



## UNIVERSITÀ DEGLI STUDI DI PADOVA

DEPARTMENT OF MATHEMATICS “TULLIO LEVI CIVITA”

*MASTER THESIS IN COMPUTER SCIENCE*

# OPEN LoRa MESH NETWORK FOR IoT-BASED AIR QUALITY SENSING

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# cosmopolitan adjective

cos·mo·pol·i·tan | \,käz-mə-pälə-tən \

From the Greek **κοσμοπολίτης** ('citizen of the world')

## Essential Meaning of *cosmopolitan*

- 1 : having worldwide scope or bearing
- 2 : showing an interest in different cultures, ideas, etc.
- 3 : composed of persons, constituents, or elements from all or many parts of the world
- 4 : someone who has experience of many different parts of the world
- 5 : informally a **cosmo**, is a cocktail made with vodka, triple sec, cranberry juice, and freshly squeezed or sweetened lime juice



# Abstract

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# Sommario

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*Ideas are common.*

*Everybody has ideas.*

*Ideas are highly, highly overvalued.*

*Execution is all that matters.*

Casey Neistat

# 1

## Introduction

In an interview from 1988 about school education and its relationship with the Internet, Isaac Asimov, one of the 20<sup>th</sup> century's most prolific science fiction writers, said “*now, with the computer, it's possible to have a one-to-one relationship for the many. Everyone can have a teacher in the form of access to the gathered knowledge of the human species*”.

At the time of writing, many things have changed since that interview: people now live in an *hyperconnected world*, where accessing Internet is considered a right, so that everyone has the same learning opportunities.

According to Cisco's 2018 - 2023 Internet Report, “the number of devices connected to IP networks will be more than three times the global population by 2023” [1]. Authors also predict there will be 29.3 billion networked devices by 2023, a major increase from 18.4 billion in 2018. Of all these, 50% is represented by Internet of Things, or IoT, devices.

As stated in one of Forbes's insights, “*IoT is ranked as the most important technology initiative by senior executives; more important than artificial intelligence and robotics, among many others*”, while, from an economical point of view, “*of all emerging technologies, the Internet of Things (IoT) is projected to have the greatest impact on the global economy*” [2]. The number of devices that are being connected to the Internet is growing day by day and the industry is at its highest peaks.

This new paradigm of computer science can be considered an enabler for the sciences that need large amount of data for creating algorithms and offering better services and more well tailored products. The ubiquity of mobile technology has opened the door to a new era of

mobile sensing.

Using the data gathered until the second half of the 20<sup>th</sup> century, computer simulations showed how the rise in CO<sub>2</sub> levels that can lead to climate change and cause global temperatures to rise steadily in the years. Scientists started to take a more common approach to pollutants and climate change by developing instruments capable of more accurate readings and by better understanding how to analyze the gathered data. In the preface of 1981's "*The Design of Air Quality Monitoring Networks*", the author states that "*the number of publications in the environmental area is increasing exponentially*" [3]. This leaves one to think about the state of this research area up to date.

Many publications have been studying the development of low-cost devices, focused on analyzing the quality of the surroundings of individual.

This thesis takes a focus on a particular project, MegaSense, a personal air quality device developed by the University of Helsinki.

In this thesis, the architecture for connecting such devices is expanded with the use of a LoRa mesh network.

## 1.1 CONTRIBUTIONS

The main contribution made in this thesis is the creation of a mesh network composed by microcontrollers which communicates via LoRa technology. This mesh has been designed to accommodate the message exchange between devices such as air quality sensors, particularly MegaSense, an air quality sensing device from the University of Helsinki.

Air quality sensing, as previously mentioned, is one of the applications of IoT, and this mesh has been designed keeping in mind the communication needed in between these set of devices.

## 1.2 DOCUMENT OUTLINE

This document follows an hourglass structure by first explaining in general the necessary notions to understand the work done and then going more in detail. The content is organized as such in the following chapters:

1. *Introduction*: introductory chapter;
2. *Background*: introduces concepts necessary to understand the project and why it has been developed;

3. *Technologies*: explains underlying technologies, starting from the general definition of a network, common network architectures, radio technologies and micro-controllers;
4. *Related work*: described related projects from which project of this thesis has drawn inspiration;
5. *Proposed solution*: describes in depth the mesh network developed;
6. *Results and experimentation*: details the experiments and the results made to test the mesh;
7. *Conclusions*: concluding chapter which revisits the concepts of this project and reflects on the possibilities to ameliorate it.



*It is one thing to mortify curiosity,  
another to conquer it.*

Robert Louis Stevenson, Dr. Jekyll and Mr. Hyde

# 2

## Background

This chapter introduces the background concepts necessary to understand the project presented in this thesis and why it has been developed.

It first explains the definition of IoT, afterwards, it describes the air pollution problem, to conclude with an overview on the background work and state or art of two devices capable of detecting pollutants in the air.

Mesh networks are better described in Chapter 4, where also previously made projects which use a similar architecture are described.

### 2.1 INTERNET OF THINGS

Internet of Things, also abbreviated with IoT, has a longer history than many people think about: its name, now known all around the globe, has been attributed to Kevin Ashton, who used it in a presentation about Radio Frequency Identification (RFID) technology, at *Protector & Gamble*, in 1999 [4] to describe the network connecting objects in the physical world to the Internet.

This constantly expanding branch of Computer Science aims to turn physical objects, as small as they may be, into nodes of an interconnected system which opens the door to new interfaces between humans and machines and how these see the physical world. IoT's importance heavily relies on data gathered from these devices, since, in combination with other computer science paradigms such as Machine Learning and Artificial Intelligence, raw data

can be transformed into valuable information.

The creation of models from all these inputs has given a more efficient workflow in companies and has improved certain aspects of everyday life, from wearable technologies to Inter-Vehicular Communication (IVC). As explained in [5], the latter is a “*key technology in order to increase driving efficiency and safety, as well as support autonomous driving and provide many other connectivity-based services*”. The biggest challenges though are *heterogeneity* of devices and *dynamicity* in vehicular scenarios.

Another important application scenario of IoT is emergency situations, where it supports first responders with adequate means to perform their operations in a safe and effective way. In this case, from a networking point of view, “*one of the main challenges is that of providing first responders with multimedia information about the emergency as soon as possible, even from a remote location*” [6]. Projects designed to provide connectivity off-grid not only to civilians, but firefighters, military operations, local law enforcement, search and rescue, are described in Section 4.4.

But first, below are two important key projects in the story of IoT the UPC, or Universal Product Code, and the Carnegie Mellon University (CMU) coke machine.

#### 2.1.1 UNIVERSAL PRODUCT CODE AND BARCODE

One of the first technologies that can be considered part of the IoT family, is the “*Universal Product Code*”, or *UPC*. Its first iteration is detailed in the patent issued to inventors Joseph Woodland and Bernard Silver on October 7, 1952, and can be described as a “*bull's eye*” symbol, made up of a series of concentric circles [7], as can be seen in Figure 2.1.

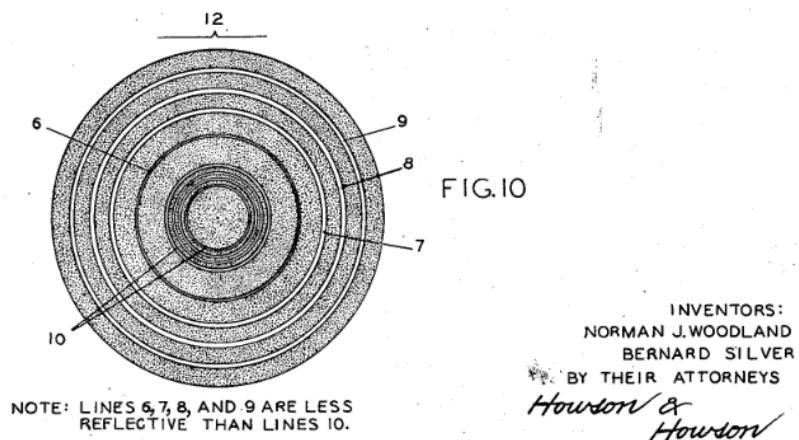


Figure 2.1: Diagrammatic view of the Universal Product Code [7]

Authors of the patent, state that “*one application of the invention is in the so called ‘super-market’ field*”, indicating they already successfully identified a need to speed up and automatizing the process of paying at super-markets.

Due to the large size and low reliability of the equipment necessary to read the figure, this concept has not been immediately released for everyday use. Commercial adoption relied on the emergence of laser optics, which started to offer a more compact reading technology.

Although, printers were vulnerable to smudge the design coped with errors as ink bleeding would result in taller bars. Thus, the ameliorated UPC print was vertical and came in the form of a barcode printed with strict rules in order to avoid errors in scanning due to smear or marks on the label. This version, developed in 1971 by George Laurer at IBM [8], became the first wide appearance of the upc.

A centralizes super-system that provided the code translations was used in order to standardize codes among different super markets and shopping places. Such system has been the first way to track products and address them at large scale, thus rendering a “*thing*” at the super market capable of providing information to a larger scale, although not directly connected.

#### 2.1.2 CMU’s COKE MACHINE AND MODERN VENDING MACHINES

It may come as a surprise, but connecting everyday “*things*” for direct interaction, contrary to the previous example, started around the 1980s.



Figure 2.2: CMU’s “coke machine”

One of the most famous and most quoted as the first IoT device, is the Carnegie Mellon University (CMU) coke machine at the Computer Science Department.

Communication from and to the machine, which allowed remote access, took place via Arpanet at CMU as the system predated the Internet. Various sensors were used to detect whether shelves were empty and to track status of coke bottles (warm, cold, empty).

As explained in the official website<sup>1</sup> dedicated to this device by the University, there are “*micro-switches in the Coke machine to sense how many bottles were present in each of its six*

---

<sup>1</sup> [www.cs.cmu.edu/~coke/history\\_long.txt](http://www.cs.cmu.edu/~coke/history_long.txt)

*columns of bottles*".

Modern day vending machines usually require continuous connectivity to the manufacturer's systems. This is not always achievable via a Wi-Fi connection where machines are placed, so other solutions, such as cellular connectivity, are used. Connection reliability in vending machines and other kiosks is important since these provide goods that can be payed by credit card, which need to establish a secure connection.

They contain multiple small, but complex, systems that interact with each other, thus it is implied that this kind of machines must have installed a secure software and that they need to be as hard as possible to be tampered with, either by brute force or by software bugs.

Otherwise it is not only possible that someone steals a snack, but some remote script may turn these machines into a botnet capable of bringing down the connectivity of an entire campus. Such attack has been described in Verizon's "*Data Breach Digest*" risk report from 2017, where the author states that "*the firewall analysis identified over 5,000 discrete systems making hundreds of DNS lookups every 15 minutes*" [9].

While credit card skimmers and chip card cloners remain viable risks to the end consumer, security measures to the environment where machines are placed must not remain an afterthought, especially when these are placed alongside other connected devices and not in their own separated network. Such kind of smart vending machines have helped bring a step closer old "*un-connected*" cities to become "*smart cities*", where these machines can be used as a mean to place devices such as routers or public Wi-Fi access points.

### 2.1.3 TRENDS, FORECASTS AND RESEARCH DIRECTIONS

IoT and related technologies have grown exponentially since the times of CMU's coke machine. According to data from Microsoft Academic<sup>2</sup>, publications about "*Internet of Things*" have grown exponentially: from the 26 in the year 2000, to 534 in 2010, 4959 in 2015, to 22454 papers published in 2020. This shows how much interest IoT has gathered among the scientific community. Nonetheless, some IoT systems can still be considered not ready for mass deployment and many technical difficulties and problems need to be solved.

Research directions in this new area are vast, since every physical device now represents a possible "*thing*" connected in the network and that can be interacted with and provide data. Authors of [10] have highlighted ten particular topic areas that span across three layers of IoT architecture: Application, Data and Physical, as represented in Figure 2.3.

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<sup>2</sup> [www.academic.microsoft.com/topic/81860439](http://www.academic.microsoft.com/topic/81860439)

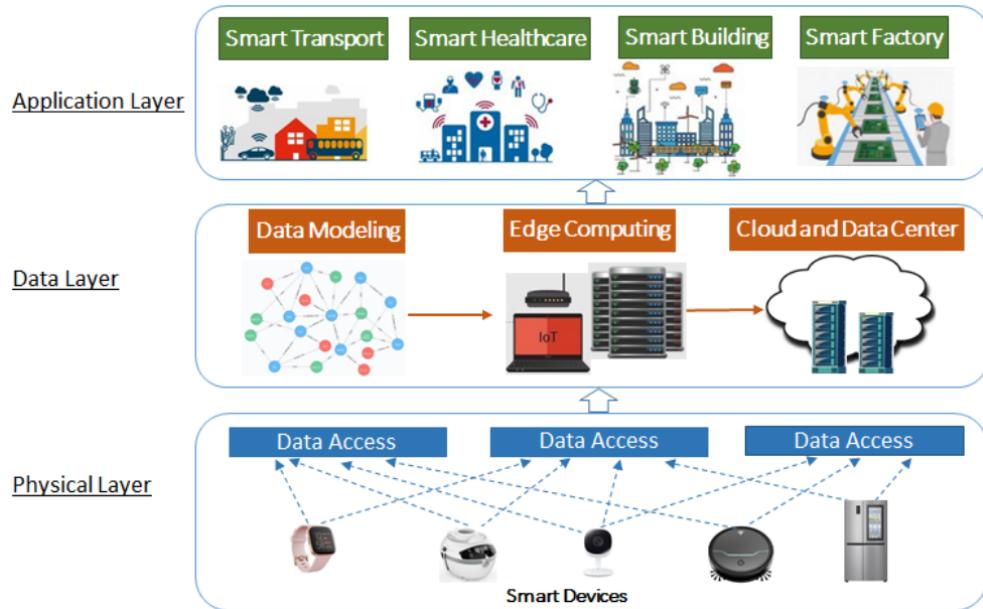


Figure 2.3: Most researched areas in IoT [10]

These topics include “*Data-driven IoT*”, “*Security, Privacy, and Trust in IoT*”, “*Social IoT*”, and “*Edge Computing and IoT*”, which have brought the need for new paradigms of computation.

