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Department of Mathematics "Tullio Levi Civita"

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Open LoRa mesh network for IoT-based air quality sensing

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This is a very
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Abstract

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Preface

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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_2 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*"[2]. 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"[3]. The number of devices that are being connected to the Internet is growing day by day and the industry is at it's highest peeks.

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

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. It's name, which is now know 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. 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*. It's 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 [5], 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.

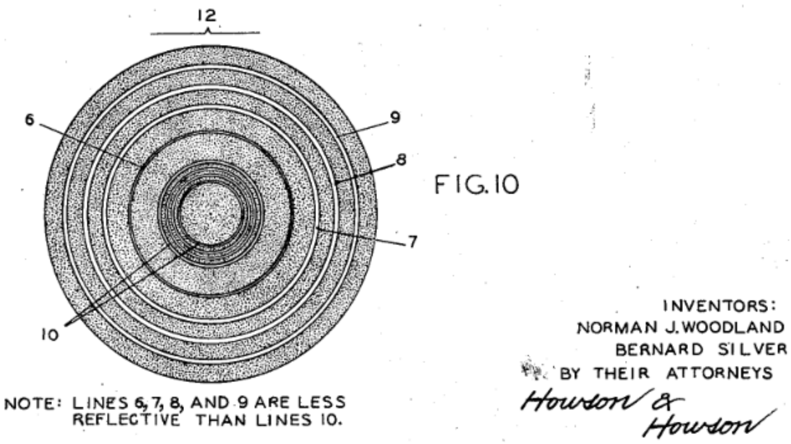

Figure 2.1: Diagrammatic view of the Universal Product Code

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 [6].

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.

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 expained in the official website[1] 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 require 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 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'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

[1] 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" [7].

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[2], 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.

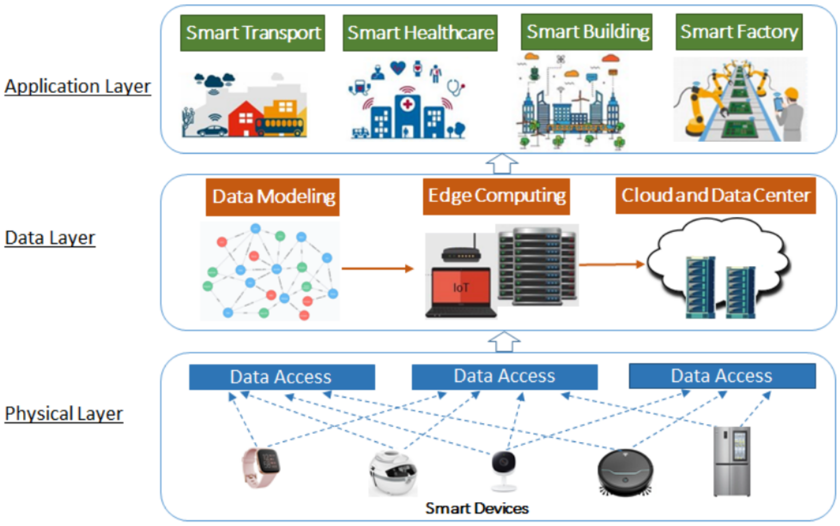

Figure 2.3: IoT research areas according to authors of [1]

[2] https://academic.microsoft.com/topic/81860439/

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 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[3]) 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.

