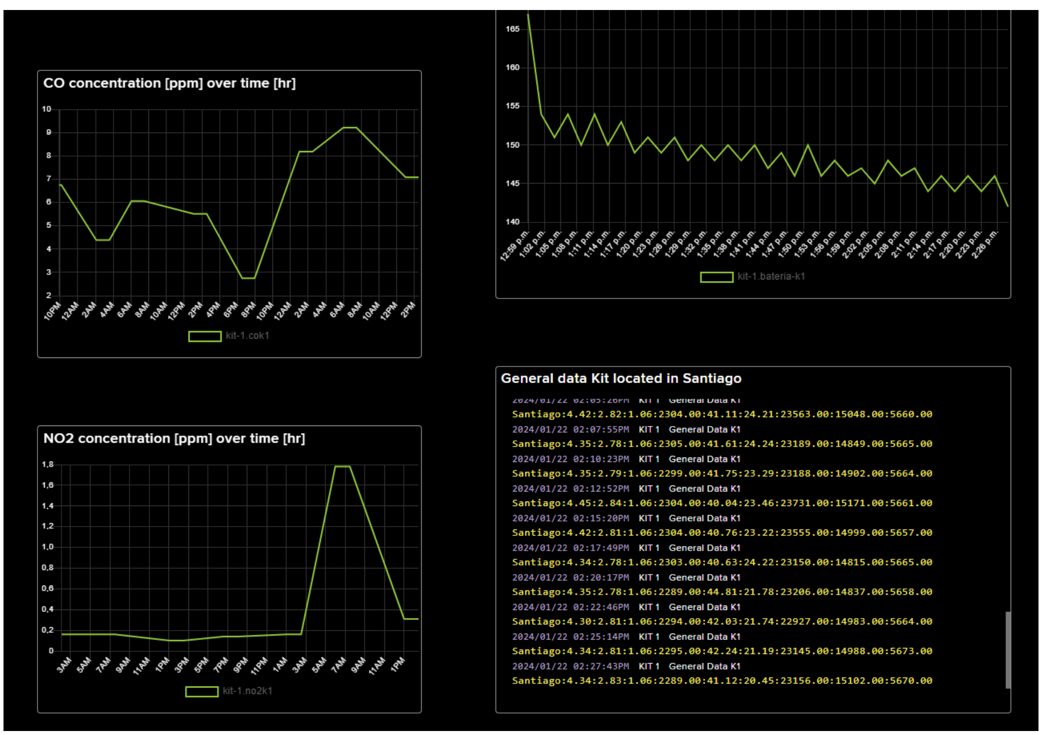


Figure 5.6: Dashboard for Kit one on Santiago part 2.

Figure 5.7: Dashboard for Kit two on Las Condes.

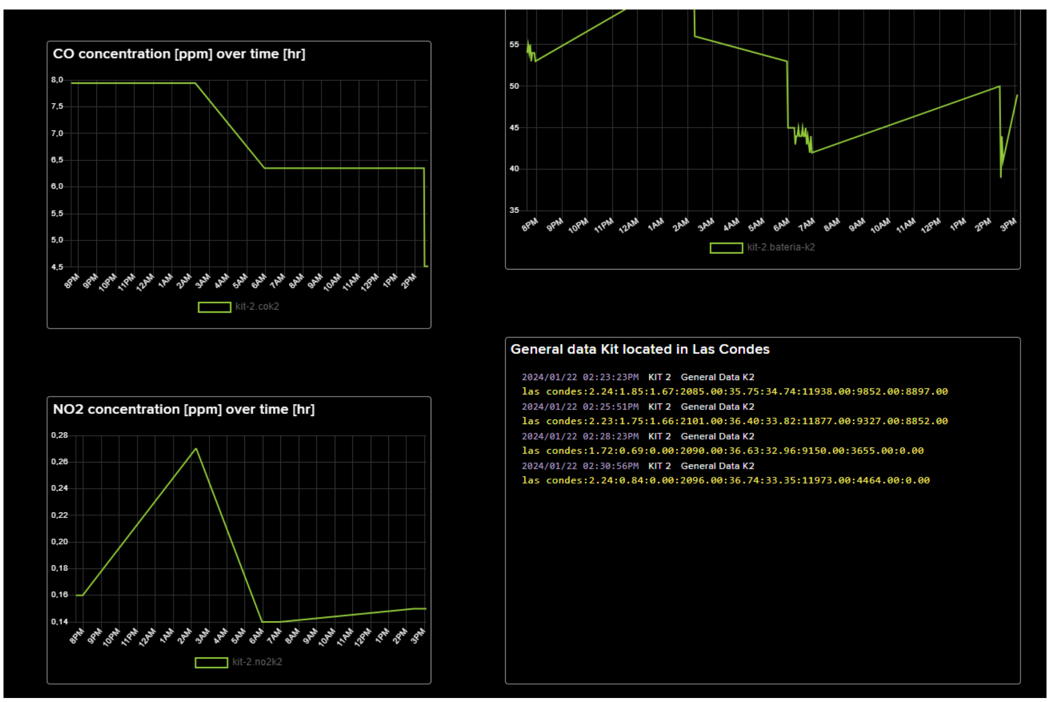


Figure 5.8: Dashboard for Kit two on Las Condes part 2.

For each of the specific kit dashboards, there are the same graphs displaying the gases values over time along with the latest read concentration for the gas and the battery life remaining along with the specific General data input for each KIT.

