

## 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

*SUPERVISOR*

**CLAUDIO ENRICO PALAZZI**

*CANDIDATE*

**VOINEA STEFAN CIPRIAN**

*STUDENT ID*

**STUDENTID**

**ACADEMIC YEAR 2018 - 2019**



Olivia H. Plant: DevOps under control, Development of a framework for achieving internal control and effectively managing risks in a DevOps environment Master Thesis, University of Twente, March 2019

**Author**

Voinea Stefan Ciprian  
Study programme:  
E-mail:

MSc Business Information Technology  
[o.h.plant@alumnus.utwente.nl](mailto:o.h.plant@alumnus.utwente.nl)

**Graduation committee**

Claudio Enrico Palazzi  
Study programme:  
E-mail:

MSc Business Information Technology  
[o.h.plant@alumnus.utwente.nl](mailto:o.h.plant@alumnus.utwente.nl)



THIS IS A VERY  
MEANINGFUL DEDICATION



# Abstract

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, plac-erat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.



# Sommario

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.



# Preface

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, plac-erat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.



# Contents

ABSTRACT	v
SOMMARIO	vii
PREFACE	ix
LIST OF FIGURES	xiii
LIST OF TABLES	xv
1 INTRODUCTION	I
1.1 Contributions . . . . .	2
1.2 Document outline . . . . .	2
2 BACKGROUND	3
2.1 Internet of Things . . . . .	3
2.1.1 Universal Product Code and Barcode . . . . .	4
2.1.2 CMU's coke machine and modern vending machines . . . . .	5
2.1.3 Trends, forecasts and research directions . . . . .	7
2.2 Air quality . . . . .	II
2.3 IoT for sensing of air quality . . . . .	12
2.4 MegaSense . . . . .	13
2.4.1 Hope . . . . .	13
3 TECHNOLOGIES	15
3.1 Fundamentals of network communication . . . . .	15
3.2 Radio technologies . . . . .	21
3.2.1 LoRa . . . . .	23
3.2.2 LoRaWAN . . . . .	23
3.2.3 Bluetooth . . . . .	23
3.2.4 WiFi . . . . .	23
3.2.5 5G and LTE . . . . .	23
3.3 LoRa and LoRaWAN . . . . .	24
3.4 Hardware (Microcontrollers) . . . . .	25
3.4.1 Arduino . . . . .	26
3.4.2 Raspberry Pi . . . . .	28

3.4.3	Pycom . . . . .	29
<b>4</b>	<b>RELATED WORK</b>	<b>31</b>
4.1	Solutions to detect air pollution . . . . .	31
4.2	Megasense . . . . .	31
<b>5</b>	<b>PROPOSED SOLUTION</b>	<b>33</b>
5.1	Idea . . . . .	33
5.2	Architecture . . . . .	33
5.3	Hardware . . . . .	33
5.4	Software . . . . .	33
5.5	Use cases . . . . .	33
<b>6</b>	<b>RESULTS AND EXPERIMENTATION</b>	<b>35</b>
6.1	Experiments . . . . .	35
6.2	Results . . . . .	35
<b>7</b>	<b>CONCLUSIONS</b>	<b>37</b>
7.1	Future work . . . . .	37
7.2	Improvements to the hardware . . . . .	37
7.3	Personal considerations . . . . .	37
<b>A</b>	<b>USER MANUAL</b>	<b>39</b>
<b>B</b>	<b>TECHINICAL MANUAL</b>	<b>41</b>
<b>ACKNOWLEDGMENTS</b>		<b>42</b>
<b>REFERENCES</b>		<b>45</b>
<b>GLOSSARY</b>		<b>47</b>

# List of figures

2.1	Diagrammatic view of the Universal Product Code . . . . .	4
2.2	CMU’s “coke machine” . . . . .	5
2.3	IoT research areas according to authors of [1] . . . . .	7
2.4	Edge, Fog and Cloud Computing . . . . .	8
3.1	Subsea Internet backbone cables between US and Europe. . . . .	17
3.2	The ISO/OSI reference model against the TCP/IP stack . . . . .	18
3.3	Common network topologies . . . . .	19
3.4	. . . . .	22
3.5	. . . . .	23
3.6	Attiny 85 on the left, in the middle two boards based on the ESP32, on the right the Asus Tinkerboard 2 . . . . .	25
3.7	Arduino UNO Rev 3 on the left, Arduino Yun in the middle, Arduino Nano 33 BLE on the right . . . . .	27
3.8	Raspberry Pi Model 3B+ on the left, Raspberry Pi Zero in the middle, Raspberry Pi Pico on the right . . . . .	29
3.9	fypy on the left, PyTrack 2X in the middle, pysense on the right . . . . .	30
4.1	Circuit of the ArduECO prototype, as contained in [2] . . . . .	32
4.2	ArduECO prototype . . . . .	32



## List of tables



# 1

## Introduction

Starting from the Middle Ages, through the Industrial Revolutions and arriving to the Modern Era, water and air pollution have haunted people all around the world. From early on, in Europe, unsanitary urban conditions favoured the outbreak of population-decimating epidemics of disease, from plague to cholera and typhoid fever. Later, with the advent of the steam engine in between of the 18th and 19th century, pollutants from factories started to spread in the air, causing problems such as smog and, in some cases, even acid rain.

Using the data gathered until the second half of the 20th 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.

This prediction came true.

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*"<sup>[3]</sup>. This leaves one to think about the state of this research area up to date.

From the point of view of Computer Science, technology has also evolved exponentially, confirming the validity of Moore's law and increasing the accuracy of sensors and other analog peripherals used to gather data from the environment. In combination with the fact that computers have also become smaller, a new paradigm of digital devices has emerged: the

Internet of Things.