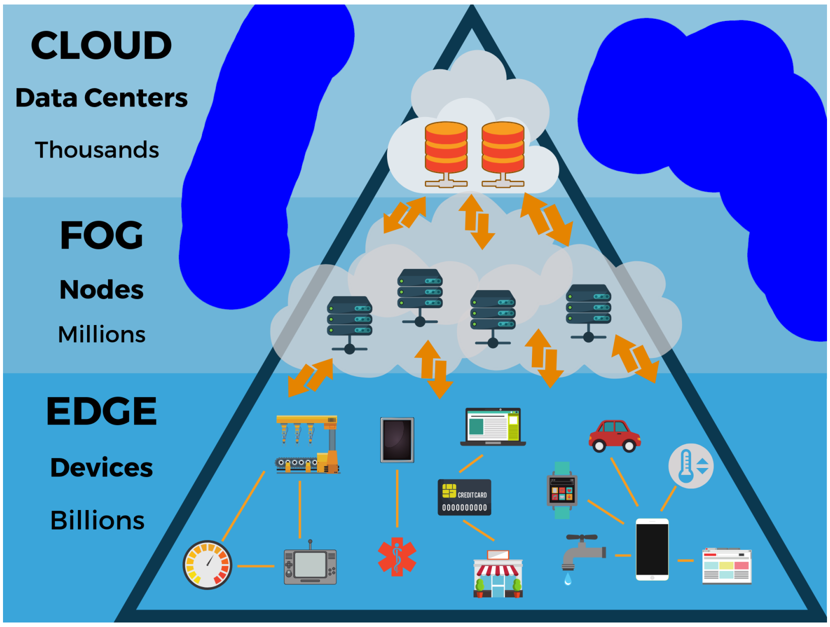

Figure 2.4: Edge, Fog and Cloud Computing

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

[3] https://aws.amazon.com/iot-core/features/

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.

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)"[8]. 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 [9] or other diseases, like Hyperkalemia [10]. Even now IoT devices and frameworks can be used for contact tracing in order to prevent the spread of Covid-19 [11].

On the other hand, from an industrial point of view, there are

with Industry 4.0 and Industrial IoT (IIoT)

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 LPWAN access technologies.

2.2 Air quality

2.2.1 Research and commercial solutions of air pollution detection

The following are two examples of solutions to detect and keep track of pollutants in the air.

2.2.2 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"[12].

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. Parlare di come questi mezzi di trasporto sono diventati sempre più utilizzati con il covid e post covid. In contrast, other approaches to shared transportation, such as car sharing, have severely suffered from the outbreak of the coronavirus.

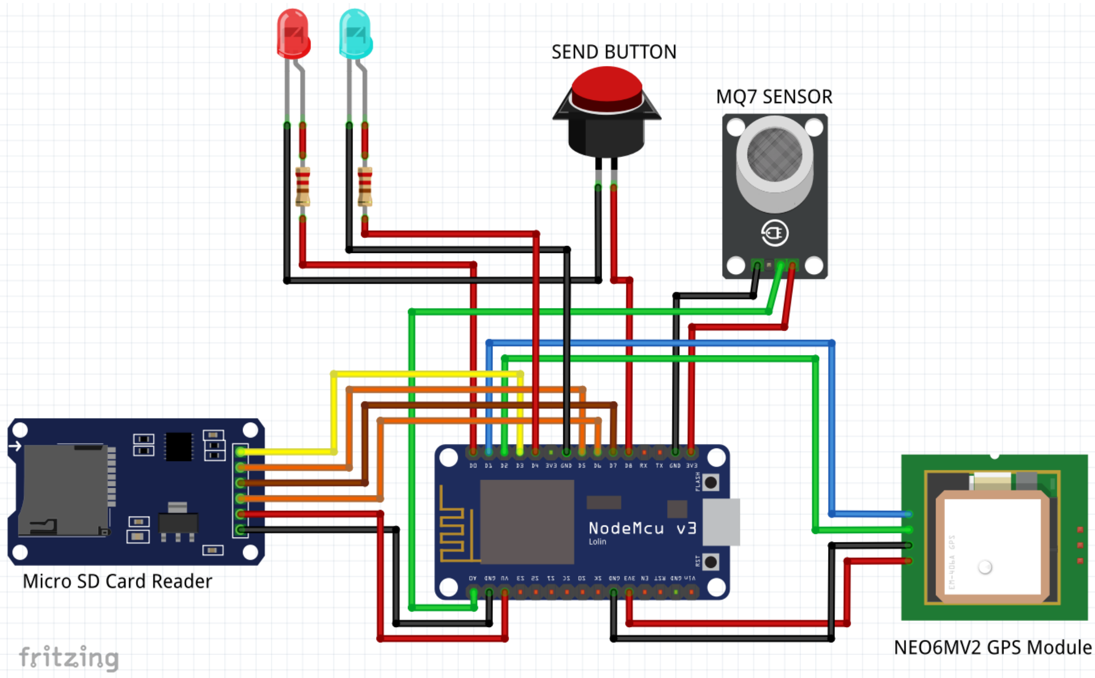

Figure 2.5: Circuit of the ArduECO prototype

The ArduECO sensor 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. Fig. 2.5 shows the full circuit of the prototype, while Fig. 2.6 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 [4]. Data is sent over the built-in wifi module of the esp8266. Server costs aside, the researchers say the sensor platform can be built in a bill of materials (BOM) of around €15 (around $18) — less, if built in bulk.