5.2. Cost and comparison with similar devices on the market

The research carried out in search for devices similar to the one designed in the project yielded few results. There are a variety of gas measurement devices on the market, but none of them accomplish what the Kit does, below on Table 5.1 the cost of making a Kit device is broken down. A comparison was made between some sensors that are available at the moment on the market in Table 5.2 with the developed Kit.

Table 5.1: Cost in Chilean peso for the creation of one Kit, values extracted from Aliexpress [38] and RAKWireless [39].

Component	Cost in USD
MT3608	1,59
MICS 6814	14,72
ADS1115	1,29
RAK19001	12,92
RAK1901	4,40
RAK11200	9,48
RAK5860	28,70
Trimpot x10pcs	0,53
Resistance x20pcs	0,68
TOTAL	**74,31**

Table 5.2: Comparison between devices that measure gas concentrations available on the market versus the KIT, values extracted from AliExpress [38].

Device	Real time measuraments	Upload data to the cloud in real time	Dashboard	Measure at least one gas between NO_2, NH_3 or CO	Cost [USD]
Starter Kit developed	yes	yes	yes	yes all of them	74,31
HONEYWELL SAFETY Detector multigas QRAE NO2-O2-LEL-CO	yes	no	no	yes CO and NO2	1598,49
Detector Multigas X-am 2500 Con Cargador y Batería LEL O2 CO NO2	yes	no	no	yes CO and NO2	1517,75
4 In 1 Gas Detector CO H2S O2 Oxygen Monitor Analyzer Leak Portable Combustible from Aliexpress	yes	no	no	yes Only CO	200,36
Dienmern New DM126-NH3 Portable Ammonia Quality Detector LCD Display Digital NH3 Sensor Tester Household Gas Monitor, Wholesale	yes	no	no	yes Only NH3	54,53

Even though these are few comparisons, its clear that in terms of cost/opportunity, the device offers a lot of services at a lower price in juxtaposition with similar sensors on the market that don't serve the IoT functionalities that the Kit offers. Its worth mentioning that the comparisons made are not direct, this is because the cost only considers hardware costs and not development costs associated with the creation of the device.

5.3. Results analysis

The general data reflect good measurements, all gas concentrations are below the dangerous level reported by international health congregations[24] and, moreover, they are around the levels expected in the environment.

The battery of the device proved to be not sufficient, from the information gathered the ESP32 even if the deep sleep mode saves a lot of power, when in use consumes an abundant quantity of charge, for this it was not possible to leave the devices running for more than 12 to 16 hours and it was necessary to maintain the Kits connected to a power source to be capable of functioning. Since these devices are supposed to be stationary when implemented massively, it would not be a problem to get them powered, but as of now that represented a problem at the time of taking measurements.
Since a comparison between battery lifetime does not make sense due to the fact that it was necessary to constantly charge the devices, the metrics reviewed are only for temperature, humidity, and gas concentration.
It is also important to keep in mind that even though the results are in ppm, it is advised to use this sensor as a comparative sensor more than an exact measurement device, for example, better than to assume that in one place there is more concentration of the gases. Its better to look at how the values change in time rather than between devices.
In Figures 5.9 and 5.10 it is possible to visualize the change in the concentrations over time of all gases for each kit. Day 23 shows an increase on both Kits for CO concentrations, this is explained since 23 of February was Friday, so there was much more traffic than other days and also earlier in the day because people leave work earlier on average.

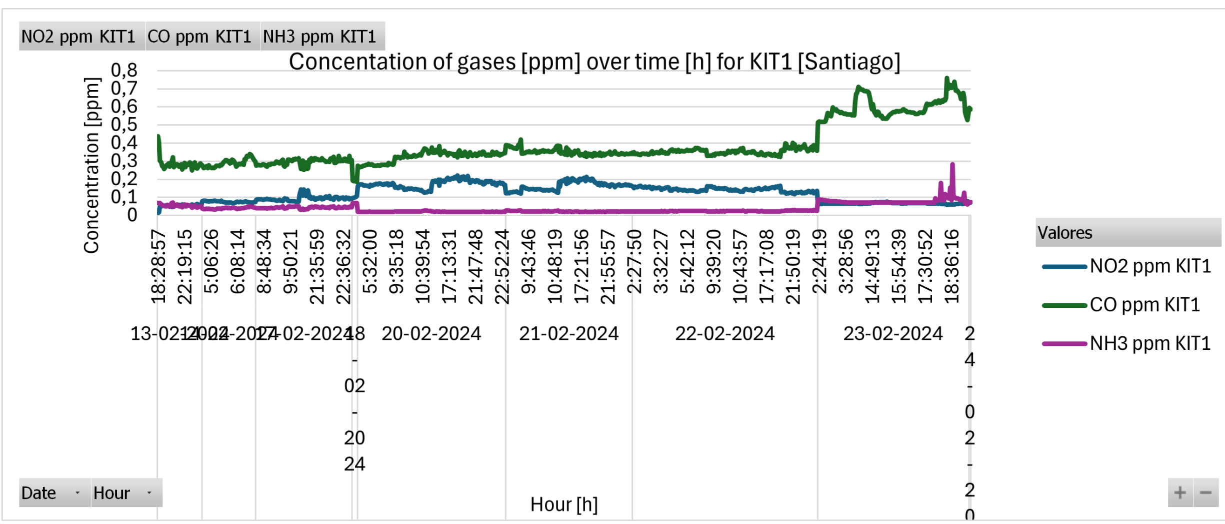


Figure 5.9: Changes of gases over time for KIT 1[Santiago]