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"<sup>[4]</sup>. The number of devices that are being connected to the Internet is growing day by day and the industry is at its highest peaks.

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 LoRa and with the evaluation of other use cases.

## 1.1 CONTRIBUTIONS

The contributions that the work described in this thesis are multiple

## 1.2 DOCUMENT OUTLINE

This document follows an hourglass structure, and the content is organized as such in the following chapters:

1. *Introduction:*
2. *Background:*
3. *Technologies:*
4. *Related work:*
5. *Proposed solution:*
6. *Results and experimentation:*
7. *Conclusions:*

# 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 what the Internet of Things is, afterwards, it describes the problem with air pollution, to conclude with an overview on the background work and state or art of IoT devices capable of detecting such pollution. In particular, it concentrates on MegaSense, the IoT air quality sensing project which the work on this thesis builds upon.

A deeper understanding of the related work on mesh networks can be found in chapter 4, where previously made projects which use a similar architecture are described.

### 2.1 INTERNET OF THINGS

IoT, which stands for Internet of Things, has a longer history than many people think about. Its name, which is 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 [5] 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. Its importance heavily relies on data gathered from these devices, since, in combination with other

paradigms such as machine learning and Artificial Intelligence, this 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, with wearable technologies used to enhance quality of life.

#### 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 [6], as can be seen in Figure 2.1.

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

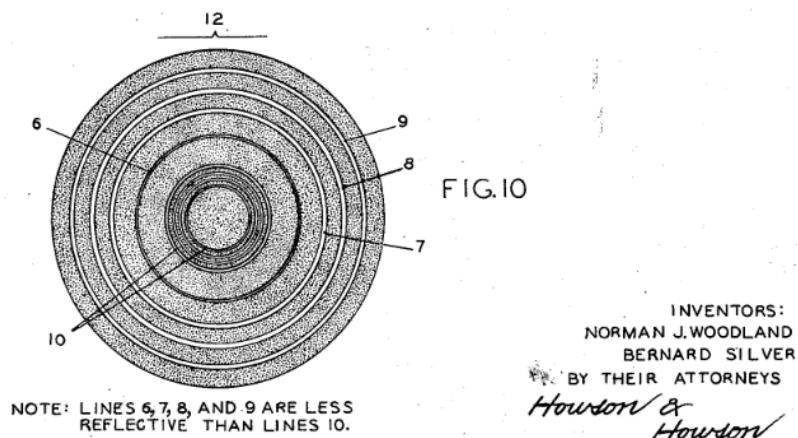


Figure 2.1: Diagrammatic view of the Universal Product Code

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 used to generate barcodes were vulnerable to smudge the design coped with errors as ink bleeding would result in taller bars.

Only later, in

The first widespread

The barcode, as it is now known, was first used commercially in 1966, and it was soon realized that it would become an industry standard.

The first appearance of the Universal Product Code (UPC) to the public and has become widespread, is the one developed in 1971 by George Laurer at IBM [7].

This invention offered the first way to track products and address them.

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

It may come as a surprise, but connecting everyday “things” started around the 1980s.



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.

**Figure 2.2:** CMU's “coke machine”

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 columns of bottles”.

Modern day vending machines are usually required to have continuous connectivity to the manufacturer’s systems. This is not always achievable via a WiFi connection where the 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 paid 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’s not only possible that someone steals a snack or a pack of cigarettes, 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

---

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

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” [8].

While credit card skimmers and chip EMV card cloners remain viable risks to the end consumer, security measures to the environment where the machines are placed must not remain an afterthought, especially when these are placed alongside other connected devices and not in their own separated network.

### 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 the "Internet of Things" are growing 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, IoT techniques still remain immature and many technical hurdles need to be overcome.

Research directions in this new area are immense, since every physical device now represents a possible "thing" connected in the network and that can be interacted with and provide data. Authors of [1] have highlighted ten particular topic areas that span across three layers of IoT architecture: Application, Data and Physical, as represented in Figure 2.3.

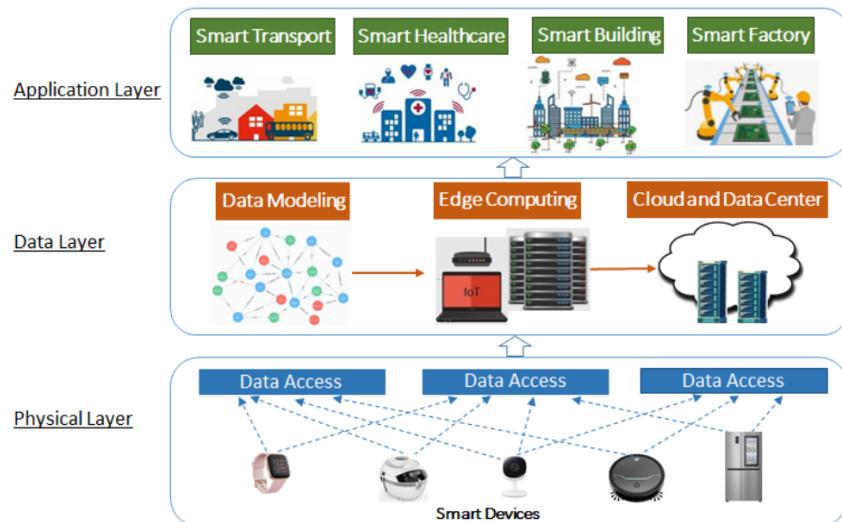


Figure 2.3: IoT research areas according to authors of [1]

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 DBMSs and brokers that allow higher processing speeds and querying frequencies. Specialized ver-

<sup>2</sup> <https://academic.microsoft.com/topic/81860439/>

sions 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 architecture of the network, which needs to take in consideration the aspects such as heterogeneity of the devices connected, velocity of data that flows across and scalability. Thus, paradigms like Cloud Computing, Fog Computing and Edge Computing have emerged.