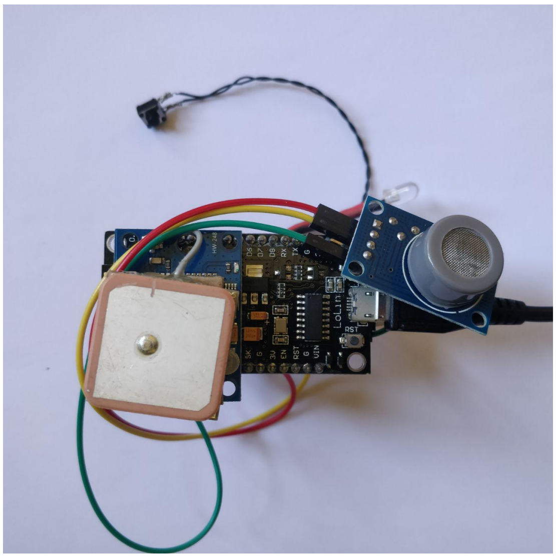

Figure 2.6: Built ArduECO prototype

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:

2.2.3 MegaSense and Hope

MegaSense has been developed by the Departments of Computer Science at the University of Helsinki [5] 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.

MegaSense feedback loop involves the actions of individuals and the physical and chemical processes, which increase exposure duration and concentration to air pollution. These exposures are tested by citizens and companies in City of Helsinki and EU projects.

[4] https://aws.amazon.com/iot-core/

[5] https://www.helsinki.fi/en/computer-science

Compared to the previously described ArduECO, the MegaSense is a full project that has brought to a

Figure 2.7: Megasense prototype

Some text here, depends on the pagination.

The system receives data from sensing platforms measuring local pollution exposure and other variables affect- ing it. This data is processed into air quality information such as maps and advice on how to reduce personal exposure, take healthier routes, and direct participants to improve measure- ments in areas that have limited sensor coverage. Below we detail the different components of the system architecture.

The core of MegaSense consists of two layers: the Edge and Cloud. The Edge layer is responsible for reactively receiving data from available data sources, such as sensor devices, traffic data systems, and weather information systems. It delivers advice and pollution maps to the mobile Exposure App which provides the user with personal air pollution exposure information as well as district exposure maps. This layer is responsible for data preprocessing for filtering and data cleanin

he Cloud layer is responsible for storing cleaned data and aggregating the crowd-sourced data while preserving the privacy of participants. It includes a scalable storage system based on Lustre, a distributed production-grade file system similar in principle to Amazon S3.

During data gathering campaigns registered citizens down- load the HOPE Exposure App from Google play store and tether their Android smart phone to HOPE sensor. The HOPE Exposure App is pre-configured with the MegaSense server address and upon launching the app and switching on the HOPE sensor, measurement data packets including the smartphone GPS location are routed by wireless connection via local mobile service provider to the MegaSense Core

The HOPE project further develops the clean air journey planner application that creates optimal walking and cycling routes based on air quality of Helsinki (Figure 6). The route guide is made by Forum Virium Helsinki.

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, 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.*" [13]

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 [14], 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 [1,2] by computer scientists that understood how ARPANET was expanding and the 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 [3].