5.3.1. NO_2 comparison

On the graph presented in Figure 5.11, the values of NO_2 over time are within the safety norms declared by the WHO. The gas concentration increases during the week for KIT1 in Santiago, with a decrease during the weekend. Meanwhile, for the KIT located on Las Condes, the concentration levels seem to be stable and low. These levels correspond accordingly to the National Air Quality Information System, in which NO_2 concentrations are lower in Las Condes than in Santiago, and also the values are close to those of the website [30].
These sensors calibrations are done on a controlled environment, and thus things as heat and other factors of the environment can affect their readings and for them the calibrations are

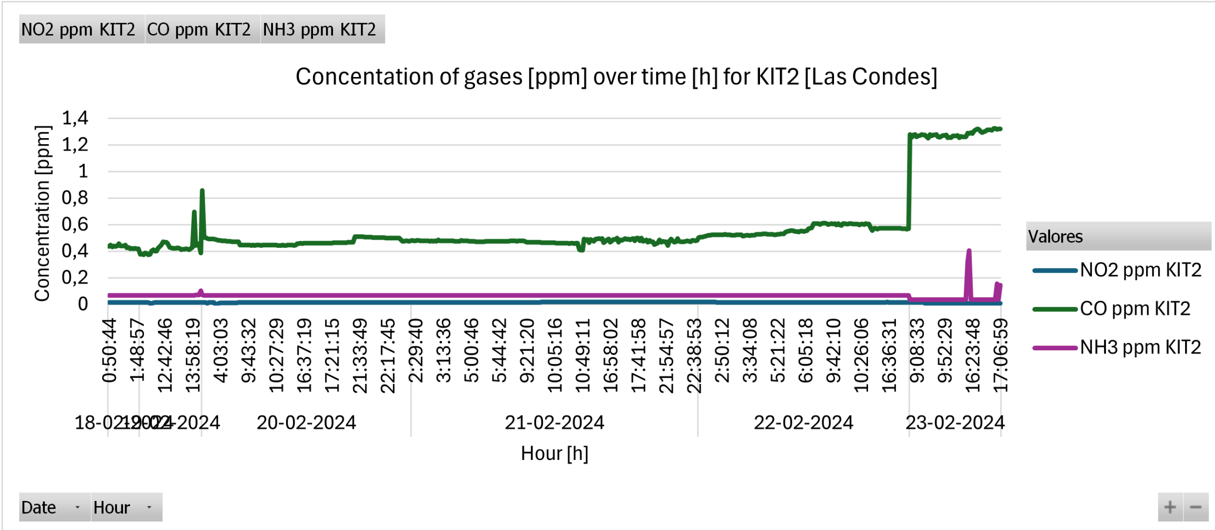


Figure 5.10: Changes of gases over time for KIT 2[Las Condes]

not accurate every time. This is also why the sensor has a heating time to suit itself before starting the readings.

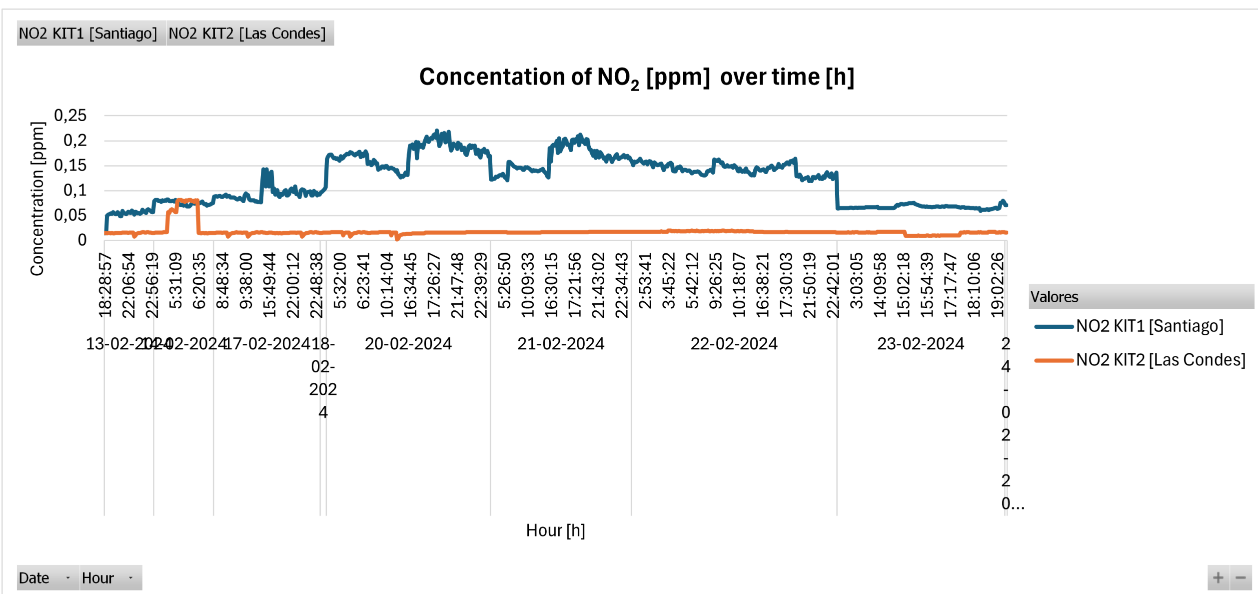


Figure 5.11: NO_2 ppm changes over time for both KITs.