Data can be created and collected at a very high speed when considering the number of devices connected. This has been stimulating the creation of faster and more reliable database management systems (DBMSs) and brokers that allow higher processing speeds and querying frequencies. Specialized versions of these are emerging, each fitted for different scenarios, that may range from a fully online (or as a service with products such as AWS IoT Core<sup>3</sup>) infrastructure to fully on premise one.

Another important aspect is the network’s architecture, which needs to take in consideration aspects such as heterogeneity of connected devices, velocity of data that flows across and scalability. Thus, paradigms like Cloud Computing, Fog Computing and Edge Computing<sup>4</sup> have emerged.

In Edge Computing, data points are used where they are produced, without traversing the network unnecessarily. This way, cloud infrastructure requirements are drastically reduced in three ways: firstly, less network traffic, secondly, less central storage and thirdly less com-

<sup>3</sup> [www.aws.amazon.com/iot-core/features](http://www.aws.amazon.com/iot-core/features)

<sup>4</sup> “*Edge Computing does not mean computers at the edge of a table.*” -cit. Alessandro Canesso

putational power. Rather, Edge Computing makes use of all the capable hardware already deployed, e.g., in a smart home where all the data could stay within the house and be used on site.

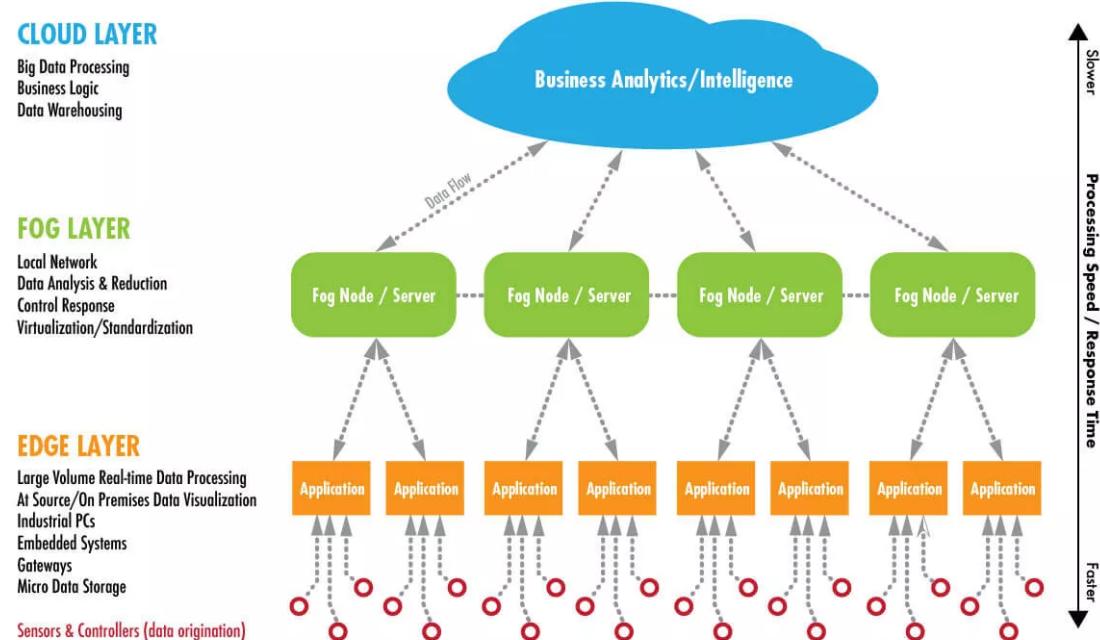


Figure 2.4: Edge, Fog and Cloud Computing

Each of these paradigms places computation on a different network layer, from Cloud Computing which lifts off all the need for end devices to compute data, to Edge Computing, where there might be specialized servers physically placed in strategic points so that they are closer to the end devices (lower latency), which may even have the ability to compute data by themselves. On the other hand, Fog Computing is less aggressive than Edge Computing, and does not require the same amount of services placed near the clients, but they can be sorted among the backbone of the network.

These communications do not take place only via Wi-Fi or Ethernet: given that “*things*” can be everywhere, the need for a network that can adapt to a fast paced environment is becoming a must. Here is where the 5<sup>th</sup> generation of cellular connectivity comes into play.

As described in a 2019 whitepaper by the GSM Association on IoT and the use of 5G, a “*combination of 5G and wireless edge technologies will support demanding use cases, such as autonomous driving, time-critical industrial IoT manufacturing processes and augmented and virtual reality (AR/VR)*” [11]. Compared to what is possible with other transmission

technologies, 5G supports a massive number in connections, with very little latency.

All of this is not only interesting from a research point of view, but also from a market point of view, where new devices, for consumer and industrial purposes, are created to suit every possible need, that is why IoT can be considered as the “*next chapter of digital communication*”.

The most notable example from a consumer’s point of view, is the smartwatch, which started with the infamous Pebble watch<sup>5</sup>, and is now considered almost a “*must-have*” extension of the smartphone. Not only smartwatches can be used for recreational purposes, but some models are crossing the line to becoming medical devices, given the improving accuracy with which they record data. Data that, in conjunction with AI, can be used to predict heart attacks [12] or other diseases, like Hyperkalemia [13]. At the time of writing, IoT devices and frameworks can be used for contact tracing in order to prevent the spread of Covid-19 [14].

Consumers want remote control of simple household devices such as coffee pots so that they may wake up to freshly brewed coffee, or schedule it to be prepared at a given time.

On the other hand, from an industrial point of view, demands are more focused on fast connectivity among devices, “*Machine to Machine*” (M2M), to constantly improve production of goods and services in Industry 4.0 and with the use of Industrial IoT (IIoT). The more data available, the more there are opportunities for science, services, business etc. to understand and improve and offer better services and more well tailored products. The growing popularity of IoT use cases in domains that rely on connectivity spanning large areas and the ability to handle a massive number of connections is driving the demand for Low-Power Wide-Area-Network (LPWAN) access technologies, that is why the goal of fifth-generation (5G) wireless networks and beyond is to realize connecting “*anything, anyone, anytime, anywhere*” [15]. LPWANs are better explained in Section 3.2.

Given the importance of this economic sector, many companies, have analyzed the trends and have been producing forecasts about the growth of IoT. One analysis, made by The Economist’s Intelligence Unit, and sponsored by Arm<sup>6</sup>, states that “*more than two-thirds of respondents agree that understanding the value of data helps them articulate the business case for IoT investments*” [16]. In the same analysis, IoT has emerged as an enabler for AI, since many companies “*view IoT and AI as two components of an advanced analytics capability*”, as previously mentioned.

Underlying hardware challenges such as battery development and energy retention and

---

<sup>5</sup> [www.kickstarter.com/profile/getpebble/created](http://www.kickstarter.com/profile/getpebble/created)

<sup>6</sup> [www.arm.com](http://www.arm.com)

consumption are among the main research areas that are being investigated, since they represent challenges to the realization of efficient IoT systems.

## 2.2 AIR QUALITY SENSING

The ubiquity of mobile technology has opened the door to a new era of mobile sensing. Through this new paradigm that is IoT, physical phenomena can be observed in a distributed way, crowd-sourcing data measurement tasks to smartphones and/or other popular smart wearables. Mobile sensing and wireless communications can hence be employed to gather data and generate new information and services, benefitting society. Two general strategies can be used to deploy an environmental monitoring system: creating a network of *fixed sensors* or resorting to *mobile sensors*.

The presence of tiny particulate matter in air is a crucial factor in health, especially when considering urban scenarios. In this context, smart mobility coupled with low-cost sensors can create a distributed and sustainable platform for social sensing able to provide pervasive data to citizens and public administrations. Sustainable and eco-aware decisions can then be supported by empirical evidence, resulting in an improved life and better city administration.

Some of the most harmful airborne agents are fine particles (PM<sub>2.5</sub>), sulphur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), PM<sub>10</sub>, carbon monoxide (CO), benzene and ozone. The maximum amount for these particulates is regulated by various local and international authorities, for example the EU has set standards<sup>7</sup> that are reinforced by constant monitoring.

One of the most important instruments in air quality measurement is the *Keeling Curve*: a meticulous record of the amount of carbon dioxide in the atmosphere.

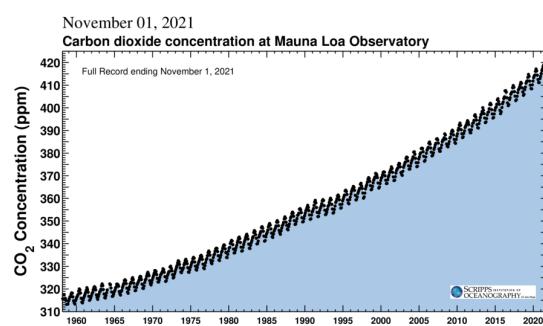


Figure 2.5: Full record Keeling curve until Nov. 1 2021

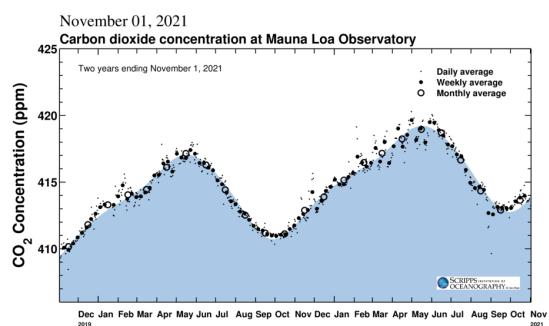


Figure 2.6: Two years Keeling curve until Nov. 2021

<sup>7</sup> [www.ec.europa.eu/environment/air/quality/standards.htm](http://www.ec.europa.eu/environment/air/quality/standards.htm)

The Keeling Curve tracks changes in the concentration of CO<sub>2</sub> in the Earth's atmosphere using data from a research station on Mauna Loa, Hawaii. Figure 2.5 shows the result of daily readings that have continued almost uninterrupted for more than 60 years, while Figure 2.6 shows the data between October 2019 and November 2021. The importance of this instrument lies in the fact that, over those six decades, the zig-zag has trended steadily upward. Real time readings can be found on the UC San Diego, Institution of Oceanography's dedicated website<sup>8</sup>.

#### // To be completed, add research on low cost outdoor air quality sensors

Many projects have been made, both for research and commercial purposes, to detect pollutants in the air and raise awareness of the conditions people are living in. Below are two research solutions that have been made for air quality sensing with low-cost sensors.

##### 2.2.1 ARDUECO

ArduECO is a wireless device based on an Arduino-like board, esp8266, capable of gathering data about air quality (and more with simple extensions) and sending them to the cloud, to be processed and displayed.

This solution has been proposed in the paper "*Air Quality Control through Bike Sharing Fleets*"[17], presented at the 2020 IEEE Symposium on Computers and Communications.

One of the main design goals of this device is to be easily fit on shared means of transportation, such as bikes and electric scooters, which been advantaged by the COVID-19 pandemic [18], contrast other shared transportation approaches, such as car sharing, that have severely suffered from the pandemic.

ArduECO is built around four core components: the NodeMCU ESP8266-based development board, a microSD card reader for local data caching, a GPS-based global navigation satellite system receiver for location data and an MQ-7 carbon monoxide (CO) sensor, which can easily be replaced with other sensors using the same pinout. Figure 2.7 shows the full circuit of the prototype, while Figure 2.8 is a picture of the built device.

As well as capturing the air quality data locally, data is cached and later sent in the cloud to an MQTT server running on Amazon Web Services IoT Core.

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<sup>8</sup> [keelingcurve.ucsd.edu](http://keelingcurve.ucsd.edu)

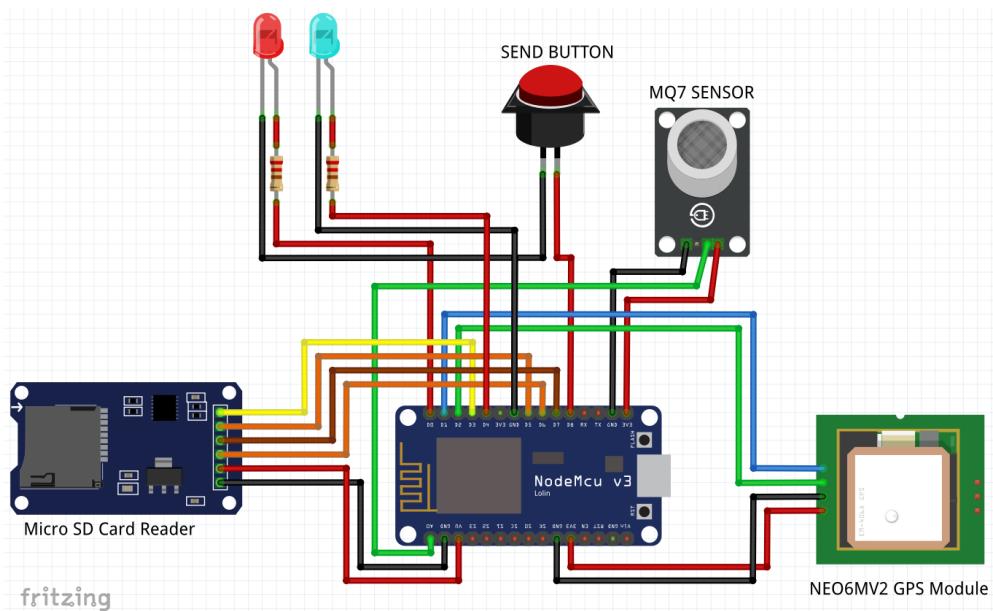


Figure 2.7: Circuit of the ArduECO prototype

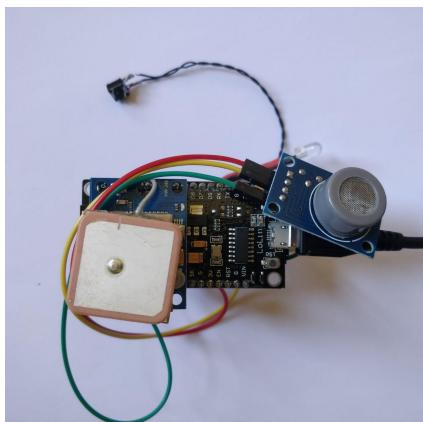


Figure 2.8: Built ArduECO prototype

Server costs aside, the sensor platform can be built in a bill of materials of around 15€, or less if the materials are bought in bulk.