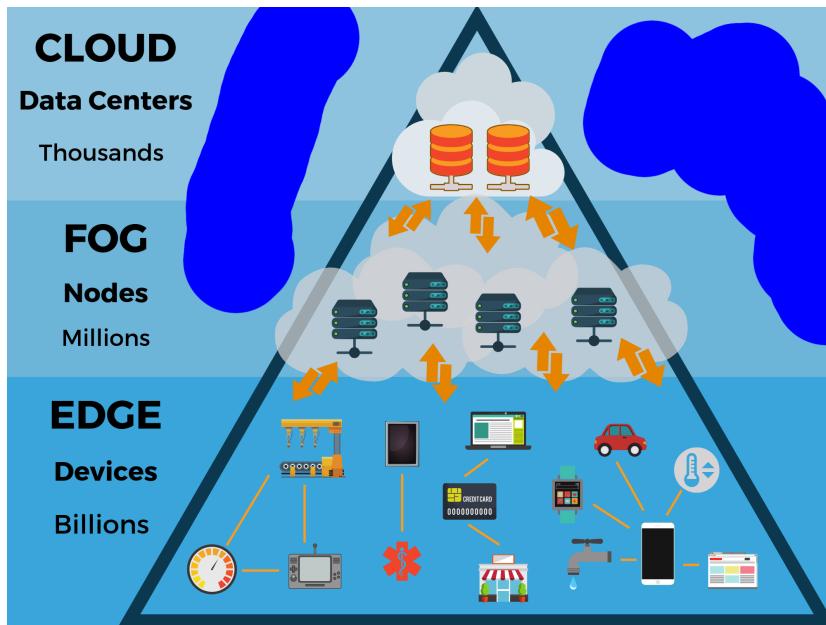


Figure 2.4: Edge, Fog and Cloud Computing

Each of these, places the computation on a different layer of the network, from Cloud Computing that lift off all the need for 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 WiFi 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 5th generation of cellular connectivity comes into play.

<sup>3</sup> <https://aws.amazon.com/iot-core/features/>

As described in a 2019 whitepaper by GSMA on the 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)”[9]. 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, and is now considered almost a “must-have” extension of the smartphone. Not only it can be used for recreational purposes, but it is crossing the line to become medical devices, given the improving accuracy with which they record data. Data that, in conjunction with AI, can be used to predict heart attacks [10] or other diseases, like Hyperkalemia [11]. Even now IoT devices and frameworks can be used for contact tracing in order to prevent the spread of Covid-19 [12].

On the other hand, from an industrial point of view, there are  
with Industry 4.0 and Industrial IoT (IIoT)

The more data available, the more there are opportunities for science, services, business etc. to understand and grow.

IoT is an enabler for the sciences that need large amount of data for creating algorithms and offering better services and more well tailored products.

Another important definition of IoT is IIoT, which stands for Industri 4.0 IoT.

Given the importance of this economic sector, many companies, both technical and not, 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>4</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.”[13]. In the same analysis, has emerged

---

<sup>4</sup> <https://www.arm.com/>

that IoT is an enabler for AI, since many companies “view IoT and AI as two components of an advanced analytics capability”.

But there is more to the IoT than consumer devices

In my opinion, it is important to understand the growth of IoT not only from an academic perspective, but from an economic perspective as well, since today’s academic discoveries should be

Underlying hardware challenges such as battery development and energy retention and 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**

## 2.3 IoT FOR SENSING OF AIR QUALITY

## 2.4 MEGASENSE

MegaSense, developed at the University of Helsinki's department of Computer Science<sup>5</sup>

### 2.4.1 HOPE

---

<sup>5</sup> text



# 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, to radio technologies work and then 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.”* [14]

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, in which people need to feel 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, that require a stable and secure connection among the systems that they use in order to provide a safe and sound 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 point of view to an economic point of view. The possibility of having a network of information exchange is the next step of globalization, which started with the exchange of goods among countries and now brings everyone together, allowing for a cultural exchange that lets people share and 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 [15], 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 that brought them in their households, especially with the advent of MS-DOS, the dominant operating system throughout the 1980s and 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" [15]:

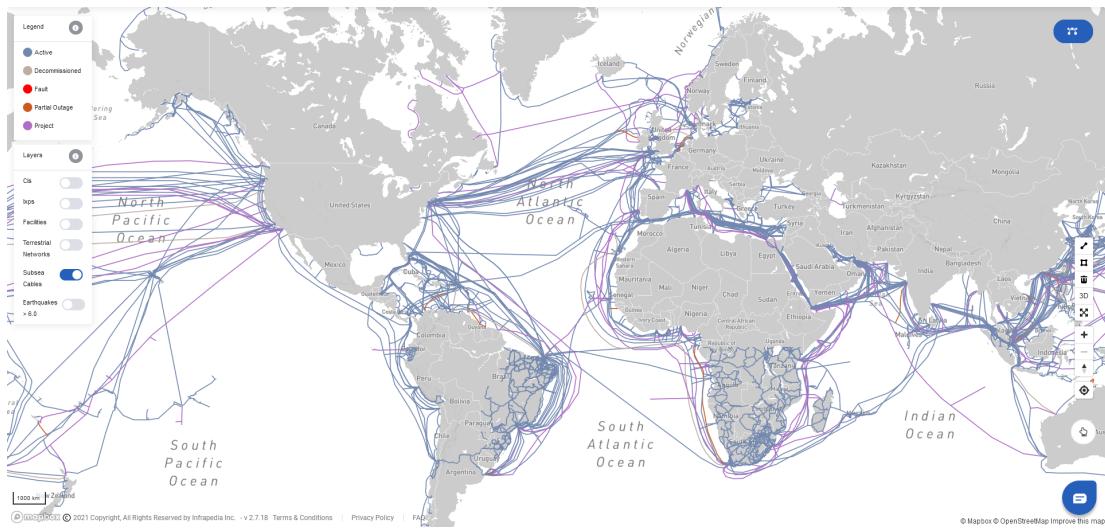
- Backbones: large and strategical data routes among core networks and routers that compose and connect the Internet;
- Regional networks that connect large facilities such as universities and colleges;
- Commercial networks that provide to their subscribers access to the Internet;
- Local networks which run, for example, across a campus university;