5.3.2. NH_3 comparison

As seen in the section above, the NH_3 also has an increase on the weekend for both KITs, the readings are stable and around the same values during the time, and the most probable reason for the small variations is that heat causes altered readings as the ones visible in Figure 5.12 around the first days.

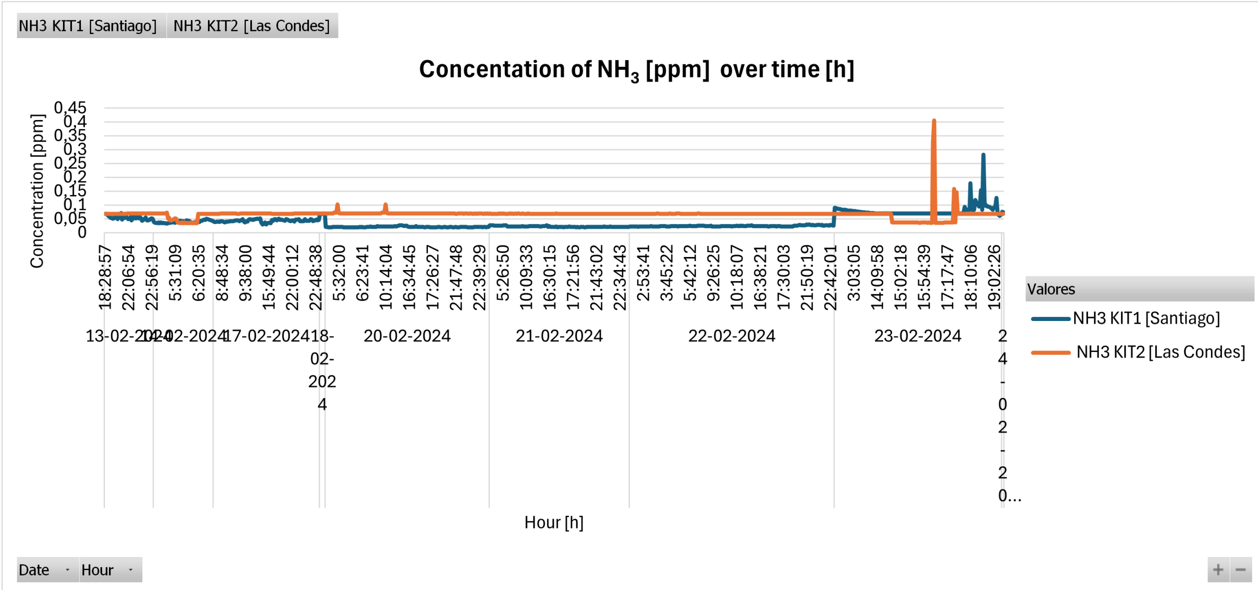


Figure 5.12: NH_3 ppm changes over time for both KITs.

5.3.3. CO comparison

As seen in Figure 5.13, CO readings appear to be the most affected by the environment, since this gas has higher concentrations and is emitted by different kinds of sources it was expected to be the most variable, CO ppm quantities increase around the expected times with an increase in the mornings around 5:00 until 10:00 AM, since its February many people are on vacation and the majority of children have not returned yet from school, due to this the usual expected spike between the times of 7:00 or 8:00 are not as present as they were expected. People tend to wake up later when on vacation so this could explain why the jump of measurements around the latter times, and it is expected that during Friday afternoon at around 6:00 PM there is the most emission, since people tend to leave work early and go out more since it is the beginning of the weekend time.

Table 5.3 shows the mean values obtained during the weeks for both KiTS. As expected, the concentration values increase around hours when there is more traffic on the street. Also, the concentrations are higher for KIT 2 located in Las Condes, it was expected to be the opposite, but this can be explained because the location of the second KIT was more in contact with the street, since there was an issue about the location for KIT 1 in Santiago, it was necessary to put KIT 1 on a higher platform than the recommended height, and this could cause alterations. Also, since the location is not directly in front of the highway and more of a street nearby, traffic can be not as frequent as expected at first. Throughout this a table containing the standard deviation is displayed in Table 5.4, there is not much deviation in the gases, but there is an increase in CO, which is probably due to the increase in readings during Friday afternoon, as shown in Figure 5.13.

5.3.4. Temperature Comparison

Temperature readings, in Celsius, are affected by the operation of the MICS sensor. Although this was expected, it is still interesting to analyze the data provided from the kits.