As described in the paper, this project is more of a proof of concept that shows the possibility of creating a small and cheap device which can be placed on shared means of transportation. Therefore there are various aspects that can be improved, such as adding multiple sensors to detect different pollutants and tweak the software so that the board can sleep and save battery.

### 2.2.2 MEGASENSE

MegaSense is a project that has been developed by the Departments of Computer Science at the University of Helsinki<sup>9</sup> and brings forward accurate portable low-cost sensing devices and an online data platform integrating multiple sources of urban data and leveraging AI network calibration producing hyper-local air quality information in real time.

<sup>9</sup> [www.helsinki.fi/en/computer-science](http://www.helsinki.fi/en/computer-science)

Compared to the previously described ArduECO, MegaSense, represented in Figure 2.9, is a more complete project which has been tested by citizens and companies in City of Helsinki and EU projects. It is also encased in a 3D printed case and has an rechargeable battery, allowing it to be immediately given to the users.

The back-end system receives data from sensing platforms, the individual MegaSense devices, measuring local pollution exposure and other variables affecting it. These data are processed into air quality information such as maps and advice on how to reduce personal exposure, take healthier routes, and direct participants to improve measurements in areas that have limited sensor coverage.



Figure 2.9: MegaSense prototype

As explained in the main paper [19] regarding this device, “*the core of MegaSense consists of two layers: the Edge and Cloud*”. The Edge layer receives data from available node and delivers pollution maps to the mobile app, which provides users with personal air pollution exposure information as well as local exposure maps. This layer is responsible for data pre-processing, filtering and data cleaning. The cloud layer, which runs on AWS, is responsible for storing cleaned data and aggregating the crowd-sourced data while preserving the privacy of participants.

Registered citizens that have been given the device, download the HOPE Exposure App from Google play store and tether their Android smart phone to the sensor. The phone gathers data from the sensor, alongside the GPS coordinates, and it sends them in the cloud.

#### // To be completed, add how calibration works + sensors

This project develops the clean air journey planner application that creates optimal walking and cycling routes based on air quality of Helsinki.

A better understanding of the architecture of MegaSense is explained in Section 5.1, while the papers in which this project is detailed are [19, 20].



*The Internet is becoming the town square for the global village of tomorrow.*

Bill Gates

# 3

## Technologies

This chapter explains more in detail the underlying technologies of this project. Starting from the general definition of a network and the most common architectures, radio technologies and micro-controllers.

### 3.1 FUNDAMENTALS OF NETWORK COMMUNICATION

*“A computer network is a structure that makes available to a data processing user at one place some data processing function or service performed at another place.”* [21]

Starting from the definition of a computer network by Paul E. Green, it is easy to understand its importance in today’s society. Smartphones, personal computers and other interconnected devices have become omnipresent in modern society, where people have the urge to be connected to each other via these devices. Not only they are used for fun, leisure and other social activities, but they allow connection to services such as online banking, government services and healthcare, which require a stable and secure connection among the systems they use in order to provide a safe experience for their users. All this to say, networks are everywhere underneath today’s technology. There are no services or devices that can stand on their own without sharing data to other devices, to synchronize and provide a better user experience, to get updates from the manufacturer or simply to send a keep-alive message.

While this raw data is important for computers, people, the final users, process it to gain information, and this exchange of information from all around the world has brought radical

changes many levels, from a cultural and economical point of view. The possibility of having a network to share information is the next step of globalization, which started with the trade of goods among countries and now brings everyone together, allowing for a cultural exchange that lets people unite across the globe.

This big network that is used to exchange information all around the world has a special name: Internet. Many countries, such as Finland, Spain and Greece, have recognized the importance of this network and have given people the “*right to Internet access*”, also known as the *right to broadband or freedom to connect*. In these countries, service providers must be able to supply a mandatory minimum connection capability to all desiring home users in the regions of the country they serve.

It is important to note that *Internet*, with a capital *I*, is a particular set of worldwide interconnected networks [22], but a common network of networks is called *internetwork*, shortened by *internet*, with a lowercase *i*.

Such distinction began in the 1980s and has been described in RFCs<sup>1,2</sup> by computer scientists that understood how ARPANET was expanding and its dimensions were not enough anymore to accommodate the amount of data traveling from one computer to another. At that time, computers such as the *IBM 5150* and the infamous *Commodore 64* were starting to become more and more available, even if highly priced, not only to companies and universities, but also to consumers who brought them in their households, especially with the advent of *MS-DOS*, the dominant operating system throughout the 1980s, now open-source<sup>3</sup>.

As described by IBM in one of their technical books from the time, ”*it is possible to divide the Internet such as the following groups of networks*” [22]:

- *backbones*: large and strategical data routes among core networks and routers that compose and connect the Internet;
- *regional networks*: that connect large facilities such as universities and colleges;
- *commercial networks*: that provide to their subscribers access to the Internet;
- *local networks*: which run, for example, across a campus university or private property.

Given this increase of computers connecting to the Internet, there came the need for a revised structure that could better organize these components in a more robust, but also flexible, large network. With more accessible operating systems, such as *Windows 95* and

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<sup>1</sup> RFC 871 (1982): A PERSPECTIVE ON THE ARPANET REFERENCE MODEL

<sup>2</sup> RFC 872 (1982): TCP-ON-A-LAN

<sup>3</sup> [www.github.com/microsoft/MS-DOS](http://www.github.com/microsoft/MS-DOS)

*Windows 98*, and the advent of Tim Berners-Lee's *World Wide Web* (or *WWW*), computers became a common commodity. The invention of the web and its ease to navigate, using hyperlinks and search engines, culminated in the *dot com* bubble, a stock market bubble in the late 90s that caused rapid rise of technology companies in stock market.

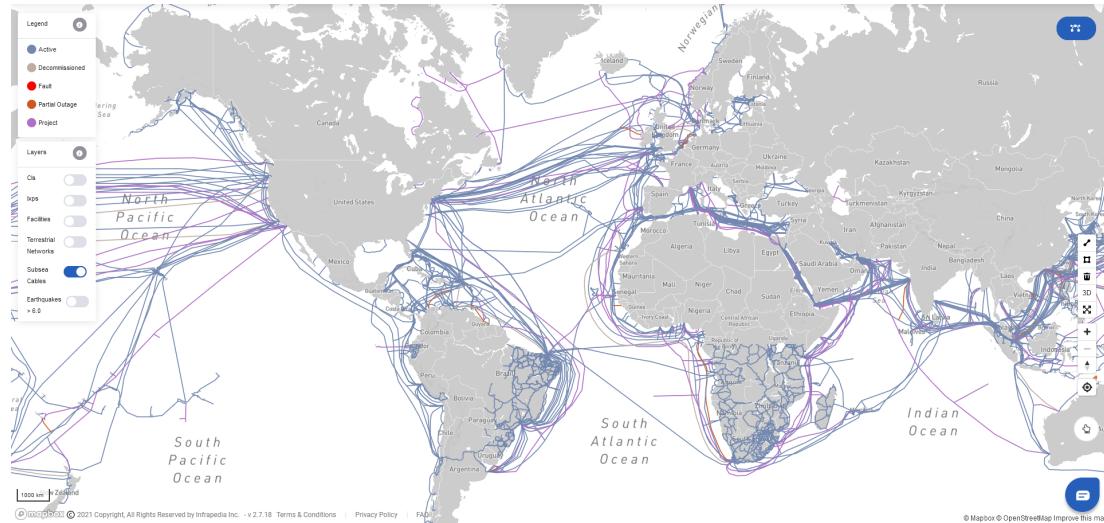


Figure 3.1: Subsea Internet backbone cables between US and Europe<sup>4</sup>

Networks can be categorized based on the area they cover and serve:

- *Wide Area Network*, or *WAN*: also called long haul networks, provide communication over long distances;
- *Metropolitan Area Network*, or *MAN*: provide communication inside a metropolitan area, which could be a single large city, multiple cities, or any given large area with multiple buildings;
- *Local Area Network*, or *LAN*: provide the highest speed connections among computers in a small and circumscribed area;
- *Personal Area Network*, or *PAN*: connects devices within a user's immediate area.

Another level of distinction among networks, which is made based on the power consumed by the transmission medium, is explained in Section 3.2.

Since now everyone can connect to the Internet and access its services, there is no need for the average user to understand what happens between his machine and the rest of the network, which means he only sees the information displayed, without knowing where it arrives from or what path it took to arrive on his monitor.

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<sup>4</sup> <https://www.infrapedia.com/app>

For computer scientists though, it is important to understand the difference between *network architecture* and *network topology*. A *network architecture*, as described by Paul E. Green, “*is a complete definition of all the layers necessary to build the network*” [21]. This is focused on the network software, which needs to be highly structured in order to allow for heterogeneous systems to communicate with each other. One example of network architecture is the *ISO/OSI reference model*<sup>5</sup>, which is implemented by the *TCP/IP protocol stack*.

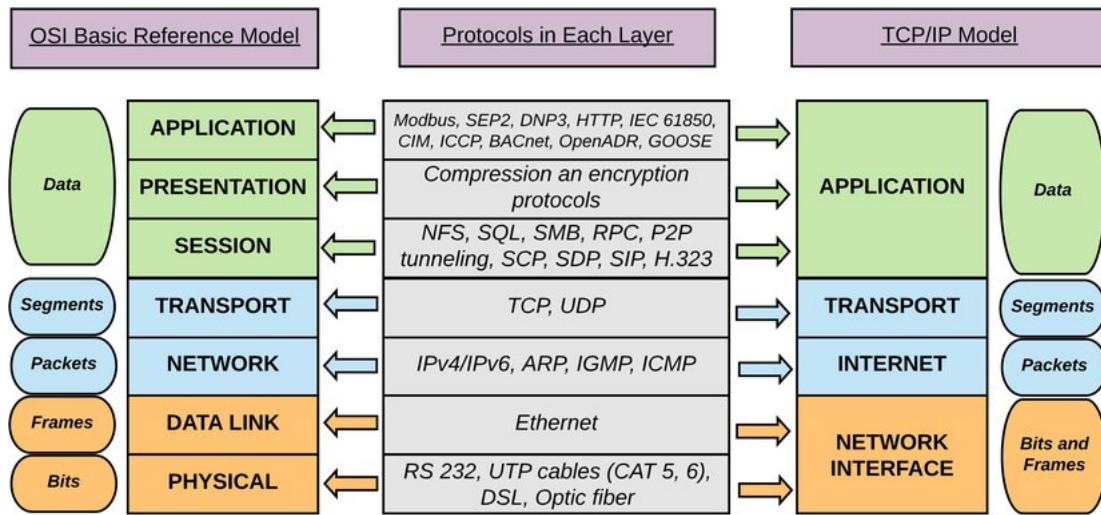


Figure 3.2: The ISO/OSI reference model against the TCP/IP protocol stack

Thus comes the definition of a protocol as “*a set of agreements for interaction of two or more parties and is expressed by three components, syntax (e.g., a set of headers, a set of commands/responses), semantics (the actions and reactions that take place, including the exchange of messages), and timing, the sequencing and concurrency aspects of the protocol*” [21]. Different types of network use distinct architectures, based on the transmission medium and how well this performs (errors, speed, etc.).

On the other hand, the *network topology* refers to the manner in which the links and nodes of a network are arranged to relate to each other.

### // To be completed w/ definition of UNICAST / MULTICAST / BROADCAST

As shown in Figure 3.3, some of the most common network topologies are:

- *point-to-point*: in which devices are connected directly;
- *bus*: devices are connected to each other via a backbone cable;

<sup>5</sup> [www.iso.org/standard/20269.html](http://www.iso.org/standard/20269.html)

- *ring*: two dedicated point-to-point links connect a device to the two devices located on either side of it, creating a ring of devices through which data is forwarded via repeaters until it reaches the target device;
- *star*: connects each device in the network to a central hub. Devices can only communicate with each other indirectly through the central hub;
- *tree*: parent-child hierarchy in which star networks are interconnected via bus networks;
- *mesh*: a dedicated point-to-point link connects each device on the network to another device on the network, only carrying data between two device;
- *hybrid*: any combination of two or more topologies.

An important factor that decides the industrial acceptance of any network topology is its “*scalability*”, concept reiterated in Section 4.2 for mesh networks.