---

<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> <https://github.com/microsoft/MS-DOS>



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

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 OSs, such as Windows 95 and Windows 98, and the advent of Tim Berners-Lee's World Wide Web (or WWW), computers became a commodity present in many households. 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.

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

- Wide Area Network, or WAN: sometimes 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.

In Sec. 3.2, is described another level of distinction based on the power consumed by the transmission medium.

---

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

Since 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 that is displayed to him without knowing where it arrives from or what path it took to arrive on his monitor.

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”<sup>[14]</sup>. 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 stack of protocols.

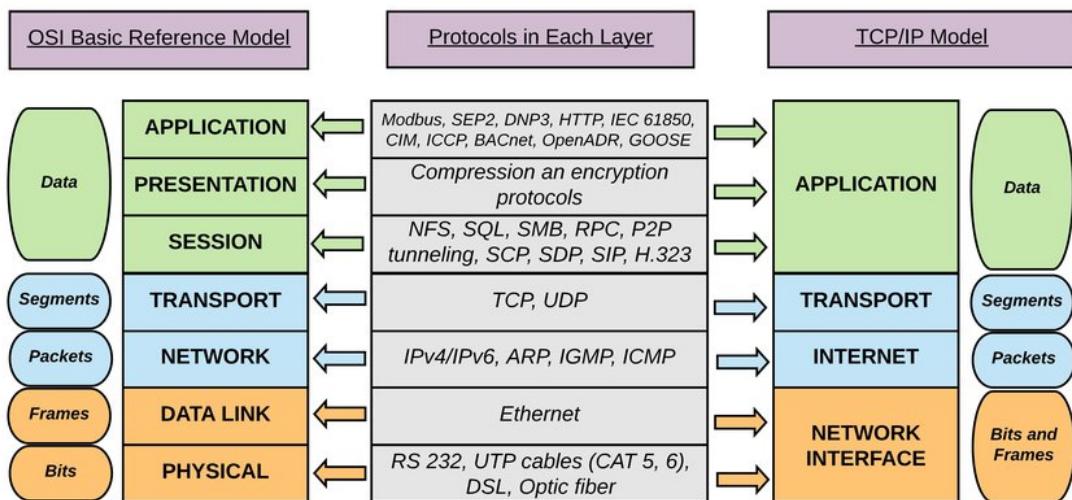


Figure 3.2: The ISO/OSI reference model against the TCP/IP stack

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.”<sup>[14]</sup>. Different types of network use different 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.

<sup>5</sup> <https://www.iso.org/standard/20269.html>

## Network Topology Types

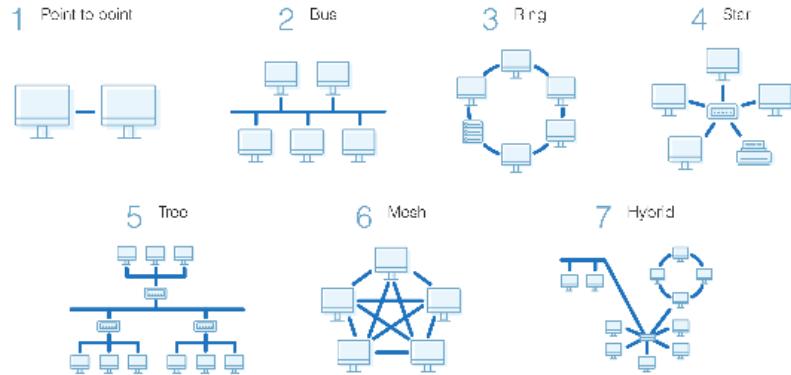


Figure 3.3: Common network topologies

As shown in Fig. 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;
- 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;

The project presented in this thesis regards a network with a mesh topology. This is better described in chaps in a more depth and technical way. The mesh proposed in this thesis 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.

Another important distinction to make is the one between a distributed systems and a computer network.

Nowadays, the organization responsible for technical management of IETF activities and the Internet standards process 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.

---

<sup>6</sup> <https://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, many scientists before him have studied radio waves.

The idea of a wireless telegraph had been around for a while before the establishment of radio-based communication and scientist tried to achieve it via electric conduction and electromagnetic induction

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.

Other important experiments were made by Nikola Tesla

Tesla invented the Tesla coil during efforts to develop a "wireless" lighting system Tesla employed the Tesla coil in his efforts to achieve wireless power transmission, his lifelong dream.

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 vs the ones that are used for longer distances.

100 years later, radio technology has massively evolved and is used on a daily basis

With new transmission technologies, new network architectures have emerged

Topologies that bring computation closer to the edge are also rising, since they allow for faster computation and they bring data closer to the user

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, COST and RANGE of the transmpter receiver

Distinction of low cost vs higher cost

da quando Tesla e Marconi studiavano questa tecnologia, l'invenzione del transistor at the infamous bell labs e la miniaturizzazione del computer, come descritto anche in [fare riferimento al paragrafo dei microcontroller], hanno permesso di implementare questi mezzi trasmissivi a vaste categorie di dispositivi

Questo ha portato alla nascita dell'Internet of Things, o IoT, come descritto anche nel Chap2.