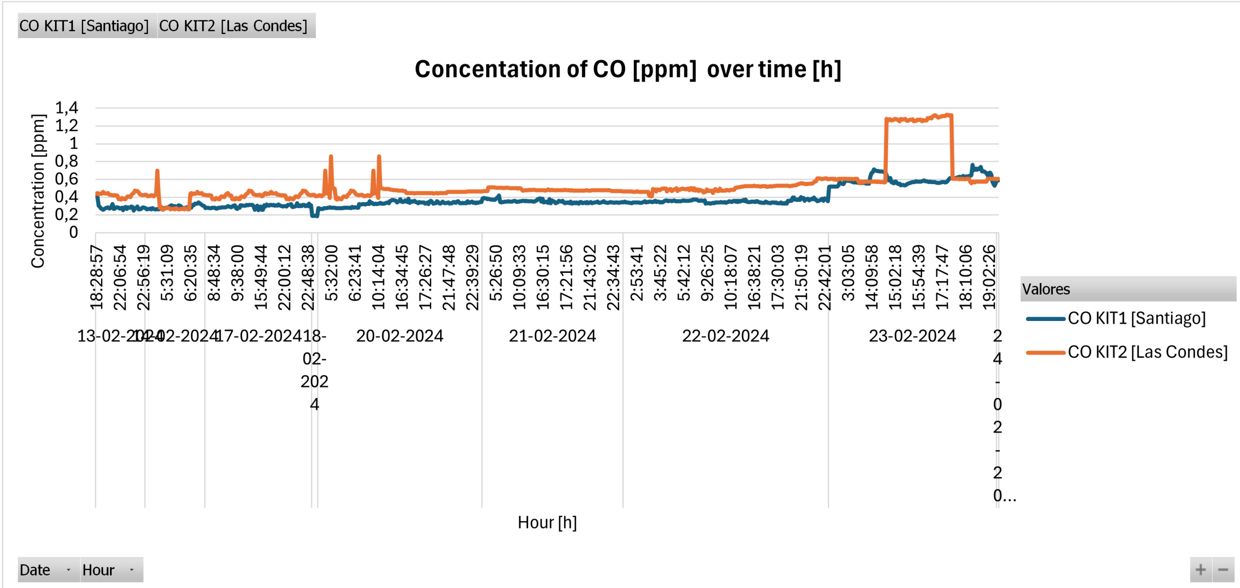


Figure 5.13: CO ppm changes over time for both KITs.

Table 5.3: Table for the means obtained by the starting hours for each KIT in [ppm]

MEAN	CO KIT1 [ppm]	CO KIT2 [ppm]	NO2 KIT1 [ppm]	NO2 KIT2 [ppm]	NH3 KIT1 [ppm]	NH3 KIT2 [ppm]
Boot 1 [2:00 AM]	0,339613	0,469265	0,131426	0,022526	0,030754	0,070182
Boot 2 [6:30 AM]	0,447660	0,762233	0,127621	0,014484	0,043373	0,062921
Boot 3 [2:00 PM]	0,378714	0,493086	0,119468	0,016022	0,042966	0,069049
Boot 4 [6:30 PM]	0,532081	0,724892	0,108387	0,016918	0,052213	0,068899

Figure 5.14 shows the temperature fluctuations over time. It is visible that the temperature is higher for KIT 2 almost all the time; this is because KIT2 is exposed to heat and external temperatures, while KIT 1 was sheltered because it was located on a balcony. When the sensor is on active mode it radiates a lot of heat, this makes the temperature monitor archive higher temperatures than the one that is really on the environment at the time, for example, for that week the mean temperature was around a maximum of 30°C, and the measured amount of the sensor is about 45 to 50 º C. These changes in temperature are due to the intrinsic temperature changes of the electronic plates.

5.3.5. Humidity comparison

The humidity sensor is located on the same chipboard as the temperature sensor, so if the behavior of one is being altered by an external force, its expected that the other one would have compromise data too. As seen in Figure 5.15, humidity values tend to decrease with higher temperatures and rise with lower temperatures; this can be due to the fact that the increase in heat blocks the environment around the sensor to build moisture and generate humidity.

Table 5.4: Table for the standard deviations obtained by the starting hours for each KIT

Standard Deviation	CO KIT1 [ppm]	CO KIT2 [ppm]	NO2 KIT1 [ppm]	NO2 KIT2 [ppm]	NH3 KIT1 [ppm]	NH3 KIT2 [ppm]
Boot 1 [2:00 AM]	0,082223	0,144961	0,049858	0,017501	0,010072	0,019275
Boot 2 [6:30 AM]	0,132626	0,177645	0,055786	0,003168	0,023604	0,038494
Boot 3 [2:00 PM]	0,125152	0,071681	0,043186	0,000992	0,027417	0,000205
Boot 4 [6:30 PM]	0,123086	0,199898	0,052369	0,001386	0,029917	0,005290