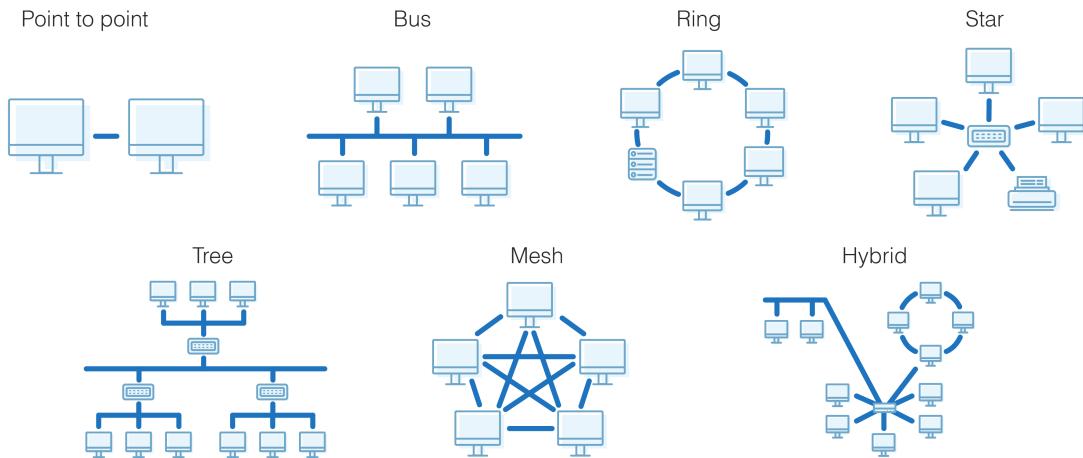


Figure 3.3: Common network topologies

The project presented in this thesis regards a network with a mesh topology, which can be considered a *multi-hop network*, since data passes from node to node until it reaches its destination. This is better described in Chapter 5, alongside the technical details of mesh proposed in this thesis, which has a span of LAN / MAN, since it connects devices that are in a circumscribed area but can be also placed further from each other, in order to cover longer distances.

The organization responsible for Internet standards is the Internet Engineering Steering Group (IESG)<sup>6</sup>. It is necessary to have an organization looking over the Internet itself since it gives the regulations that allow all devices to interconnect with each other.

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<sup>6</sup> [www.ietf.org/about/groups/iesg](http://www.ietf.org/about/groups/iesg)

### 3.2 RADIO TECHNOLOGIES

Although Guglielmo Marconi is usually credited as the inventor of radio due to the creation of the first commercially successful wireless communication system [23], many scientists before him have studied the subject of radio waves. The discovery of electromagnetic waves, including radio waves, by Heinrich Rudolf Hertz in the 1880s, came after theoretical development on the connection between electricity and magnetism that started in the early 1800s. Scientists tried to achieve the idea of a wireless telegraph via electric conduction and electromagnetic induction for a while before the establishment of radio-based communication.

Other important experiments were made by Nikola Tesla, who invented the *Tesla coil*, a device essential to sending and receiving radio waves, during efforts to develop a “wireless” lighting system. This Tesla coil has been used by Marconi in his experiments and is present in the patent he presented for radio transmission of data.

More than a century later, radio technology has massively evolved and is used on a daily basis. Devices have shrunk in dimension and the amount of transmission meanings have increased far from what both Tesla and Marconi could have thought of. Thus, in order to give a complete picture of radio transmitting technologies, it is important to make a distinction among the ones that are made for internal or nearby use compared to the ones which are used for longer distances.

Many users opt for wireless transmission media because it is more convenient than installing cables, even if they might sacrifice some performance. Also, using wireless technology allows transmission in locations where it is impossible to install cables. Types of wireless transmission media used in communications include:

- *infrared*: wireless transmission medium that sends signals using infrared light waves;
- *broadcast radio*: wireless transmission medium that distributes radio signals through the air over long distances such as between cities, regions, and countries and short distances such as within an office or home. Bluetooth, UWB, Wi-Fi, and WiMAX communications technologies use broadcast radio signals;
- *cellular radio*: form of broadcast radio that is used widely for mobile communications, specifically wireless modems and cell phones, which use high-frequency radio waves to transmit voice and digital data messages;
- *communications satellite*: space station that receives microwave signals from an earth-based station, amplifies (strengthens) the signals, and broadcasts the signals back over a wide area to any number of earth-based stations. Applications such as air navigation, television and radio broadcasts, weather forecasting, video conferencing, paging,

global positioning systems, and Internet connections use communications satellites.

With new transmission technologies, new network architectures and topologies that are better suited for the transmission method have emerged. Topologies that bring computation closer to the edge are also rising in popularity, since they allow for faster computation and they bring data closer to the user. These are Cloud, Edge and Fog Computing, as mentioned in Chapter 2.

LAN, MAN and WAN are not enough anymore to describe the new topologies. An important distinction is now made by other factors such as power consumption, cost of the devices and range of transmitter and receiver. The most important new category of wireless communication, that interests IoT and represents a large portion of the market at the time of writing, as described in Chapter 2, is *LPWAN*, which stands for *Low Power Wide Area Networks* and is composed by nodes that are capable of *long range communication, low power consumption* and *low cost*. Lightweight protocols also allow reducing complexity in hardware design and lower device costs. Its long range combined with a star topology reduces expensive infrastructure requirements, and the use of license-free or licensed bands reduces network costs. Growing popularity of IoT use cases in domains that rely on connectivity spanning large areas and the ability to handle a massive number of connections is driving the demand for LPWAN access technologies [24], and the project presented in this thesis falls under this category of communication. LPWAN allows connectivity in many applications, from crowded areas in smart cities to smart farming and smart environment, from security and emergencies to e-health.

Various wireless transmission methods can be used to create a LPWAN, some of the most used in IoT are Sigfox, LoRa and NarrowBand IoT (NB-IoT). In Subsection 3.2.1, follows a more complete explanation on LoRa and LoRaWAN. One crucial factor for these transmission methods is to “*support a massive number of simultaneously connected devices with low data rates*” [24].

Other important communication technologies in IoT are RFID, NFC, for contact purposes, Bluetooth, Zigbee for a personal network and IEEE 802.11, or Wi-Fi, for a local area. The latter was used in the ArduEco project, described in Sec. 2.2.1. Fig. 3.4 contains a representation of the geographic coverage in meters of the various aforementioned wireless transmission methods.

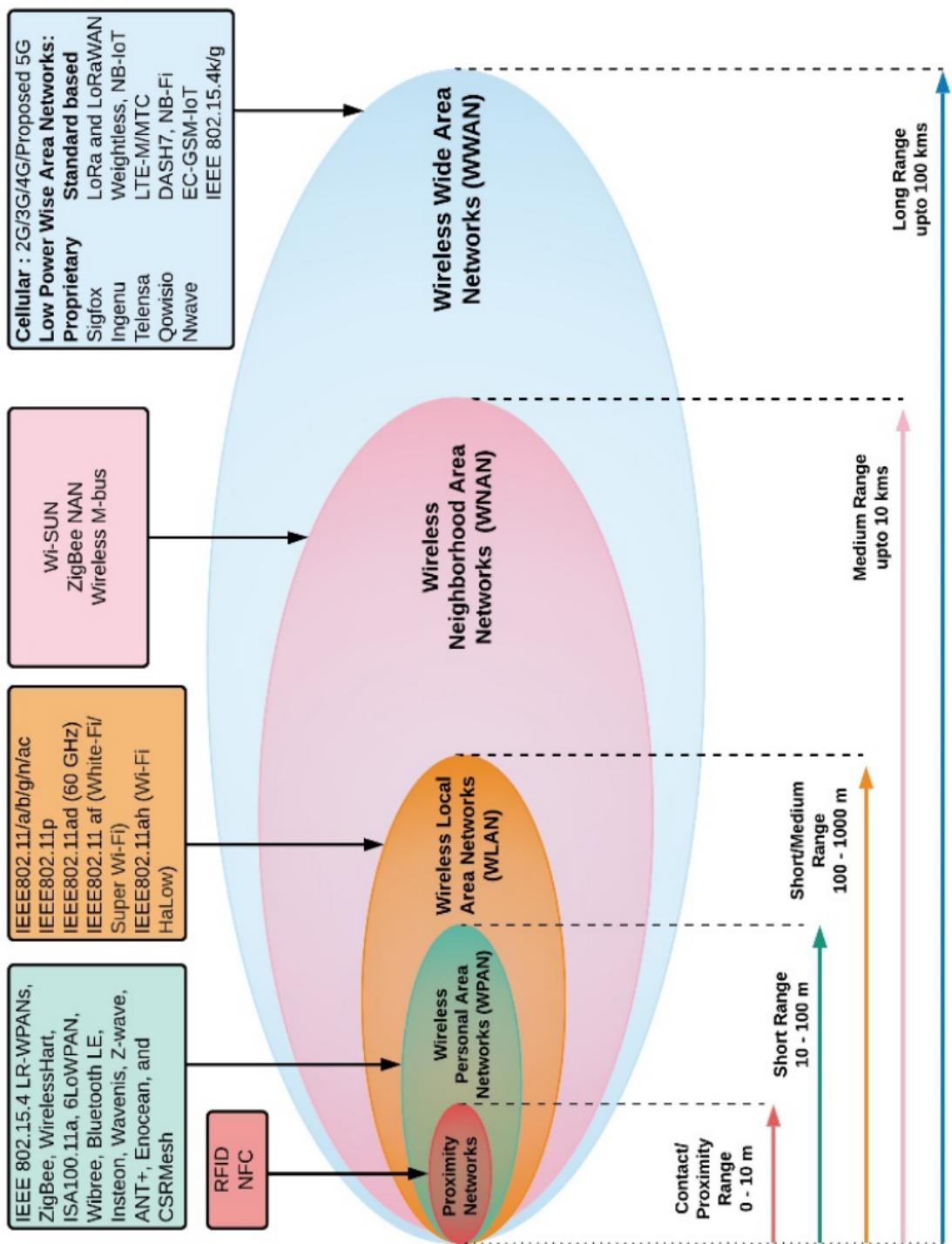


Figure 3.4: Wireless access geographic coverage [24]

### 3.2.1 LoRa AND LoRaWAN

*LoRa* (short for *long range*) is a spread spectrum modulation technique derived from the *chirp spread spectrum (CSS)* technology. LoRa devices provide a long range, low power wireless platform that is being widely adopted for the IoT networks worldwide. In conjunction with the LoRaWAN protocol, LoRa devices enable smart IoT applications in various contexts, like: energy management, natural resource reduction, pollution control, infrastructure efficiency, disaster prevention, and more.

LoRaWAN, on the other hand, is a comprehensive network architecture that details a LPWAN technology. It was designed to interconnect battery operated “things” and provides a bi-directional communication service with end-to-end security features.

The architecture is based on a star-of-stars topology in which specific devices called gateways relay messages between end-devices and a central network server. The wireless communication takes place through a single-hop link between the end-device and one or many gateways. The specification defines the device-to-infrastructure physical layer parameters (LoRa) and the specific LoRaWAN protocol to allow for full interoperability among manufacturers. It defines the technical implementation but it does not define any commercial model or type of deployment, e.g., public, shared, private, enterprise.

The LoRaWAN specification is developed and maintained by the LoRa Alliance, an open association of collaborating members. With LoRa and LoRaWAN the intention was to provide the possibility to deploy Internet of Things applications fast in areas where large distances are involved, yet low bandwidth is needed.

Low bandwidth makes it ideal for practical IoT deployments with less data or where data transmissions are not constant, for example with waste management where the information that is required is whether a waste bin is full or not. Moreover, the *end-to-end* delay (or the *RTT, Round-Trip-Time*) can be relatively high, with values below one second being acceptable.

Conversely, packet loss is a more crucial factor. In LoRaWAN, once a message has been delivered, there is no acknowledgement of receipt. However, nodes can request acknowledgements. In this case, if many gateways receive the same packet, the cloud has to choose one gateway to respond at a fixed time, usually a couple of seconds later. The problem is that when a gateway is transmitting back to the node, it stops listening to everything else. So, if an application needs a lot of acknowledgements, the gateway will very likely spend more time transmitting acknowledgements than listening, which will eventually lead to a network

saturation.

Therefore, classical applications do not require acknowledgments and that's why having a reliable network with very small packet loss rate is crucial to not lose relevant information.

Chirp spread spectrum has been used in military and space communication for decades due to the long communication distances that can be achieved and robustness to interference, but LoRa is the first low cost implementation for commercial usage.

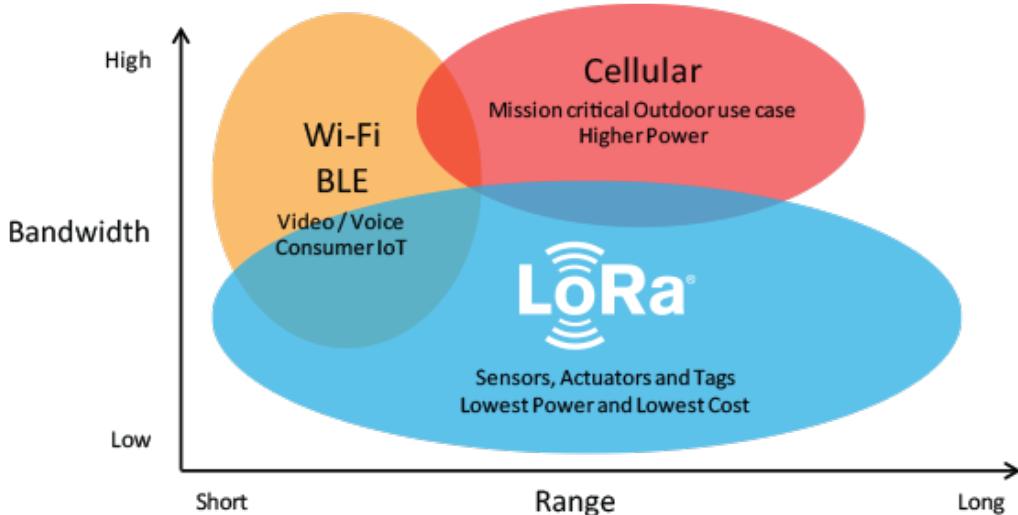


Figure 3.5: Range of LoRa transmission compared to Wi-Fi, BLE and Cellular

The advantage of LoRa is in the technology's long range capability, as can be seen in Figure 3.5 and in Figure 3.4. Range highly depends on the environment or obstructions in a given location, but LoRa and LoRaWAN have a link budget greater than any other standardized communication technology.