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”[14]:

- 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;

[1] RFC 871 (1982): A PERSPECTIVE ON THE ARPANET REFERENCE MODEL
[2] RFC 872 (1982): TCP-ON-A-LAN
[3] https://github.com/microsoft/MS-DOS
[4] https://www.infrapedia.com/app

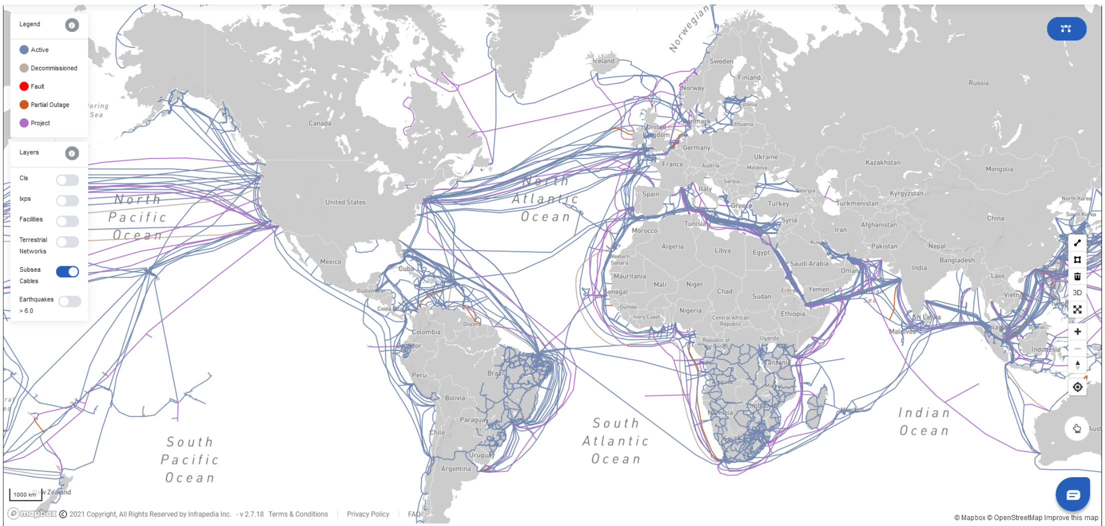

Figure 3.1: Subsea Internet backbone cables between US and Europe. [4]

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 Ara 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.

Since everyone can connect to the Internet and access it's 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 by Paul E. Green, "is a complete definition of all the layers necessary to build the network"[13]. This is focused on the network software, which needs to be highly structure in order to allow for heterogeneous systems to communicate with each other. One example of network architecture is the ISO/OSI reference model [5], which is implemented by the TCP/IP stack of protocols.

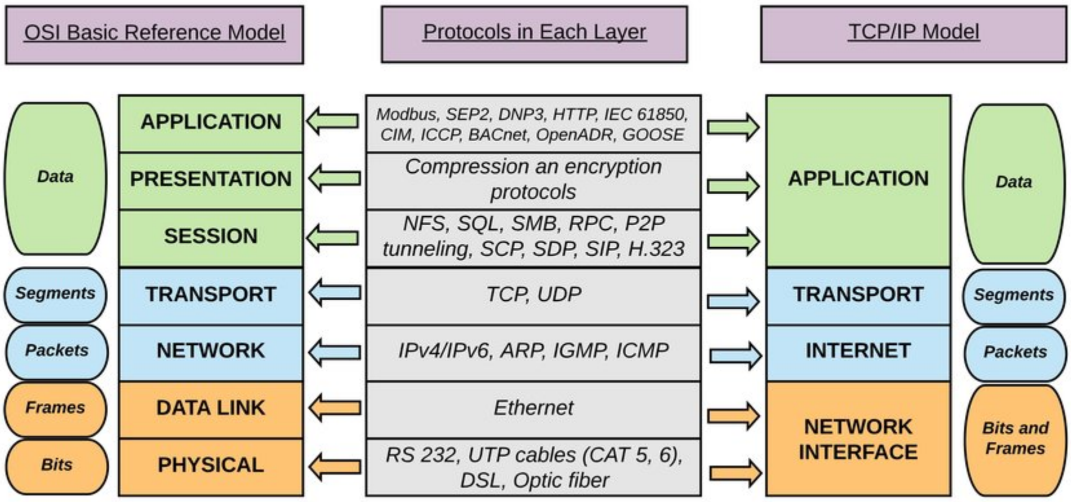

Figure 3.2: The ISO/OSI reference model against the TCP/IP stack

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."[13]. 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.