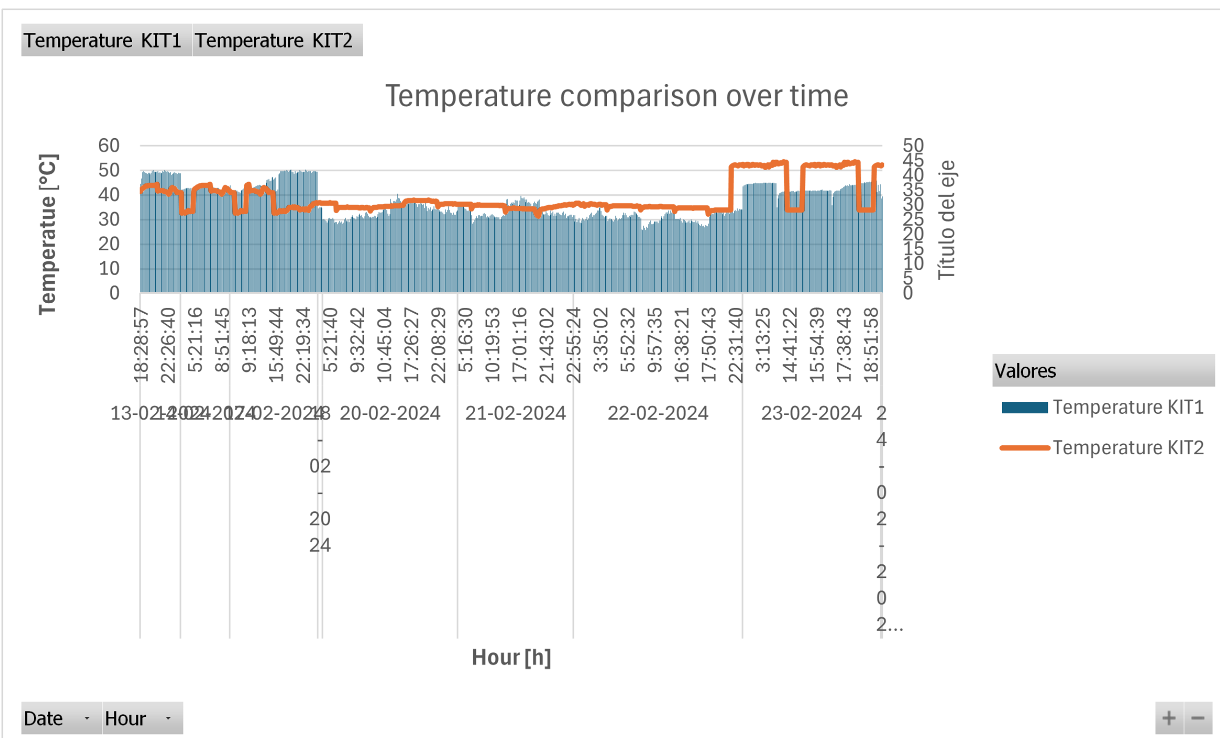


Figure 5.14: Temperature changes over time for both Kits.

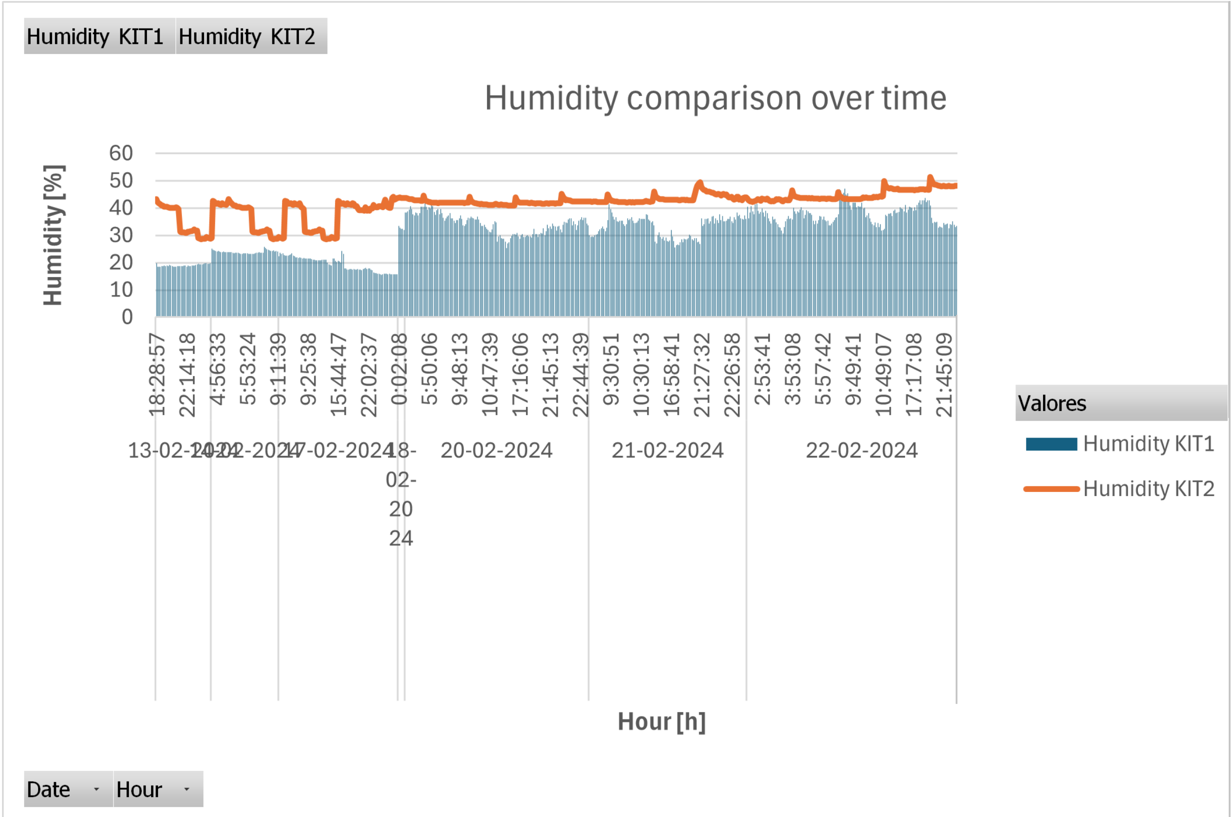


Figure 5.15: Humidity changes over time for both Kits.

Chapter 6

Conclusions

The development of devices for monitoring the levels of contamination becomes urgent for the whole population, not only for the ones that seem more vulnerable to diseases. Its reported that even little increase of the current concentration of certain gases in the environment can cause significant damage even when expose for short periods of time.
Having access to this kind of monitoring can be life saving for some people and beneficial to all of the community. It is even more important if this information is available in real time since the dashboards and displays can be made public for everyone's access.
The main goal of the device was archived, ensures a safe communication, is able to process and communicate the information in a correct and efficient way, and complies with all the functionalities needed such as waking at determined times, entering deep sleep and light sleep, calibrating the sensor, and sending the data to the cloud.
The sensor functionality was proven to be working correctly and accurately; even though it could be made better, more research would be needed, and it would be better if there were a way to communicate with the environmental ministry to get access to their sensor data so the calibration can be done more precisely.
The power consumption aspect was not archived, there were several adjustments made to the device as both hardware and software implementations, even waking up at only four times a day for about an hour and a half drained almost the entire battery. This problem is not particular to this case as many users report that it is due to the higher consumption rates that the ESP32 reaches. But since these devices are expected to be stationary, making power supply connections or sockets where they would be located and using external batteries could be a prominent solution for this issue.