Vengono descritte adesso alcune delle più importanti tecnologie radio per il mondo dell'iot

Altre tecnologie sono RFID, ecc. ma quelle sono per un'altra storia

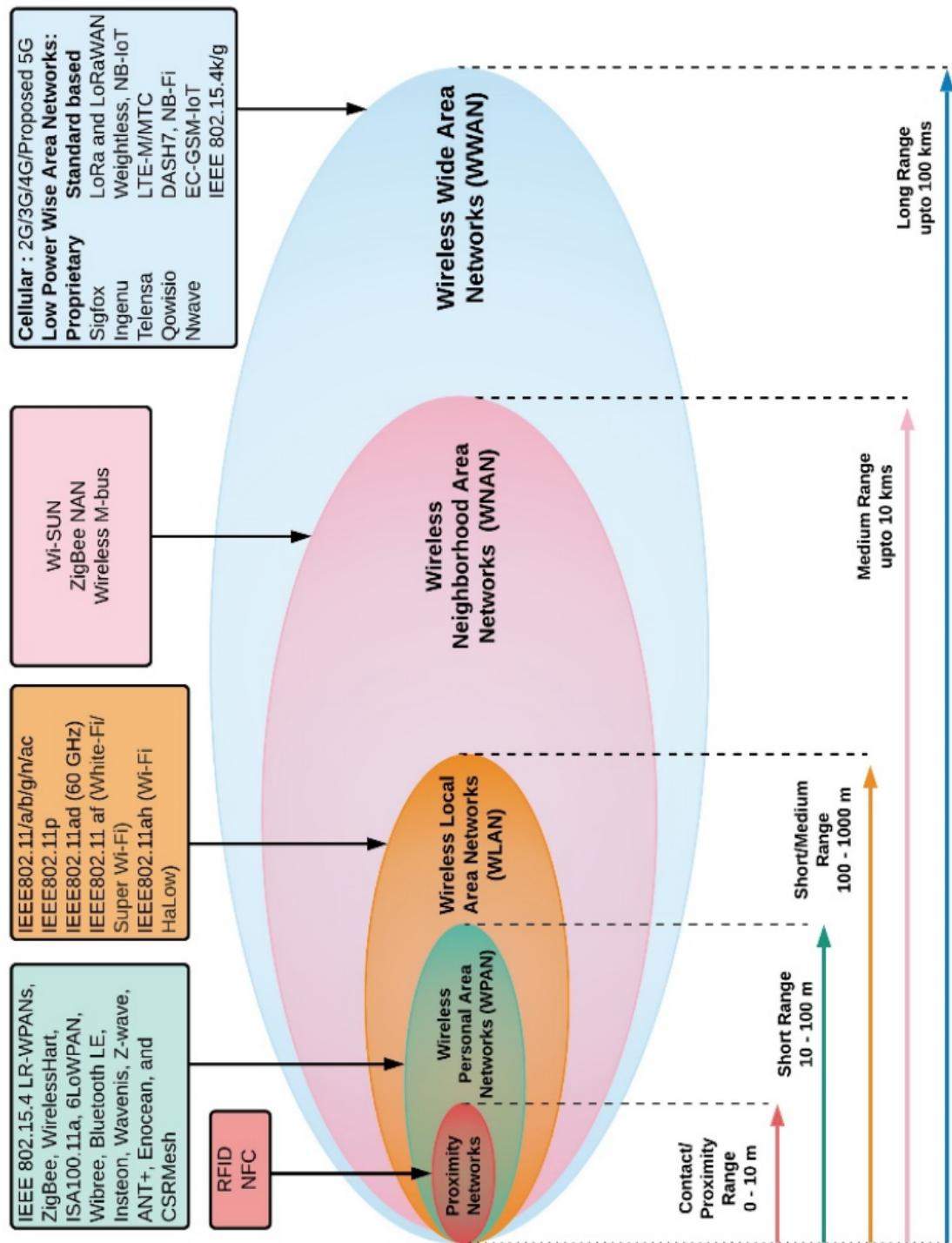


Figure 3.4

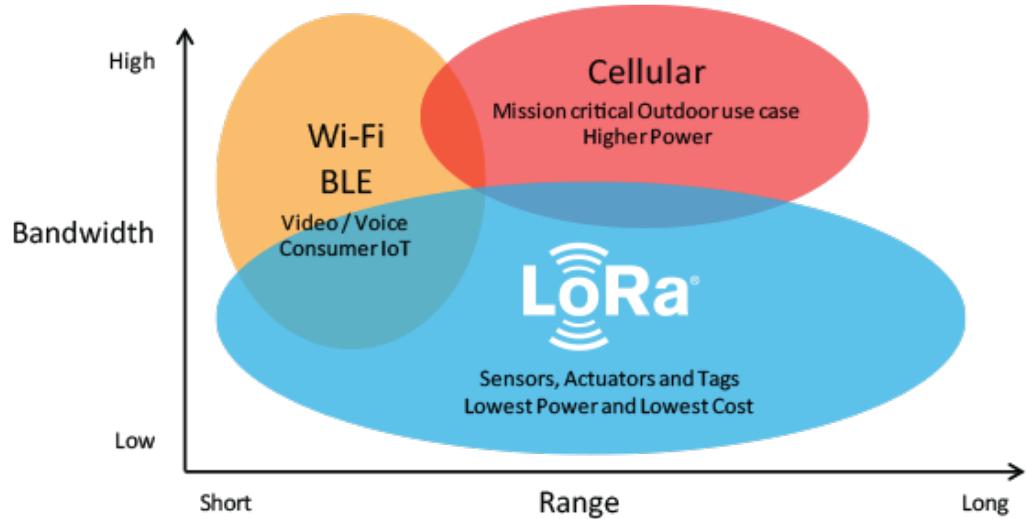


Figure 3.5

### 3.2.1 LoRA

<https://lora-alliance.org/>

<https://www.semtech.com/lora>

The smaller the package, the greater the range. The greater the range, the fewer receiving antennas. The fewer antennas, the lower the total costs for the user.