### 3.3 HARDWARE (MICROCONTROLLERS)

Microcontrollers (or MCUs, short for Microcontroller Unit) are compact integrated circuits designed to fit in specific environments or to perform specialized functions, which usually do not require any particular computation, memory capacity or power. This has been made possible thanks to the continuous shrinking of transistors, which makes almost all the components more compact, and the improved power sources. In junction with the previously described wireless technologies, microcontrollers are at the heart of IoT devices, described in Chapter 2, and they require long-lasting, low-cost, and sustainable batteries.

The number of IoT connected devices is expected to grow up to 75 billion worldwide by 2025 [25], and connection density is expected to be one million devices per square Km [26]. Hence, these devices will generate massive data and consume significant energy.

Given the amount of specific functions an MCU can perform, there are many boards on the market. Some are very alike, while others are very different, since they are expected to be used in other types of environments. All boards consist on a similar architecture, which contains the processing unit (CPU), along with memory and programmable input/output (or I/O) peripherals.



Figure 3.6: ATtiny 85 on the left, in the middle two boards based on the ESP32, on the right the Asus Tinker Board 2

In Figure 3.6, there are four different boards, the one farthest on the left is the *ATtiny 85*<sup>7</sup>, a low-power, 8-bit microcontroller that is made for general purpose and can be programmed for easy tasks, from simple LEDs flashing, to more “elaborate” small sensor projects. The two boards in the middle are based on the ESP32 chip, a series of low-cost, low-power system on a chip microcontrollers with integrated Wi-Fi and dual-mode Bluetooth. They both are more powerful compared to the ATtiny 85, and the right one offers an integrated LoRa antenna on board. Far on the right, there is the Asus Tinker Board 2<sup>8</sup>, a board powered by an Arm 6-core system on a chip (SoC), with a 64-bit Armv8 architecture. This board provides much more computing power compared to the previous ones and is able to run operating systems such as Linux and Windows.

One of the strong points of these boards is the price: the ATtiny is priced around 1€ when bought in bulk, the boards on the middle cost around 7€ and 15€ respectively, while the board by Asus is the most expensive of the four and starts from 70€.

It is important to note though that using a generic board in a production environment might not be ideal, since it might lack of customer support and documentation from the

<sup>7</sup> [www.microchip.com/en-us/product/ATTINY85](http://www.microchip.com/en-us/product/ATTINY85)

<sup>8</sup> <https://tinker-board.asus.com/product/tinker-board-2.html>

company. The boards described subsequently are from three of the major MCU producers, Arduino, Raspberry Pi and Pycom, which have built hardware that is well documented and suited for many different environments, from hobbyists to industrial use.

The simplified architectures and the constraints of embedded devices are reflected in the narrow choice for programming languages. It is hard to find an MCU programmed in Java since this would require the JVM running in the background. Popular languages for MCUs are, for example, C/C++, Assembly, Rust, Ada, Erlang, etc. All these have in common the fact that they are compiled and the bytecode has a small footprint. A particular microcontroller company, Arduino, has developed a version of C++ specific for their boards, but given the simplicity of this new dialect, many boards on the market can be programmed with it. Arduino is explained further in Subsection 3.3.1.

Another programming language that is quickly taking hold at the time of writing, is MicroPython. As explained in their website it is an “*efficient implementation of the Python 3 programming language that includes a small subset of the Python standard library and is optimised to run on microcontrollers and in constrained environments*”<sup>9</sup>. Python’s fast learning curve and talkative code advantages are reflected in this smaller version, available for most microcontrollers.

### 3.3.1 ARDUINO

Arduino is a company founded by Massimo Banzi *et al.* in Ivrea, Italy, in 2005, and has released the first commercially available microcontroller. They wanted a device that was simple, easy to connect to various “things” (such as relays, motors, and sensors), and easy to program, besides being inexpensive.

They selected the AVR family of 8-bit microcontroller devices from Atmel and designed a self-contained circuit board with easy-to-use connections, wrote bootloader firmware for the microcontroller, and packaged it all into a simple *Integrated Development Environment (IDE)* that uses programs called “sketches” and Arduino was the result.

The most famous version of their board is the *UNO* (*one* in English). Arduino UNO, the one on the left in Figure 3.7, is the most used and most documented board of the whole Arduino family, even if this board does not have any integrated sensors or particular ports for peripherals. At the time of writing, the current revision of the board is the Arduino UNO Rev 3<sup>10</sup>, which consists of 14 digital pins, 6 analog inputs, a power jack and USB connection.

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<sup>9</sup> [www.micropython.org](http://www.micropython.org)

<sup>10</sup> <https://store.arduino.cc/products/arduino-uno-rev3>

The Arduino family of products can be programmed in a particular programming language based on C/C++, using a special open-source IDE. Arduino was so disruptive in the market that many boards, included the ones in Figure 3.6, support the special C++ dialect.

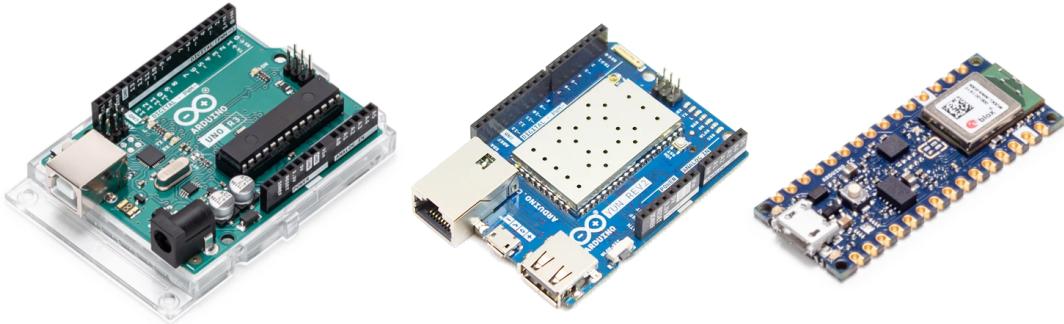


Figure 3.7: Arduino Uno Rev 3 on the left, Arduino Yún in the middle, Arduino Nano 33 BLE on the right

*Shields* are modular circuit boards that can be added to extend capabilities to different application needs. These can be attached directly on top of the board and provide sensors, interfaces, peripherals on a single board, rather than attaching to the Arduino singularly. Some of the functionalities that can be added by a shield are Ethernet, Wi-Fi, GPS, displays and cameras, motor drivers. Most of the additional shields on the market have been developed for the Arduino UNO, since it is the most common board.

The choice of making the Arduino schematics open-source and accessible to anyone has largely favored the development of newer boards, similar in capacity to the Arduino but more specialized, since producers and board makers are able to keep only the components needed or add different ones. An example can be the two middle boards in Figure 3.6, which rode the wave of Arduino's popularity. Not only the datasheets are available for all boards, but also the Arduino IDE software is open-source.

The versatility of Arduino and its easy-to-understand interface makes it a leading choice for a wide range of users around the world from hobbyists, designers, and artists to product prototypes.

Newer Arduino boards offer many integrated functionalities, for example:

- *Arduino MKR NB1500*: offers an all-in-one solution for Narrowband IoT large-coverage solutions;
- *Arduino MKR WiFi 1010*: offers integrated WiFi and Bluetooth;

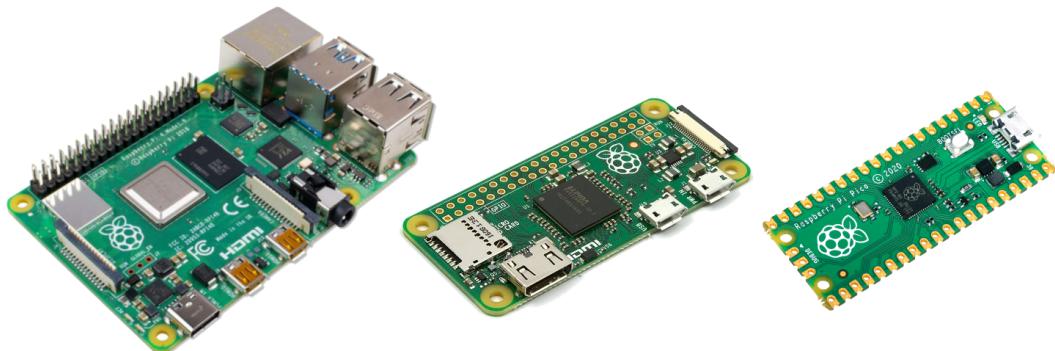
- *Arduino Nano 33 BLE Sense*: contains BLE connectivity and multiple sensors, such as 9 axis inertial, humidity, and temperature, barometric, microphone, gesture, proximity, light color and light intensity.

Particularly, this last model, the board on the right in Figure 3.7, has been considered as one of the possible choices as development board for this project. As better explained in Section 5.2, it has been discarded since it does not offer LoRa connectivity and an additional module would have been necessary to connect the board in a mesh.

### 3.3.2 RASPBERRY PI

Another important microcontroller on the market is the Raspberry Pi, developed by Eben Upton at the University of Cambridge in the United Kingdom with the aim of teaching and improving programming skills of students in developing countries.

Compared to the Arduino specifications, it offers more functionalities, since the flagship board of the company includes an ARM processor, a GPU with HDMI output connectivity, an Ethernet port, USB ports to connect mouse and keyboard, a camera interface, more RAM memory and more I/O pins. ARM processors, or Advanced RISC Machine processors, are better suited to mobile computing, since they use a simplified, less power-hungry method of processing. This allows the Raspberry Pi to run full operating systems such as some Linux distributions, included the official operating system Raspbian OS.



**Figure 3.8:** Raspberry Pi Model 3B+ on the left, Raspberry Pi Zero in the middle, Raspberry Pi Pico on the right

Since the entire Computer (the Processor, RAM, Storage, Graphics, Connectors, etc.) is sitting on a single Printed Circuit Board (PCB), the Raspberry Pi (and other similar boards) are called as Single Board Computers (SBC).

Letting their differences aside, both are very popular boards among hobbyists and even professionals. Some projects involve the use of both boards in a master-slave architecture, where the Raspberry Pi acts as a master and gathers the data from the Arduinos, which are equipped with the sensors.

Some of the main competitors of the Raspberry Pi are the Banana Pi and the Asus Tinker Board (in Figure 3.6). Since, like the Arduino, the Raspberry Pi boards schematics are open-source and available online<sup>11</sup>, board makers have been able to adapt them in their own way.

There are now different Raspberry Pi boards, or models, each a bit more specialized than the other. Some of the most important models are:

- *3B+/4*: the model *3B+* and *4* are their key products, marketed as a “*tiny, dual-display, desktop computer*”<sup>12</sup>;
- *Zero*: the smallest form factor Raspberry Pi;
- *Pico*: a low-cost microcontroller board with flexible digital interfaces.

They are represented in Figure 3.8 and can be considered as the latest evolution of what is needed to learn programming in a Unix like environment at a low cost, in fact these boards cost 35\$, 5\$ and 3\$ respectively. A complete list of the available boards can be found on their online store<sup>13</sup>.

The Raspberry Pi Pico was considered for this project, but was rejected since, as the Arduino, it would have needed additional modules for LoRa and Bluetooth Low Energy (*BLE*) connectivity, while the other models have a computational power much greater than the one needed.

### 3.3.3 PYCOM

While Raspberry Pi and Arduino share a longer history, Pycom is a younger company. It was founded in 2015 via a crowdfunding campaign on Kickstarter with the goal to create a new board for immediate development in the world of IoT, with all the possible connectivity. As the other two previously described companies, Pycom offers multiple board choices, such as the FiPy, represented in Figure 3.9, the WiPy and the LoPy. These boards are very similar to each other, since all of them offer Wi-Fi and BLE, have the same chipset, interfaces and memory.

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<sup>11</sup> [www.raspberrypi.org/documentation/computers/raspberry-pi.html](http://www.raspberrypi.org/documentation/computers/raspberry-pi.html)

<sup>12</sup> [www.raspberrypi.org/products/raspberry-pi-4-model-b](http://www.raspberrypi.org/products/raspberry-pi-4-model-b)

<sup>13</sup> [www.raspberrypi.org/products](http://www.raspberrypi.org/products)



Figure 3.9: FyPy on the left, PyTrack 2X in the middle, PySense on the right

In particular, the FiPy board, has been chosen for this project since it packs five networks in one small board. This choice is furthered in Chapter 5.

As described in the product page<sup>14</sup>, it is capable to communicate via Wi-Fi, Bluetooth, LoRa, Sigfox and dual LTE-M (CAT-M1 and NB-IoT), and gives access to global LPWAN networks. All the boards offered by Pycom at the time of writing are equipped with an Espressif ESP32 chipset, 4MB of RAM and an flash memory of 8MB.

Contrary to Arduino and Raspberry Pi, Pycom has decided to maintain the datasheets and the firmware of their boards proprietary, which means there is far less support from the community when comes to finding bugs in the software or improving the component placement on the board. Nonetheless, Pycom boards have been chosen for the affordability of the company producing them, also because of their high density of hardware on a board with a small footprint.

Additional sensors and functions can be added to Pycom boards via shields, just like the Arduino. Particularly for this project, the FiPy has been integrated with the Pytrack 2.o, which add accelerometer and GPS, and the Pysense, which add ambient light, pressure and humidity. Both expansion boards are represented in Figure 3.9.