6.1. Future work

For future work, it would be ideal to add a section about the possible problems encountered and how to fix them since during the development of the project there were various missteps that delayed the progress of the work ultimately into being able to do as much in dept, since most of the project was focused on the design and implementation part.
Also, it would be useful to be able to gather data for longer periods of time to have more statistically accurate information, the battery of the devices proved to be not sufficient even when enhancing the model to save as much power as possible, so searching for less consuming components and microcontrollers in exchange for the ESP32 could improve this aspect. The improvement of these would also provide a way to make more and better estimations and

predictions, and not to conform only to comparisons between the two devices.

There are ways to make this device even more affordable, the use of the RAK Wireless supplements, although convenient, present an unnecessary cost that when trying to develop and design multiple devices can elevate the cost even further. Opting for using a generic Arduino can be a better way to improve it, there are also many components that can be bought on bulk, so the cost can decrease significantly.

Bibliography

[1] Vallero, D., Grand Challenges, pp. 953–961. Elsevier, 2014, doi:10.1016/b978-0-12-401733-7.00033-5.

[2] O, E. U., "Biden-harris administration announces nearly 83 million in funding to expand air quality monitoring across the nation as part of investing in america agenda," www.epa.gov, Feb. 16, 2024. https://www.epa.gov/newsreleases/biden-harris-administration-announces-nearly-83-million-funding-expand-air-quality-0 (accessed Feb. 25, 2024).

[3] Zhang, K. y Batterman, S., "Air pollution and health risks due to vehicle traffic," Science of The Total Environment, vol. 450–451, pp. 307–316, 2013, doi:10.1016/j.scitotenv.2013.01.074.

[4] Kong, L., Tang, X., Zhu, J., Wang, Z., Fu, J. S., Wang, X., Itahashi, S., Yamaji, K., Nagashima, T., Lee, H.-J., Kim, C.-H., Lin, C.-Y., Chen, L., Zhang, M., Tao, Z., Li, J., Kajino, M., Liao, H., Wang, Z., Sudo, K., Wang, Y., Pan, Y., Tang, G., Li, M., Wu, Q., Ge, B., y Carmichael, G. R., "Evaluation and uncertainty investigation of the noamp;lt;subamp;gt;2amp;lt;/subamp;gt;, co and nhamp;lt;subamp;gt;3amp;lt;/subamp;gt; modeling over china under the framework of mics-asia iii," Atmospheric Chemistry and Physics, vol. 20, no. 1, pp. 181–202, 2020, doi:10.5194/acp-20-181-2020.

[5] Wang, P., Zhang, R., Sun, S., Gao, M., Zheng, B., Zhang, D., Zhang, Y., Carmichael, G. R., y Zhang, H., "Aggravated air pollution and health burden due to traffic congestion in urban china," Atmospheric Chemistry and Physics, vol. 23, no. 5, pp. 2983–2996, 2023, doi:10.5194/acp-23-2983-2023.

[6] Prasad, S. S. y Kumar, C., "A green and reliable internet of things," Communications and Network, vol. 05, no. 01, pp. 44–48, 2013, doi:10.4236/cn.2013.51b011.

[7] ASHTON, K., "That 'internet of things' thing," " www.rfidjournal.com, Jun. 22, 2009. https://www.rfidjournal.com/that-internet-of-things-thing (accessed Feb. 08, 2024).

[8] Wood, A., "The internet of things is revolutionising our lives, but standards are a must," https://www.theguardian.com/media-network/2015/mar/31/the-internet-of-things-is-revolutionising-our-lives-but-standards-are-a-must(accessed Feb. 09, 2024), 2015.

[9] of the European Communities, C., "Internet of things – an action plan for europe," Internet of Things – An action plan for Europe (PDF). COM(2009) 278 final, 2009.

[10] Radouan Ait Mouha, R. A., "Internet of things (iot)," Journal of Data Analysis and Information Processing, vol. 09, no. 02, pp. 77–101, 2021, doi:10.4236/jdaip.2021.92006.

[11] HIGHLIGHTS, "The internet of things: Mapping the value beyond the hype june," 2015.

[12] Kumar, S., Tiwari, P., y Zymbler, M., "Internet of things is a revolutionary approach for future technology enhancement: a review," Journal of Big Data, vol. 6, no. 1, 2019, doi:10.1186/s40537-019-0268-2.

[13] Tabbane, S., "Microsoft powerpoint - iot standards part ii st," 2018.

[14] Chen, M., Miao, Y., Hao, Y., y Hwang, K., "Narrow band internet of things," IEEE Access, vol. 5, pp. 20557–20577, 2017, doi:10.1109/access.2017.2751586.

[15] Migabo, E. M., Djouani, K. D., y Kurien, A. M., "The narrowband internet of things (nb-iot) resources management performance state of art, challenges, and opportunities," IEEE Access, vol. 8, pp. 97658–97675, 2020, doi:10.1109/access.2020.2995938.