### 3.2.2 LoRAWAN

### 3.2.3 BLUETOOTH

### 3.2.4 WiFi

IEEE 802.11, better known in the public as WiFi, short for wireless fidelity

### 3.2.5 5G AND LTE

The goal of fifth-generation (5G) wireless networks and beyond is to realize connecting “anything, anyone, anytime, anywhere” [1] reliably and energy-efficiently [ M. Agiwal, A. Roy and N. Saxena, ”Next generation 5G wireless networks: A comprehensive survey”, IEEE Communications Surveys & Tutorials, vol. 18, no. 3, pp. 1617-1655, 2016.]

### 3.3 LoRa AND LoRaWAN

### 3.4 HARDWARE (MICROCONTROLLERS)

Microcontrollers (or MCUs, short for Microcontroller Unit) are compact integrated circuits designed to govern a specific operation in an embedded system. They are specially made to fit in particular environments or to perform specific 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 Chap. 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 [16], and connection density is expected to be one million devices per square km[17]. 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 peripherals.



Figure 3.6: ATTiny 85 on the left, in the middle two boards based on the ESP32, on the right the Asus Tinkerboard 2

In Fig. 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 simple 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

<sup>7</sup> <https://www.microchip.com/en-us/product/ATTINY85>

powerful than the ATtiny 85, and right one offers an integrated LoRa antenna on board. Far on the right, there is the Asus Tinkerboard 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€, while the board by Asus is the more expensive 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 support and documentation. 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.

Regarding the programming language ... Micropython ...

#### 3.4.1 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 used programs called "sketches". Arduino was the result.

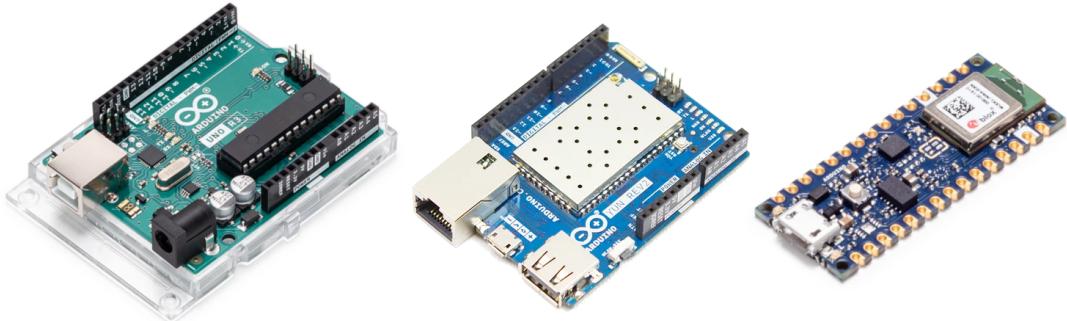
The most famous version of their board is the UNO (one in English). Arduino UNO, the one on the left in Fig. 3.7, is the most used and documented board of the whole Arduino family. Although this board does not have any integrated sensors or particular ports for peripherals. The current revision of the board is the Arduino UNO Rev 3<sup>9</sup>, which consists of 14 digital pins, 6 analog inputs, a power jack, USB connection and ICSP header.

The Arduino family of products can be programmed in a particular programming language based on C/C++, using a special open-source integrated development environment

---

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

<sup>9</sup> <https://store.arduino.cc/products/arduino-uno-rev3>



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

(IDE). Arduino was so disruptive in the market that many boards, included the ones in Fig. 3.6, support the Arduino C++.

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, WiFi, GPS, displays and cameras, motor drivers.

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 Fig. 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 simple 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 NB 1500: 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 Fig. 3.7, has been considered as one of the possible choices as development board for this project. As better explained in chap

5, 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.

### 3.4.2 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 also offers more functionalities, since they include 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 Raspian OS

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

Letting their differences aside, both are very popular boards among electronics DIY builders, 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 Tinkerboard (in Fig. 3.6). Since, like the Arduino, the Raspberry Pi boards schematics are open-source and available online<sup>10</sup>, board makers have been able to adapt them in their own way.

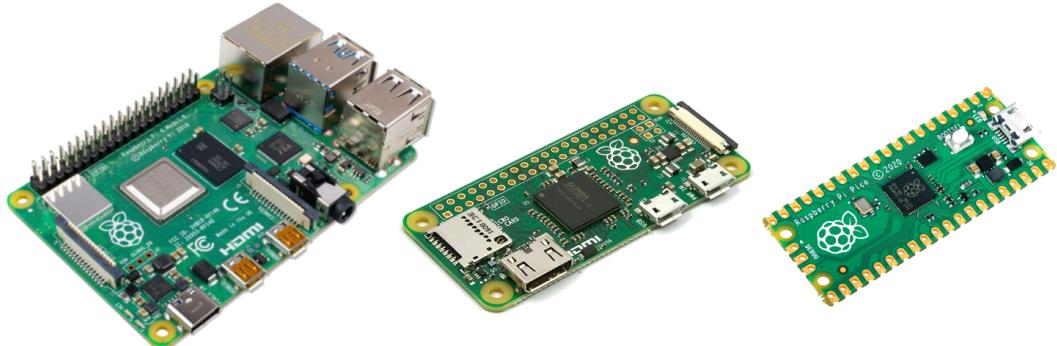
There are now different Raspberry Pi boards, or models, each a bit more specialized than the other. Some of the most important models are:

- 3 B+ / 4: the model 3B+ and 4 are their most selling products, they are marketed as a "tiny, dual-display, desktop computer"<sup>11</sup>;
- Zero: it's the smallest form factor Raspberry Pi on the market;
- Pico: a low-cost, high-performance microcontroller board with flexible digital interfaces.