[5] https://www.iso.org/standard/20269.html

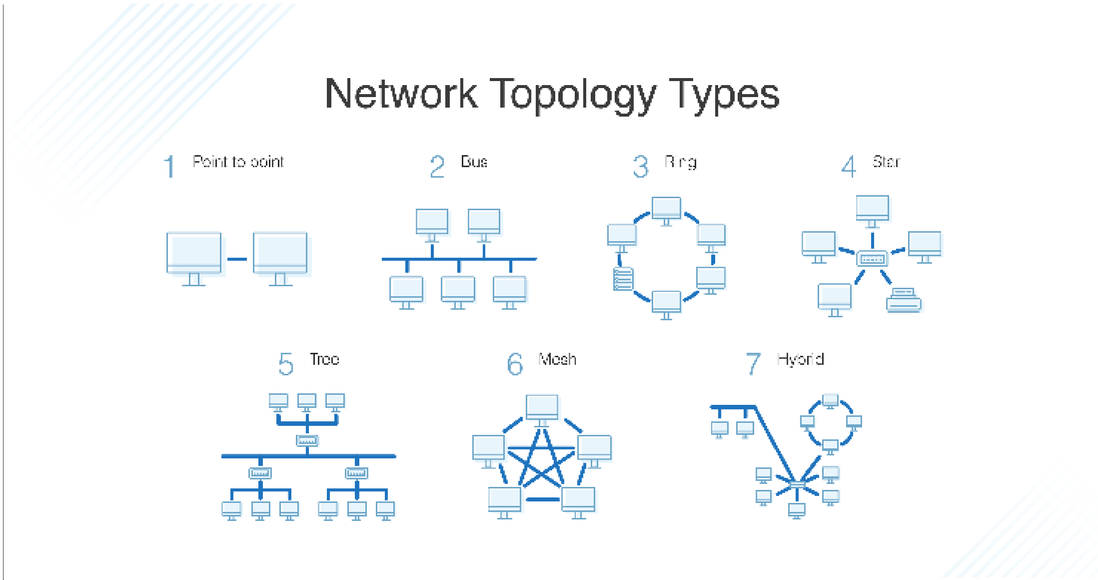

Figure 3.3: Common network topologies

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 chap5 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)[6]. 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.

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 [15], 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 has shrunk 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 vs the ones that 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, broadcast radio, cellular radio, microwaves, and communications satellites.

- 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.

[6] https://www.ietf.org/about/groups/iesg/

- 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.

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 the transmiter and receiver.

The most important new category of wireless communication, that interests IoT and reprents a large portion of the market at the time of writing, as described in chap2, is LPWAN, which stands for Low Power Wide Area Networks.

The characteristics of LPWAN are: long range, low power and low cost. Lightweight protocols reduce complexity in hardware design and lower device costs. Its long range combined with a star topology reduce expensive infrastructure requirements, and the use of license-free or licensed bands reduce network costs.

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 LPWAN access technologies [16], 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 important factor for all these transmission methods is to support a massive number of simultaneously connected devices with low data rates [16].

Other important communication technologies in IoT are RFID, NFC, for contact purposes, Bluetooth, Zigbee for a personal network and IEEE 802.11, or WiFi, for a local area.

The latter was used in the ArduEco project, described in chap2. Fig. 3.4 contains a representation of the geographic coverage in meters of the various aforementioned wireless transmission methods.

3.2.1 LoRa and LoRaWAN

LoRa (short for long range) is a spread spectrum modulation technique derived from chirp spread spectrum (CSS) technology. Semtech's LoRa is a long range, low power wireless platform that has become the de facto wireless platform of Internet of Things (IoT).

Since it's development in 2009, by the french company Cycleo, now acquired by the semiconductor company Semtech, LoRa has come a long way. On top of it, there is a proprietary MAC protocol called "LoRaMAC", which specifies the message formats and security layers for a true networking protocol.

In February 2015, the LoRa Alliance was founded and the networking protocol was renamed "LoRaWAN." The LoRa Alliance is a non-profit organization committed to enabling large-scale deployment of Low Power Wide Area Networks (LPWAN) IoT through the development and promotion of the LoRaWAN open standard.