[16] Malik, H., Khan, S. Z., Leonel Redondo Sarmiento, J., Kuusik, A., Alam, M. M., Le Moullec, Y., y Parand, S., "Nb-iot network field trial: Indoor, outdoor and underground coverage campaign," en 2019 15th International Wireless Communications amp; Mobile Computing Conference (IWCMC), IEEE, 2019, doi:10.1109/iwcmc.2019.8766568.

[17] World, R. W., "Nb-iot architecture | lte-nb iot architecture," https://www.rfwireless-world.com/Terminology/LTE-NB-IoT-Architecture.html (accessed Feb. 25, 2024).

[18] Mahbub, M., "Nb-iot: applications and future prospects in perspective of bangladesh," Rep. Tec. Ericsson, 2020.

[19] Gillis, A. S., "What is narrowband iot (nb-iot)? | definition from techtarget," ttps://www.techtarget.com/whatis/definition/narrowband-IoT-NB-IoT: :text=NB-IoT

[20] Comonline, "Telefónica, huawei y kamstrup lanzan en chile el primer proyecto con tecnología narrowband iot en latinoamérica," https://www.telefonica.com/es/sala-comunicacion/prensa/telefonica-huawei-y-kamstrup-lanzan-en-chile-el-primer-proyecto-con-tecnologia-narrowband-iot-en-latinoamerica/ (accessed Mar. 06, 2024)., vol. Telefónica, Feb. 15, 2017.

[21] Chile, C., "Claro chile lanza dispositivo iot de rastreo en tiempo real," https://noticias.clarochile.cl/noticias/claro-chile-lanza-dispositivo-iot-de-rastreo-en-tiempo-real/ (accessed Feb. 09, 2024).

[22] News, D., "Claro busca posicionarse como proveedor global de soluciones iot con su nueva red narrow band | dpl news," https://dplnews.com/claro-busca-posicionarse-como-proveedor-global-de-soluciones-iot-con-su-nueva-red-narrow-band/ (accessed Feb. 11, 2024).

[23] Digital, E., "Narrowband-iot," enteldigital.cl. https://enteldigital.cl/narrowband (accessed Feb. 08, 2024).

[24] for Europe, W. R. O., "Who guidelines for indoor air quality : selected pollutants," 2100.

[25] OSHA, "Carbon monoxide poisoning,".

[26] Goel, N., Kunal, K., Kushwaha, A., y Kumar, M., "Metal oxide semiconductors for gas sensing," Engineering Reports, vol. 5, no. 6, 2022, doi:10.1002/eng2.12604.

[27] Pérez, E., "Vodafone diseña junto a una empresa española la primera luz conectada con la dgt para sustituir a los triángulos de emergencia," Xataka, Jun. 02, 2021. https://www.xataka.com/internet-of-things/vodafone-disena-a-empresa-espanola-primera-luz-conectada-dgt-para-sustituir-a-triangulos-emergencia (accessed Feb. 07,

2024).

[28] Ferrovial, “Ci3 despliega el sistema de monitorización medioambiental smairt en guadalajara ferrovial,” https://newsroom.ferrovial.com/es/noticias/contaminacion-del-aire-monitorizacion-medioambiental/ (accessed Feb. 14, 2024).

[29] Studio, S., “Grove - multichannel gas sensor | seeed studio wiki,” wiki.seeedstudio.com, Jan. 04, 2023. https://wiki.seeedstudio.com/Grove-Multichannel$_{Gas_S}ensor/(accessedFeb.27, 2024)$.

[30] de Medio Ambiente, M., “Sistema de información nacional de calidad del aire,” sinca.mma.gob.cl. https://sinca.mma.gob.cl (accessed Feb. 27, 2024).

[31] Wireless, R., “Rak19001 wisblock dual io base board datasheet,” rak documentation center,” https://docs.rakwireless.com/Product-Categories/WisBlock/RAK19001/Datasheet/wisblock-dual-io-base-board-overview (accessed Feb. 22, 2024).

[32] Wireless, R., “Rak11200 wisblock wifi module datasheet,” rak documentation center,” https://docs.rakwireless.com/Product-Categories/WisBlock/RAK11200/Datasheet/specifications (accessed Feb. 22, 2024).

[33] Wireless, R., “Rak5860 wisblock nb-iot interface module datasheet,” rak documentation center,” https://docs.rakwireless.com/Product-Categories/WisBlock/RAK5860/Datasheet/ (accessed Feb. 22, 2024).

[34] Wireless, R., “Rak1901 wisblock temperature and humidity sensor datasheet,” rak documentation center,” https://docs.rakwireless.com/Product-Categories/WisBlock/RAK1901/Datasheet/hardware (accessed Feb. 24, 2024).

[35] hzsdakj2.cl, “Mics-6814 sensor de gas monóxido de carbono co no2 nh3 nitrógeno oxígeno detección de calidad del aire módulo numérico,” https://shorturl.at/kxNZ8 (accessed Feb. 10, 2024).

[36] Detection, M. G., “Macurco qa,” rep. tec., 3601.

[37] Macurco, “Fixed gas detector mounting height,” Macurco Gas Detection, Aug. 03. https://macurco.com/detectormountingheight-2/ (accessed Feb. 01, 2024).

[38] AliExpress, “Aliexpress,” https://shorturl.at/iuLT0(accessed Feb. 01, 2024).

[39] Limited, R. T., “Collections,” RAKwireless Store. https://store.rakwireless.com/products/ (accessed Feb. 07, 2024).

Annex

Annex A. Code

The code used can be found in the repository listed below by the name of “Thesis main code”, all the library needed is also provided on the repository. https://github.com/aurithemas/Thesis-NB-IOT.git