---

<sup>10</sup> <https://www.raspberrypi.org/documentation/computers/raspberry-pi.html>

<sup>11</sup> <https://www.raspberrypi.org/products/raspberry-pi-4-model-b/>



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

They are represented in Fig. 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\$ each. A complete list of the available boards can be found on their online store<sup>12</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 BLE connectivity, while the other models have a computational power much greater than the one needed.

### 3.4.3 PYCOM

While Raspberry Pi and Arduino share a longer history, Pycom was founded in 2015 via a crowdfunding campaign on Kickstarter. The goal was to create a 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, the wipy and the lopy. These boards are very similar to each other, since all of them offer at least WiFi and BLE, have the same chipset, interfaces and memory.

---

<sup>12</sup> <https://www.raspberrypi.org/products/>



**Figure 3.9:** fipy on the left, PyTrack 2X in the middle, pysense on the right

In particular, the FiPy board, present in Fig. 3.9, has been chosen for this project since it packs five networks in one small board. It is capable to communicate via WiFi, Bluetooth, LoRa, Sigfox and dual LTE-M (CAT-M1 and NB-IoT), and gives access to global LPWAN networks.

Contrarily to Arduino and Raspberry Pi, the Pycom company has decided to maintain the datasheets and the firmware of the boards proprietary.

the MicroPython-programmable FiPy takes up the same footprint as our other boards. Featuring

A Pycom development board has considerably more I/O than a standard Arduino, but probably comparable to an Arduino Mega. Easy to program via Python. Good example code from Pycom. Small community. Low cost. Not at all comparable to Raspberry Pi in terms of software flexibility.

A complete LoRa gateway (Pygate + WiPy + IP67 box + antenna) costs around \$100, which is pretty good. So far very stable, and it was easy to configure. There's a PoE unit, but I use WiFi (at my home).

Come mai sono state scelte le board di pycom per il progetto

Mettere una tabella comparativa tra arduino raspberry e picom per dimostrare le capacità computazionali di ciascuno

A more in depth description of how the chosen technologies interact is present in chap

# 4

## Related work

To better understand the proposed solution, this chapter describes the state of the art and the related work that has been done in this field, both commercially and in research.

The solution this thesis focuses on is MegaSense  
cina mattina/sera smog

### 4.1 SOLUTIONS TO DETECT AIR POLLUTION

#### ArduECO

#### 4.2 MEGASENSE

<https://www.megasense.org/>

Describe the consortium

HOPE and Megasense

The calibration of the megasense device is made via

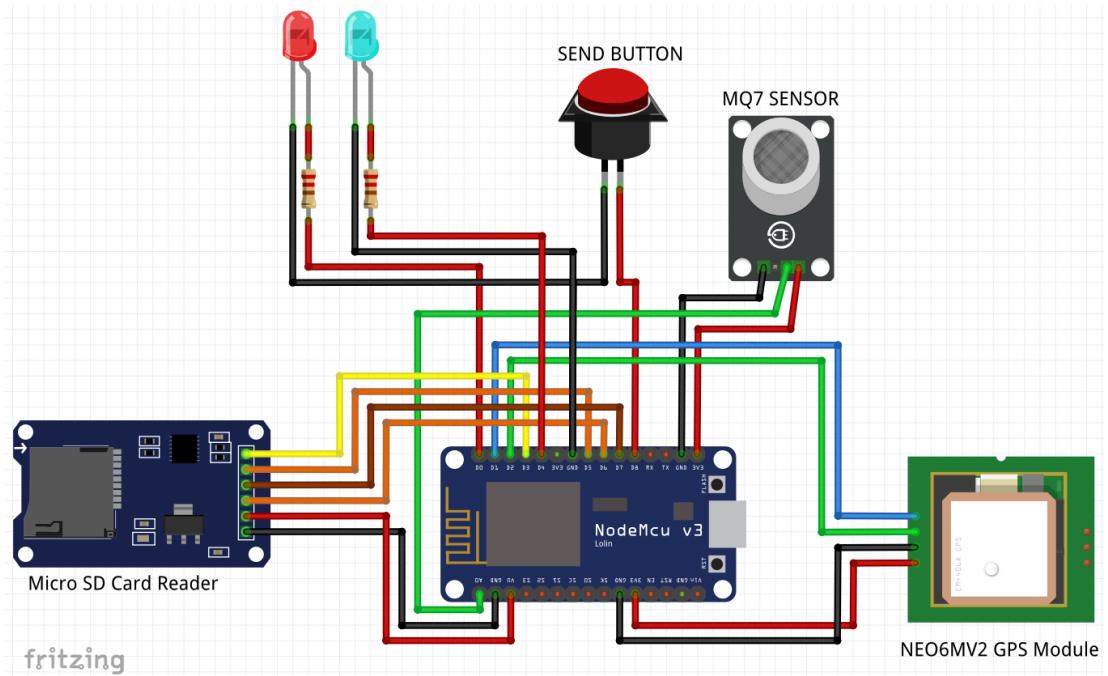
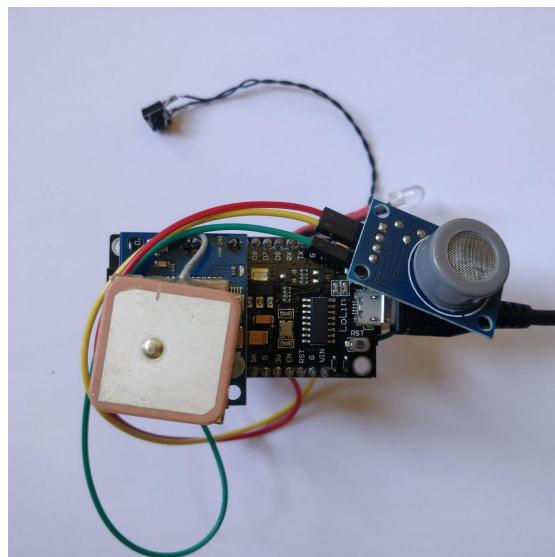