This organization is alike with the 3GPP

Applications of LoRa in IoT varies from smart agriculture, to smart cities, to contact tracing, to logistics and healthcare. A complete list of the whitepapers on LoRa based communication can be found on Semtech's official website [7].

[7] https://www.semtech.com/lora/lora-applications

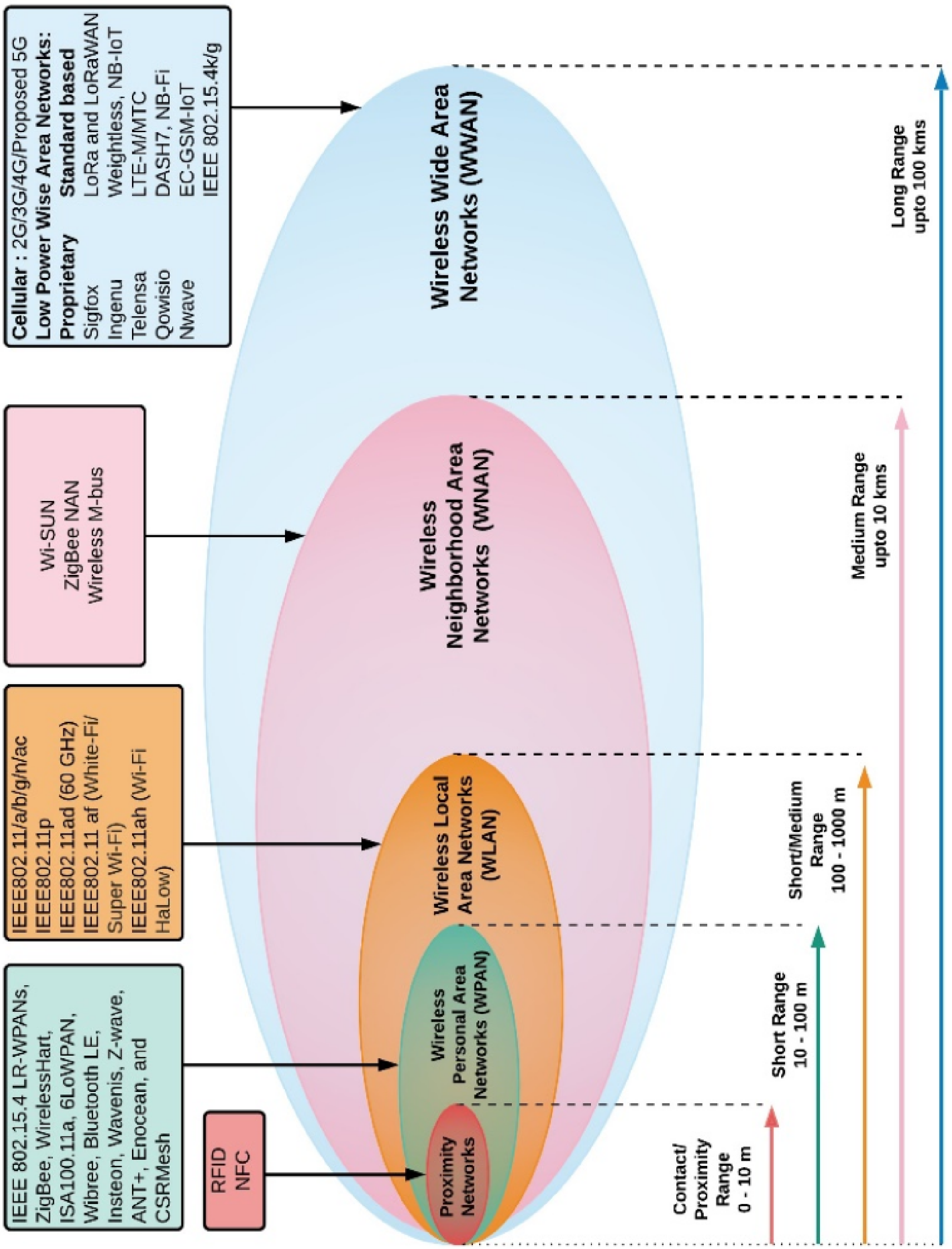

Figure 3.4: Wireless access geographic coverage. [16]