For the programming language, Pycom boards can be programmed using Micropython via their Pymakr suite of IDE plugins, the Pymate mobile app, and Pybytes an online middleware platform and desktop application to remotely manage the boards.

About the cost of the boards, the price of the single major components used for this project are, at the time of writing:

- FiPy: 59.40€
- Pytrack 2.o: 40.65€

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<sup>14</sup> [www.pycom.io/product/fipy](http://www.pycom.io/product/fipy)

- Pysense: 29.65€

Although the costs are higher compared to those of Arduino boards, it is important to consider that these offer an all-in-one solution. The additional cost in buying an external generic shield for an Arduino board would be reflected not only on the money spent on the shield itself, but also in the time and effort of configuring and troubleshooting it in case of errors.

An overall advantage of Pycom's products is the tight ecosystem, which allows for faster and easier troubleshooting, configuration and programming. All these factors are well described in Pycom's documentation on their website<sup>15</sup>.

A more in depth description of the chosen technologies is described in Chapter 5, while a personal consideration on working with such boards is expressed in Section 7.3.1.

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<sup>15</sup> <https://docs.pycom.io>



*To succeed, planning alone is insufficient.*

*One must improvise as well.*

Isaac Asimov, Foundation series

# 4

## Related work

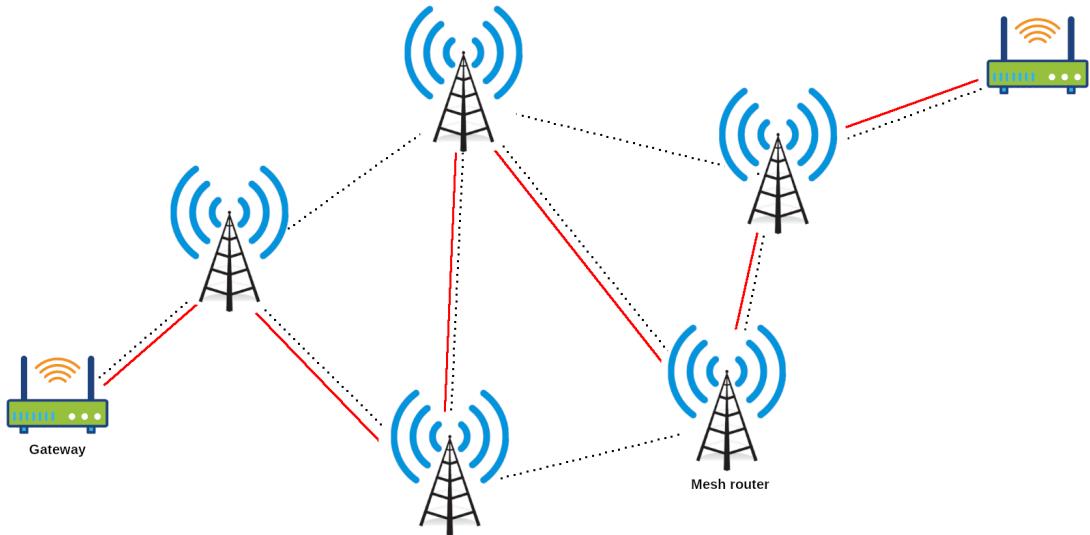
IoT is one of the most discussed topics in both academical and industrial research, as mentioned in Section 2.1.3.

By contrast, mesh networks that use wireless technologies have been researched for decades, but have yet to be put into use in large scale. The correct definition of a *wireless mesh network*, or WMN, is “*a communications network made up of radio nodes organized in a mesh topology instead of star topology*” [27]. This particular *multi-hop network*, Figure 4.1, where data “*hops*” from a node to another until it reaches its destination, can make a difference when it comes to the interconnections in the IoT world. It is important that “*future IoT deployments need to focus on sustainability since huge centralized data centers (Cloud Computing) have become a critical part of the infrastructure*” [28].

This chapter anticipates the technical one, and shows some related projects from which the project has drawn inspiration. At first, challenges and solutions are presented for these WMS, alongside their advantages and disadvantages. Below are also presented some of the projects which have been made at various levels from homemade projects, to research, to the ones already available on the market.

### 4.1 OVERVIEW OF WIRELESS MESH NETWORKS

With new technologies, such as the ones presented in Section 3.2, wireless mesh networking has been evolving and has reached an ideal point of maturity, which allows it to be useful



**Figure 4.1:** Multi-hop network

in the development of IoT devices for mass production. Also, the rising number of connected homes and industry support on open-source resources has made mesh networking truly accessible and low-cost. Such networks are starting to be regarded as more viable and real choices for commercial as well as industrial IoT applications. Besides the possibilities such networks can bring in optimizing communication among nodes, a big advantage is the possibility of bringing connectivity in a system where nodes might have limited connection.

Some of the applications for this network topology are:

- *smart cities*: extending radio signals through campus grounds, business parks, parking garages, and other outdoor facilities;
- *healthcare equipment*: monitoring and locating medical equipment, also serve as a backup for medical devices that always require to stay online;
- *smart home*: track and manage data from sensors all around the house;
- *farming*: in areas where power and connectivity are highly limited, mesh networking is ideal to track sun exposure and water levels across the crops and fields, for example.

Before choosing a mesh network topology it is important to evaluate aspects such as *installation, device management and support*.

*Energy management* represents an important factor as well, since the connected devices could be small battery operated. Thus, efficient transmission techniques and protocols that consider the amount of energy used, must be developed in order to optimally use the batteries

on such devices. That is why there is a particular network topology, *Low Power Wireless Area Network*, focused on the interconnection of these devices, described in Section 3.2.

Solutions to optimize the networks can be implemented both via hardware, via repeaters, and software. The latter is mainly implemented with AI techniques, which allow protocols to “learn” how to spatially coordinate and adapt contention patterns. Authors of [29], for example, have developed new distributed MAC scheduling algorithms by combining synchronous two-level priority RTS/CTS<sup>1</sup> handshaking with randomized time slot selection. From these “adaptively biasing time-slot selection probabilities based on past history, one can develop variations that are also provably throughput-optimal and exhibit better convergence rates”.

Classic network topologies, such as the ones in Figure 3.3, are not designed for IoT communication and might not be able to meet the requirements for such, and more, dynamic devices, which are also low-powered sensors. Another important setback of such networks is their single point of failure nature, which “makes the entire system extremely vulnerable when it comes to disasters or even difficult environment as the sensors may need to be deployed into some hardly reachable locations” [28].

An example of a multi-hop wireless mesh network is *VANET* (*Vehicular Ad-Hoc Network*), a particular case of wireless multi-hop network, which has the constraint of fast topology changes due to the high node mobility, Figure 4.3.

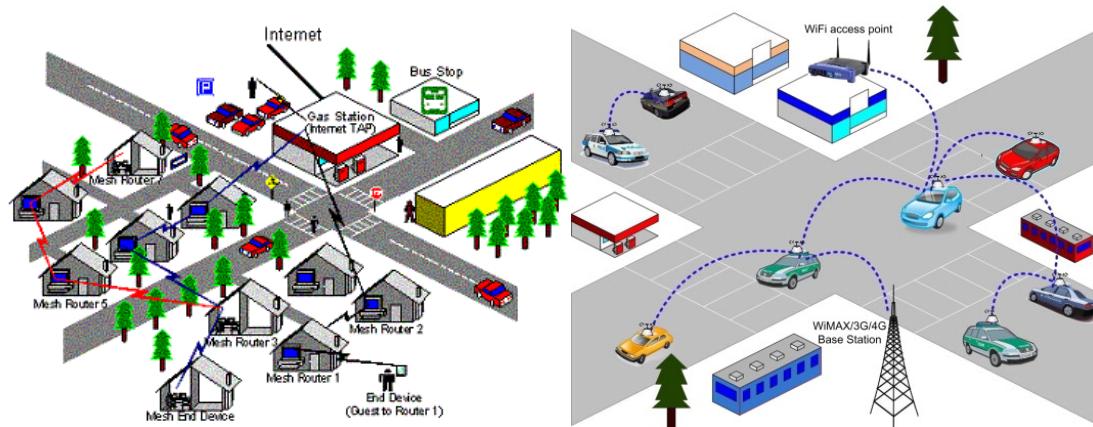


Figure 4.2: Self organizing wireless mesh networks [30]

Figure 4.3: An example of a VANET [31]

This is a very important type of network, giving the increasing number of vehicles equipped with computing technologies and wireless communication devices. Authors of [31] explain

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<sup>1</sup> Request To Send / Clear To Send

how such increase “*intervehicle communication is becoming a promising field of research, standardization, and development*”. A tangible example can be seen in the rising of electric vehicles and their constant rise in sells on the market, which brought more attention on the aforementioned factors.

Microsoft has also tried to apply mesh networking to normal Internet household use [30], however, given the improvements in telecommunication infrastructures and the advancement of fiber optics and Internet via cable, the project has been abandoned. Their proposed topology is represented in Figure 4.2. This shows how each network topology is better suited for particular scenarios.

Compared to the example of Microsoft’s project, a VANET is more suited for a wms since the data transferred among cars is less than the one transferred among houses.

A more personal approach consideration about this networking topology is made in Section 7.3.2.

The components of a mesh network usually are:

- *nodes*: devices that communicate data with each other;
- *gateway*: allows devices to transfer data in the network, also provides a backhaul to the Internet for the local mesh network;
- *repeater*: repeaters that maintain signal and forward messages between endpoints
- *endpoint*: mesh-only devices that don’t route messages for other devices, but send them to other nodes.

#### 4.1.0.1 ADVANTAGES OF WMS

Mesh Network for IoT devices offers enormous benefits that make it sought-after in enterprises and significant in an IoT app development company.

Mesh networks can offer substantial benefits in the development of IoT applications:

- *self-healing*: they automatically adjust allowing data to take the best path to transfer even if a few nodes lose connection;
- *self-configuration*: new nodes calibrate automatically and connect to the network without any previous setup;
- *reliability*: more nodes create multiple routes in which data packages can travel, which makes the network reliable and error-resistant in case of a node failing;
- *cost*: when considering the nodes that typically compose a mesh network, they are inexpensive, thus adding more nodes and sensors to expand the network should not be a substantial cost.

These are just some of the advantages that using a mesh network brings, but it is also important to consider the scenario where the network is deployed. Not always a mesh network is necessary, but when it is well suited, it reduces expenses in many other ways like better management, optimization of resources usage, and more.

#### 4.1.0.2 DISADVANTAGES OF WMS

Despite the numerous advantages previously described, there are also some drawbacks when using mesh networks in IoT. That is how come is so important to know when such network topologies can fit in the project.

These disadvantages are:

- *low capacity*: such networks are well suited for sending small data packages and they do not perform well while transferring larger file sized data;
- *latency*: sending data from a node to another requires longer time than direct transfer, it might not be an issue when the system requires few packages, but, it might take too long for some systems;
- *maintenance*: finding bugs in a mesh network might be time-consuming since there could be a lot of factors that could create errors. Also, even if there is not a single-point-of-failure that could take down the whole network, it might not be easy to untangle logs from the nodes.

The amount of data that a mesh network is capable to handle also depends on the transmission technology which is used, as explained in Section 3.2. For large amount of data Wi-Fi represents a better option than LoRa or BLE, for example.

## 4.2 SCALABILITY OF WMS

Scalability of mesh networks is treated in a separate section, since it cannot be considered as an advantage, nor as a disadvantage.

Alongside topological stability, these are two of the most challenging issues in current wireless mesh networks deployments, as explained in [32].

In the case of wireless mesh networks, scalability has to be considered “*both in terms of increased geographical area and coverage and number of users*” [33]. Each solution for scalability brings advantages and disadvantages, since it may impact one or the other terms from above.

There are numerous various scaling relationships in this network topology: as number of nodes increases, the load increases and load increases as the communication distance increases and the total one-hop capacity increases as the coverage of the network increase.

Some of the factors that affect the scalability of a wireless mesh network in particular are:

- *co-channel interference*
- *routing protocol overhead*
- *half-duplex nature of radio antennas*
- *difficulties in handling multiple frequency radio systems*
- *deployment architecture*
- *medium access control*
- *density of nodes and degree of nodes*
- *communication pattern (locality and number of hops)*.

A formula that determines the capacity of an arbitrary mesh network is  $\theta(1/\sqrt{n})$ , where  $n$  is the number of nodes in the network. In other words, with the increase of nodes in the network, the information carrying capacity becomes negligibly small. Such formula is described in depth in a seminal paper by Gupta and Kumar [34].

Although this is a theoretical description of the effects of scaling on the amount of data that can be exchanged in a network, it is very different to what can happen in practice. Such comparison is described in the paper “Scalability of Mobile Ad Hoc Networks: Theory vs practice” [35], where the author inspects how different relationships between the previously mentioned factors affect scalability in real life mesh networks.

#### 4.3 ROUTING ALGORITHMS FOR WIRELESS MESH NETWORKS

// To be completed

#### 4.4 PROJECTS

This section describes three categories of projects: open-source, research and commercial. These categories should represent a sample of what is the current state of the art for wireless mesh networking, particularly the ones communicating via LoRa.

#### 4.4.I OPEN SOURCE PROJECTS

##### 4.4.I.I LoRa MESH CHAT

This project consist in an add-on for mobile phones that enable text messaging in a group when outside cellular and Internet coverage.



Figure 4.4: LoRa Mesh Chat ESP32 device

As explained on the project's webpage<sup>2</sup>, an ESP32 microcontroller with a LoRa antenna and an OLED display is programmed to connect to the phone either via and OTG cable or BLE. By using an application on the phone, the user is capable of sending text messages in a group.