Figure 4.1: Circuit of the ArduECO prototype, as contained in [2]



# 5

## Proposed solution

### 5.1 IDEA

### 5.2 ARCHITECTURE

Describe sensing pipeline

### 5.3 HARDWARE

Describe hardware requirements, connect to the sections in chap 3

Altri microcontroller, come esp8266 che sono stati generati da arduino sono stati scartati in quanto poca documentazione, ecc

### 5.4 SOFTWARE

#### UART

How I programmed the pycom  
calcolare transmission times

### 5.5 USE CASES



# 6

## Results and experimentation

6.1 EXPERIMENTS

6.2 RESULTS



# 7

## Conclusions

### 7.1 FUTURE WORK

### 7.2 IMPROVEMENTS TO THE HARDWARE

Note from the author, it must be taken in consideration that the device can run hot, an application of the device such as on a bike that is parked out in the sun may overheat the device. On pycom's documentation it is written that the fipy can support temperatures up to x Thus an interesting improvement could be to add a heatsink in order to lower the temperatures and improve the lifespan of the device

### 7.3 PERSONAL CONSIDERATIONS



# A

User Manual



# B

Techinical Manual



# Acknowledgments

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.



# References

- [1] W. E. Zhang, Q. Z. Sheng, A. Mahmood, D. H. Tran, M. Zaib, S. A. Hamad, A. Aljubairy, A. A. F. Alhazmi, S. Sagar, and C. Ma, “The 10 research topics in the internet of things,” in *2020 IEEE 6th International Conference on Collaboration and Internet Computing (CIC)*, 2020, pp. 34–43.
- [2] S. C. Voinea, A. Bujari, and C. E. Palazzi, “Air quality control through bike sharing fleets,” 2020. [Online]. Available: <https://ieeexplore.ieee.org/document/9219618>
- [3] R. E. Munn, “The design of air quality monitoring networks,” *Palgrave Macmillan, London*, pp. XIII, 109, 1981.
- [4] Intelligent world: the state of iot.
- [5] K. Ashton. That ‘internet of things’ thing. [Online]. Available: <https://www.rfidjournal.com/that-internet-of-things-thing>
- [6] W. E. A. N. J., “Classifying apparatus and method,” Patent US2 612 994A. [Online]. Available: <https://patents.google.com/patent/US2612994A/en>
- [7] D. Savir and G. J. Laurer, “The characteristics and decodability of the universal product code symbol,” *IBM Systems Journal*, vol. 14, no. 1, pp. 16–34, 1975.
- [8]
- [9] “Internet of things in the 5g era - opportunities and benefits for enterprises and consumers.”
- [10] S. Ali and M. Ghazal, “Real-time heart attack mobile detection service (rhamds): An iot use case for software defined networks,” in *2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE)*, 2017, pp. 1–6.

- [11] C. Galloway, A. Valys, F. Petterson, V. Gundotra, D. Treiman, D. Albert, J. Dillon, Z. Attia, and P. Friedman, “Non-invasive detection of hyperkalemia with a smartphone electrocardiogram and artificial intelligence,” *Journal of the American College of Cardiology*, vol. 71, p. A272, 03 2018.
- [12] L. Garg, E. Chukwu, N. Nasser, C. Chakraborty, and G. Garg, “Anonymity preserving iot-based covid-19 and other infectious disease contact tracing model,” *IEEE Access*, vol. 8, pp. 159 402–159 414, 2020.
- [13] “The iot business index 2020: a step change in adoption.”
- [14] P. E. Green, *Computer network architectures and protocols / edited by Paul E. Green, Jr.* Plenum Press New York, 1982.
- [15] *TCP/IP Tutorial and Technical Overview. An IBM Redbooks publication.*
- [16] “test.” [Online]. Available: <https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/>
- [17] *noma*. [Online]. Available: <https://arxiv.org/abs/1504.07751>



**T**HIS THESIS WAS TYPESET using L<sup>A</sup>T<sub>E</sub>X, originally developed by Leslie Lamport and based on Donald Knuth's T<sub>E</sub>X. The body text is set in 11 point Egenolff-Berner Garamond, a revival of Claude Garamont's humanist typeface. The above illustration, *Science Experiment 02*, was created by Ben Schlitter and released under CC BY-NC-ND 3.0. A template that can be used to format a PhD dissertation with this look & feel has been released under the permissive AGPL license, and can be found online at [github.com/suchow/Dissertate](https://github.com/suchow/Dissertate) or from its lead author, Jordan Suchow, at [suchow@post.harvard.edu](mailto:suchow@post.harvard.edu).