##### 4.4.I.2 MESHTASTIC

Meshtastic is an open-source<sup>3</sup> LoRa signal extending mesh communicator that uses LoRa. This project allows the use of inexpensive (around 30\$) GPS radios as an extensible, long battery life mesh GPS communicators for who practices sports like hiking, skiing, paragliding. Essentially for who needs connectivity in places without Internet access.

This project consists of private meshes created by its users, and allow the share of GPS location and text messages. The radios automatically create a mesh to forward packets as needed, so everyone in the group can receive messages from even the furthest member. Optionally devices can connect with phones, but no mobile is required.

#### 4.4.2 RESEARCH PROJECTS

// To be completed

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<sup>2</sup> [www.hackster.io/scottpowell69/lora-mesh-chat-5267d9](http://www.hackster.io/scottpowell69/lora-mesh-chat-5267d9)

<sup>3</sup> [www.github.com/meshtastic](http://www.github.com/meshtastic)

#### 4.4.2.1 LoRaCTP

### 4.4.3 COMMERCIAL APPLICATIONS

#### 4.4.3.1 OFF GRID MESH DEVICES: SONNET AND GOTENNA

Both of the following devices use LoRa to create a mesh network and have been designed for emergency off-grid communication, where cellular towers or land-line phones are not physically reachable.

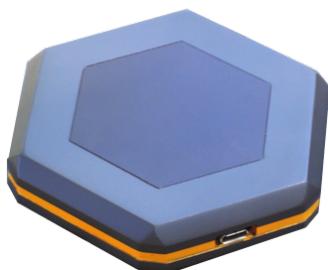


Figure 4.5: Sonnet

Sonnet<sup>4</sup>, in Figure 4.5, connects to the smartphone via Wi-Fi allowing the user to send texts, voice messages, images, data, files and share GPS locations to any other Sonnet users up to several kilometers away, thanks to LoRa. This completely removes smartphones' dependency on cellular grid and other network infrastructure, and allows Sonnet to be used even when there is no cellular connectivity or Internet access.

According to the product's Kickstarter page<sup>5</sup> “with Sonnet, data can be relayed up to 16 times to achieve a maximum range of 80 km (50 miles)”.



Figure 4.6: goTenna Mesh



Figure 4.7: goTenna Pro

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<sup>4</sup> [www.sonnettech.com](http://www.sonnettech.com)

<sup>5</sup> [www.kickstarter.com/profile/sonnet/created](http://www.kickstarter.com/profile/sonnet/created)

The goTenna<sup>6</sup>, in Figure 4.6, offers similar functions as the Sonnet, allowing to send text and GPS locations without the use of a cellphone with Internet connectivity. Mesh-networking allows to relay messages from a node to another until they reach destination.

A compact and ruggedized kit, the goTenna Pro X, in Figure 4.7, allows control for larger teams that operate in complex environments where it is not possible to be offline.

As Sonnet, goTenna has raised the funds necessary to enter the market as a crowdfunded project on Kickstarter<sup>7</sup>.

Compared to the projects in Section 4.4.1.1 and Section 4.4.1.2, Sonnet and goTenna offer a more stable network, thanks to the fact that they can be considered finished products which have been thoroughly tested and produced on a bigger scale.

#### 4.4.3.2 WI-FI MESH

*Wi-Fi mesh*, or *whole home Wi-Fi* systems, consists of a main router that connects directly to the main modem, and a series of satellite modules, or nodes, placed around the house for full Wi-Fi coverage. Each node serves as a hop point for other nodes in the system and are all part of a single wireless network and share the same SSID and password, unlike traditional Wi-Fi routers. Weakened signal or Wi-Fi dead spots of the latter are the result of physical obstructions (floor, doors, and walls).

A modular mesh whole home Wi-Fi system is flexible and scalable, giving a customizable method of expanding Wi-Fi coverage without the need to add range extenders, which are certainly effective when it comes to increasing the router range, but they do so at the expense of Wi-Fi performance, which gets cut in half.

Wi-Fi 6 is an evolution of 802.11ac technology, which promises increased throughput speeds (up to 9.6Gbps), less network congestion, greater client capacity, and better range performance thanks to the improved wireless technologies, including *Orthogonal Frequency-Division Multiple Access (OFDMA)*. The latter improves overall throughput by breaking Wi-Fi channels into sub-channels, allowing up to 30 users to share a channel at the same time.

Many important manufacturers for network hardware, like Netgear and Cisco, have already implemented such technology and functions in their products available not only for industrial purposes, but also for average users.

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<sup>6</sup> [www.gotenna.com](http://www.gotenna.com)

<sup>7</sup> [www.kickstarter.com/profile/gotenna/created](http://www.kickstarter.com/profile/gotenna/created)

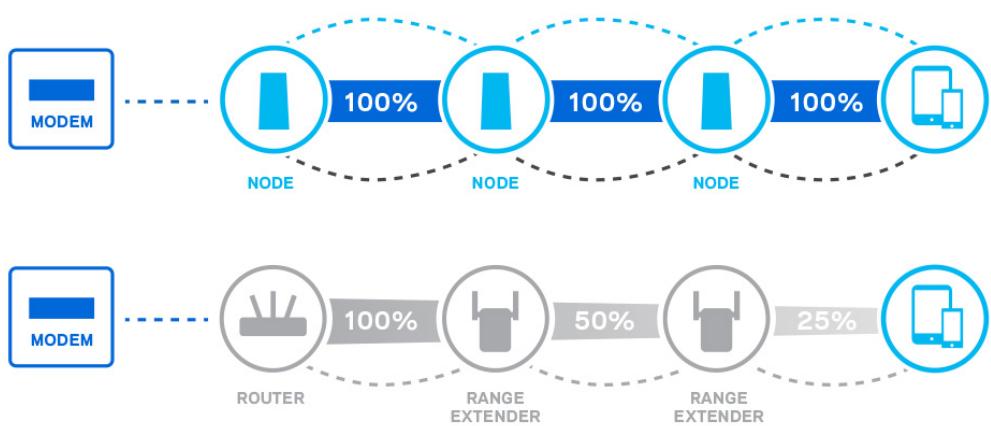


Figure 4.8: Wi-Fi 6 mesh nodes compared to Wi-Fi range extenders performance

*Keep  
It  
Simple  
Stupid*

Kelly Johnson

# 5

## Proposed solution

### // To be completed with one or two phrases

This chapter contains the technical description of the mesh network developed with the FiPy and communicates using LoRa. Such mesh network will be referred as “*Open LoRa Mesh*”. Especially such networks is able to accommodate small messages, such as the ones sent by MegaSense, described in Section 2.2.2.

Even though it would have been possible to use a simulator, such as “*The one1, for demonstrating the usefulness of such network, the final project has been realized with Pycom hardware, discussed in Section 5.2.*

The code created for this project is open sourced and available on GitHub<sup>2</sup>. Such code is better explained later in Section 5.3 and its subsections.

### 5.1 NETWORK ARCHITECTURE

Before talking about the architecture of the mesh, it is important to understand the one of the MegaSense. As can be seen in Figure 5.1, since each MegaSense device is made to be carried by a person, devices connect each one to the user’s phone. The latter then communicates with the MegaSense and, via the application developed by the Computer Science Department at the University of Helsinki, sends the air-quality readings and the GPS location,

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<sup>1</sup> [akeranen.github.io/the-one](https://akeranen.github.io/the-one)

<sup>2</sup> [www.github.com/cipz/OpenLoRaMesh](https://www.github.com/cipz/OpenLoRaMesh)

which has been read by the application from the phone itself, to the servers in the cloud.

Communication between MegaSense and phone is done via BLE, and exchanges data such as sensor readings (like NO<sub>2</sub>, O<sub>3</sub>, CO, battery percentage, *etc.*) and calibration measurements, in JSON format. Thus each device has to be linked to a person's phone, which might enhance the portability of the device, but not its possibility to read data independently if placed in a specific location.

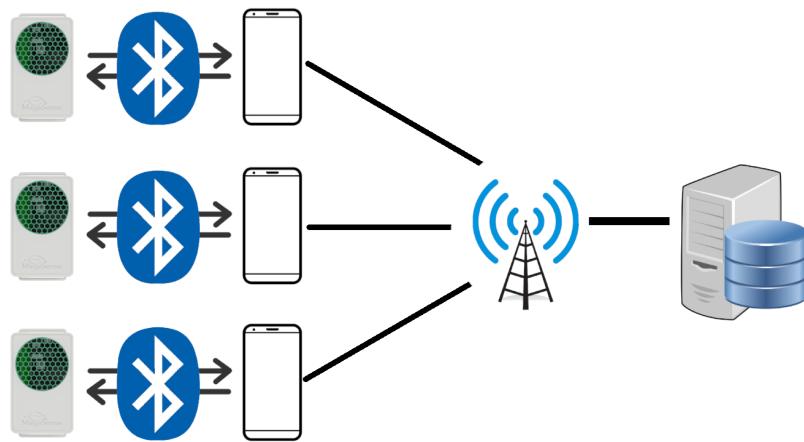


Figure 5.1: MegaSense architecture

One of the goals Open LoRa Mesh tries to achieve, is to give independence to these devices, so that they can communicate one another and allow information to be passed along between nodes without the aid of a user's phone.

This is why the architecture would evolve from the one in Figure 5.1 to Figure 5.2: the phone is replaced by a FiPy, which also connects to the MegaSense via BLE, and sends the data acquired from the sensors in the network. Nodes communicate with each other via LoRa, detailed in Section 3.2.1, and exchange data using mainly *LoRaCTP*, described in Section 4.4.2.1.

Each FiPy board represents a node on the network, which in this case is a "*Flat Wireless Mesh*", where each node acts both as data provider and as data forwarder. Although simple, such network architecture is well known from the previously mentioned, Section 4.2, Gupta and Kumar [34]. Besides not scaling well and having the potential to put very high resource constraints, "*addressing schemes and service discovery would prove to be a major bottleneck against scalability*" [33].

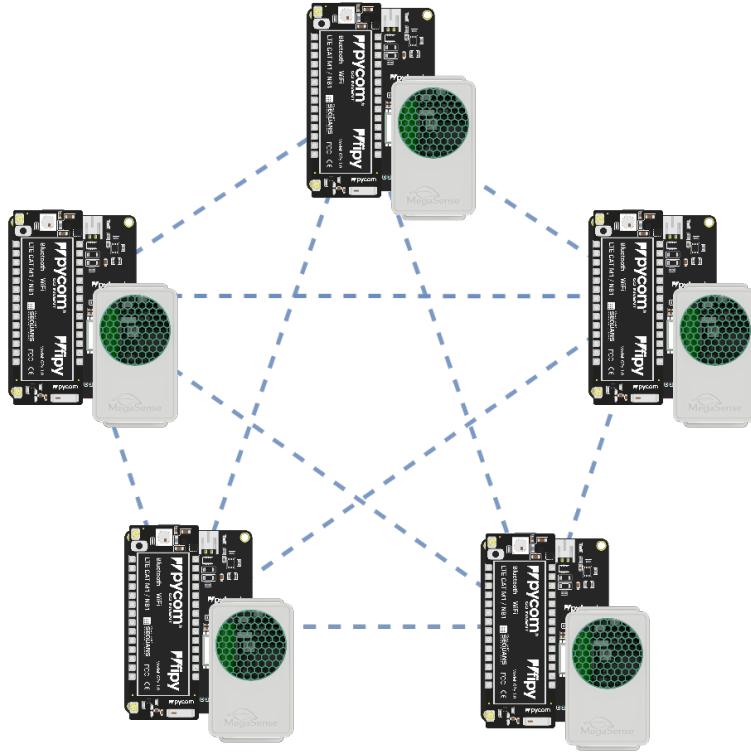


Figure 5.2: Open LoRa Mesh architecture

## 5.2 OPEN LoRa MESH HARDWARE

For the development of Open LoRa Mesh, the chosen hardware to replace the phone in the original MegaSense architecture is composed by Pycom's FiPy microcontrollers, along with its shields, like the PyTrack and the PySense. A prototype of the MegaSense device was also given from the developers of the project in order to test the connectivity with the Pycom boards and test its capacity to send and receive data from other nodes in the network. All devices can be seen together in Figure 5.3.

Although the expansion board is important, the FiPy is the one that contains all the chips that allow connectivity, as said in Section 3.3.3. After an initial evaluation on the requirements necessary in creating a network for exchanging messages among air quality sensing devices, Pycom's boards have come first considering the numerous possibilities it allows for prototyping.

The exact hardware with which this project has been completed is: four FiPy boards, one PyTrack 2X, one PyTrack, two PySense shields and one MegaSense prototype, Figure 2.9. Py-

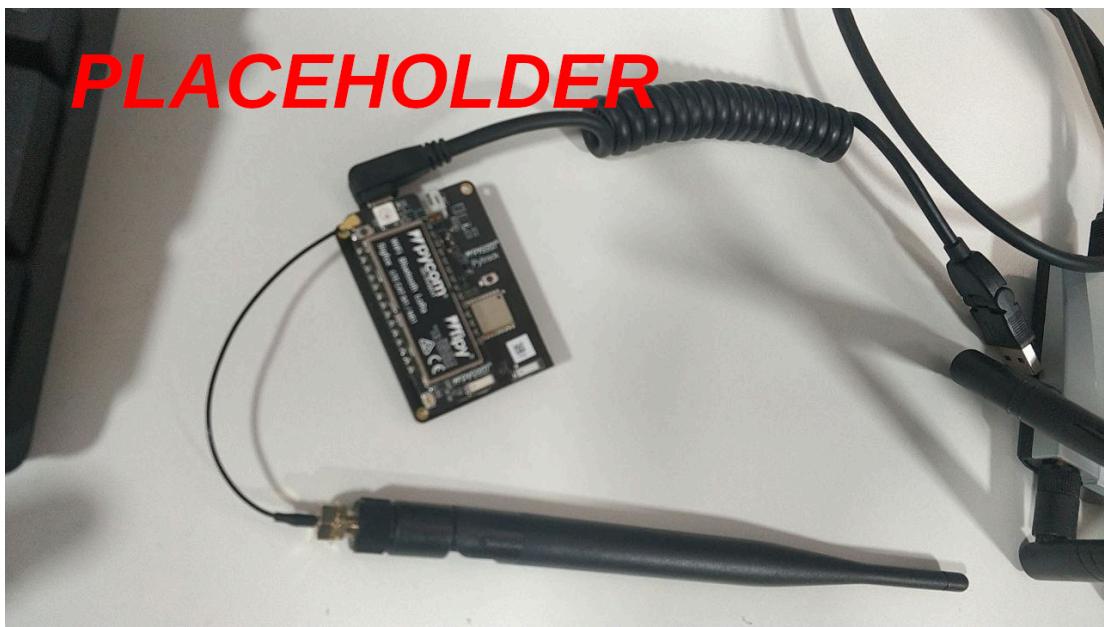


Figure 5.3: FiPy with PyTrack, LoRa antenna, GPS antenna and MegaSense prototype

com boards do not have a USB connection directly on them, so they can be programmed either using a shield or via an UART (Universal Asynchronous Receiver-Transmitter) to USB.

Alternative microcontrollers, such as the Raspberry Pi Pico, Raspberry Pi 4, Arduino Nano 33 BLE Sense, and ESP32 boards have been discarded given either their excessive power or their need for multiple expansion shields.

### 5.3 OPEN LoRa MESH SOFTWARE

While the Arduino's C++ dialect divides the code in two main functions, the `setup()` and `loop()`, as mentioned in Chapter 3, the Pycom boards use two files to separate an initial bootstrap of the board and a main section of the code. These two special files are called `boot.py` and `main.py` respectively.

The following section explains the addressing scheme in LoRa, which is important to understand. Afterwards, the algorithms made for this project are delineated and it is shown how they have been implemented.

The FiPy boards have been programmed using Micropython, and the firmware flashed on the boards, at the time of writing, is v1.16.5.

### 5.3.1 LoRa ADDRESSING SCHEME

// To be completed

### 5.3.2 ALGORITHMS

This section shows in depth how the software works: for each significant building block of the code there are flowcharts and finite-state automata (or FSA). The flowcharts describe the algorithms and show what functions are called, while finite-state machines show what states the devices can be in and how they arrive in such states. For a graphical reason, each state of the following automata is abbreviated, and the full state is described in a table underneath it.

Such vision should allow to understand the system from a broader point of view to a more detailed one, where every function is analyzed.

#### 5.3.2.1 OVERVIEW OF THE WHOLE SYSTEM

As previously said, the FiPy is divided in two files, `boot.py` and `main.py`.

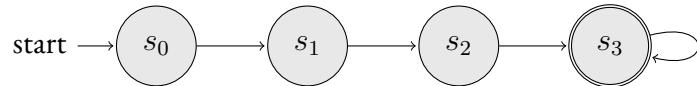
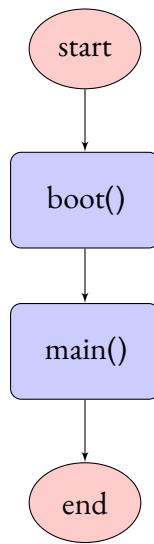


Figure 5.4: FSA for the overview of the whole system

State abbreviation	Full state name	State description
$s_0$		

Table 5.1: Main algorithm fsm description



**Figure 5.5:** test

5.3.2.2 BOOT

5.3.2.3 MAIN

5.3.2.4 MESH INITIATION

5.3.2.5 BROADCAST MESH INFORMATION

5.3.2.6 LOOP

5.3.2.7 LISTEN

5.3.2.8 MESSAGE FORWARDING

5.3.2.9 MEGASENSE COMMUNICATION

5.3.2.10 MESSAGE TRANSMISSION

5.3.3 SUPPORTED MESSAGES

5.4 OTHER FILES

5.5 MICROCONTROLLER SLEEP CYCLE

Most IoT devices that compose LPWANs have three main modes, or profiles: *sense*, *connect* and *sleep*. Sense and connect refer respectively to gathering data from the sensors and sending

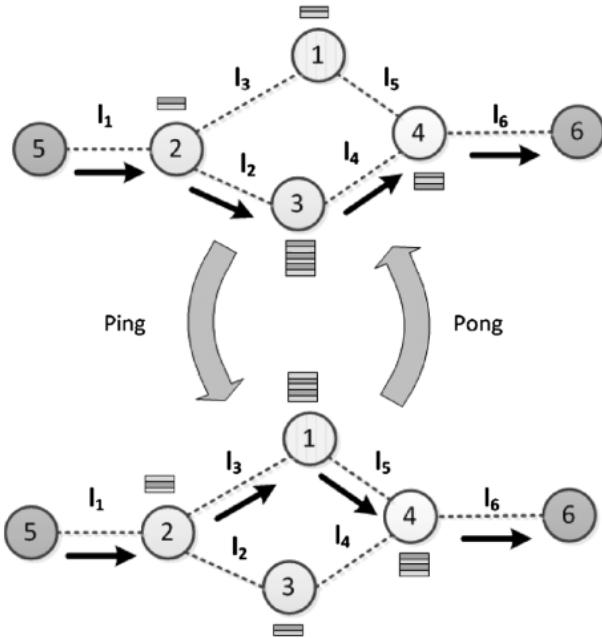


Figure 2. Airtime ‘ping-pong’ effect illustration.

Figure 5.6: “Open LoRa Mesh” architecture

it into the network, while sleep refers to a sleep-mode energy consumption where most processes in the device are halted, and some circuits may be powered down. It can be considered a design trade-off between functionality, size, and battery lifetime.

This energy consumption profile is important because it helps maximizing the battery life, which currently is one of the most considerable bottlenecks in IoT low-power devices, as explained in Section 2.1.3.

However, in the implementation of the Open LoRa Mesh, nodes do not have such functionality implemented, since might it be the cause for network disruptions.

For example, if a new node might want to join a network, but the nearest physical node is in sleep mode, there would be no possibility for the new node to request data about the network, thus wasting time and resources while waiting for the other node to come back online.

Such mode could be implemented but would require a careful analysis on the evolution of the network in time, also would require a network made entirely, or mostly of static nodes. This thought is reviewed again in Section 7.2.2.

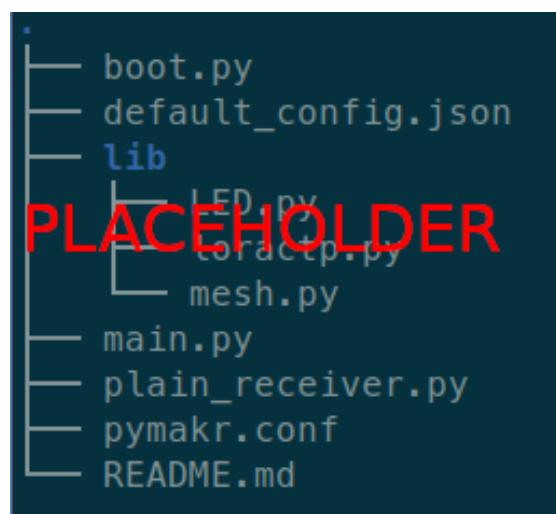


Figure 5.7: List of files that compose the Open LoRa Mesh project

## 5.6 USE CASES

### 5.6.1 MOBILE NETWORK

### 5.6.2 FIXED NETWORK

### 5.6.3 HYBRID NETWORK

*There's no reason to have a plan B  
because it distracts from plan A.*

Will Smith

# 6

## Results and experimentation

### 6.1 EXPERIMENTS

### 6.2 RESULTS



*Be fearful when others are greedy,  
and greedy when others are fearful.*

Warren Buffet

# 7

## Conclusions

Mesh networks are “*decentralized, easy to deploy, and characterized by dynamic self-organization, self-configuration, and self-healing properties*” [32]. Such properties enable fast deployment, low installation cost, and reliable communication.

This thesis describes an implementation of a mesh network solution for IoT devices, particularly for an air quality sensing device: MegaSense, described in Section 2.2.2.

Besides summarizing the previously discussed arguments, this chapter contains some personal considerations by the author.

### 7.1 CONTRIBUTIONS

// To be completed

### 7.2 FUTURE WORK

// To be completed

#### 7.2.1 HARDWARE IMPROVEMENTS

// To be completed

## 7.2.2 SOFTWARE IMPROVEMENTS

### // To be completed

Another factor that would improve the performance of each node on the network is the implementation of a sleep mode, Section 5.5. This would allow each node to have a longer battery life and only activate when necessary. Although adding such mode requires more data and in depth testing, it is not an impossible upgrade.

## 7.3 PERSONAL CONSIDERATIONS

This final section of the thesis contains some personal considerations from the author regarding the work with Pycom boards and mesh networks.

### 7.3.1 ABOUT THE PYCOM BOARDS

Compared to working with other boards, such as the Arduino, Pycom boards are more complete, since they offer better specifications, for both computing power and memory, connectivity and support. For prototyping, Arduino boards offer very good opportunities and have been on the market for a longer time, allowing consumers to get acquainted and know the brand. Sometimes, working with Arduino feels like “*everything that can be invented has been invented*”, as said by Charles H. Duell, since there is so many people who have made all kind of projects and are sharing them online.

The FiPy, on the other hand, offers more connectivity and more power, at the expense of the open source advantages of most of its competitors. As explained in Section 3.3.3, besides keeping the blueprints of their boards private, Pycom also has a proprietary firmware on their boards, which sometimes gets in the way of developers that require to fully use the hardware capabilities. This also reflects on the software, where some functionalities that are functioning on other boards are not implemented in Pycom’s firmware for their devices. Nonetheless, the official forum<sup>1</sup> available for Pycom’s boards is full of useful comments and the users are fairly active.

An example where the FiPy would offer a great improvement over an Arduino board would be this smart home application<sup>2</sup>. Such project contains an Arduino Mega board with various sensors and relays, all connected via a specifically build website, with the use of a

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<sup>1</sup> <https://forum.pycom.io/>

<sup>2</sup> [www.instructables.com/Smart-Home-With-Arduino-Ethernet-Shield-and-Teledu](http://www.instructables.com/Smart-Home-With-Arduino-Ethernet-Shield-and-Teledu)

third-party API handler for the Arduino. The Arduino connects to the Internet via an Ethernet shield, thus sends data by cable. A FiPy would allow a smaller footprint and no need for a shield, besides avoiding the use of a third-party API handler.

In my personal opinion, these boards are quite powerful and resilient for research purposes. They can be used as multiple testbenches for different projects, but might result excessive if their powerful specifications are not necessary.

### 7.3.2 ABOUT MESH NETWORKING

As said in Chapter 3, each network topology is better suited for particular scenarios. It is not possible to have a “*one size fits all*” network for all possible applications that need to exchange data. As for all questions in computer science, the answer to the question where a mesh network is useful is “*it depends*”.

Mesh networking is a very interesting network topology which, compared to all the others in Figure 3.3, has still a lot of research possibilities. In conjunction with AI and machine learning, it is possible to achieve an optimal level of connectivity in such networks. The bottlenecks would then be represented by the computing power in the nodes, and in the algorithm used in case one of the nodes fail, or new nodes are added into the network.

Scalability of such networks, as spoken about in Section 4.2, is a very interesting research scenario since it is one of the major deciding elements for any new networking technology to be accepted. Factors such as multi-hopping, protocol overhead, and wireless interference limit the scalability of such networks. Mesh networks will be more and more common, but I believe they will be used in conjunctions with other topologies: for example a local mesh network that allows communication between sensors in a house and a gateway node interacts with other networks in a different topology.

Security is another important factor when considering in mesh networking. Since each node receives and analyzes packages, there is no totally effective solution for a secure network. Adding security features such as encryption/decryption algorithms and other checks, would result in a big overhead on small IoT devices. Also, like other radio technologies, anyone can read messages, encrypted or not, “*flying*” through the air.



# Acknowledgments

At the beginning of this thesis, instead of having a dedication, I choose to have the meaning of a word which I believe describes me the best: *cosmopolitan*. This word means a lot to me because I love traveling and meeting new people, getting involved in international projects and exchanges. That is how I got to meet some of the most interesting people I know, and why thanks to them, I want to expand my horizon even more and seek out new experiences.

Networking for me does not only mean connecting computers, but getting to know new people, either in a hot Finnish sauna in Helsinki, at a pub in Dublin, or at a convention center in Milan.

I would like to thank my supervisors for their continued support and encouragement: Prof. Claudio Palazzi and Prof. Pietro Manzoni. Also thanks to Samu Varjonen, Ashwin Rao, Andrew Rebeiro Hargrave and Naser Hossein Motlagh, who are Professors and Researchers at the University of Helsinki. They have provided me with the MegaSense device and part of the hardware to develop this project.

I offer my sincere appreciation for the learning opportunities provided by all of them, both as teachers, in Padova and Helsinki, and as supervisors.



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when it is beneficial to enable the repeater functionality. In this paper, we propose an initiation protocol that ensures that repeater functionality is enabled only when appropriate. Also, our system can run directly on top of today's 802.11 infrastructure networks. We evaluate our system using simulation and testbed implementation, and find that SoftRepeater can improve cumulative throughput by up to 200[Online]. Available: <https://www.microsoft.com/en-us/research/publication/opportunistic-use-of-client-repeaters-to-improve-performance-of-wlans-3/>

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