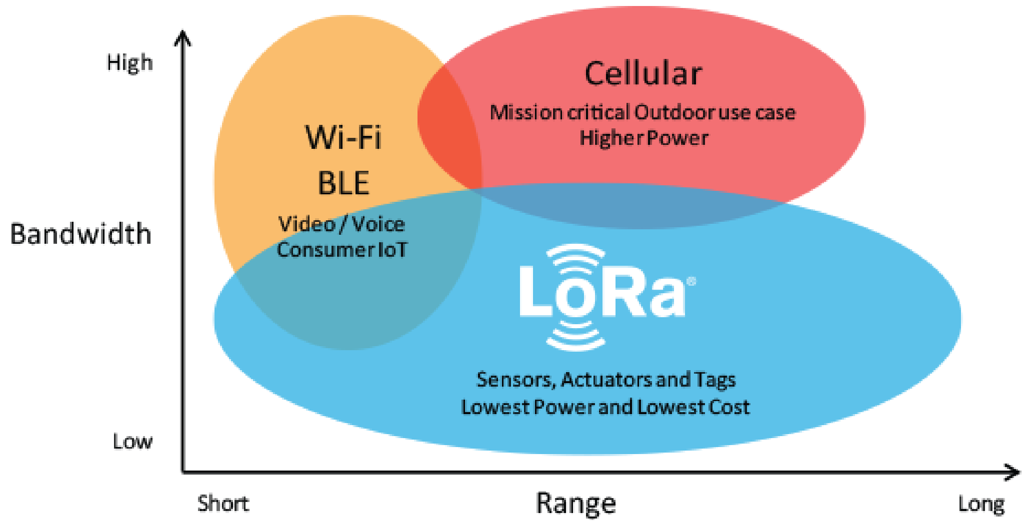

Figure 3.5

3.3 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 hearth 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 [17], and connection density is expected to be one million devices per square km[18]. 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.

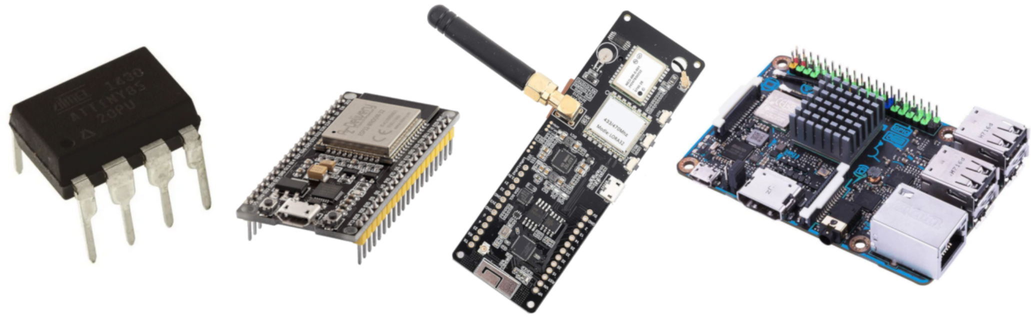

Figure 3.6: Attiny 85 on the left, in the middle two boards based on the ESP32, on the right the Asus Tinkerboard 2

In Fig. 3.6, there are four different boards, the one farthest on the left is the ATtiny 85 [8], 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 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 [9], 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 hobbysts 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 microcon-

[8] https://www.microchip.com/en-us/product/ATTINY85
[9] https://tinker-board.asus.com/product/tinker-board-2.html

troller company, Arduino, have developed a version of C++ specific for their boards, but given the simplictity 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 Mycropython. 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" [10]. Python's fast learning and explicit code advantages are reflected in this smaller version for microcontrollers, available for most of them.

Below is a table with the specifications of microcontrollers from Arduino, Raspberry Pi and Pycom, which are better described in the following subsections.

	Arduino UNO R3	Arduino Nano BLE	Raspberry Pi	Rasperry Pi Pico	Pycom FyPy
CPU					
RAM					
ROM					
IO PINS					
PORTS					

Table 3.1: Specifications of Arduino, Raspberry Pi and Pycom 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 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

[10] https://micropython.org/

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 [11], which consists of 14 digital pins, 6 analog inputs, a power jack, USB connection and ICSP header.

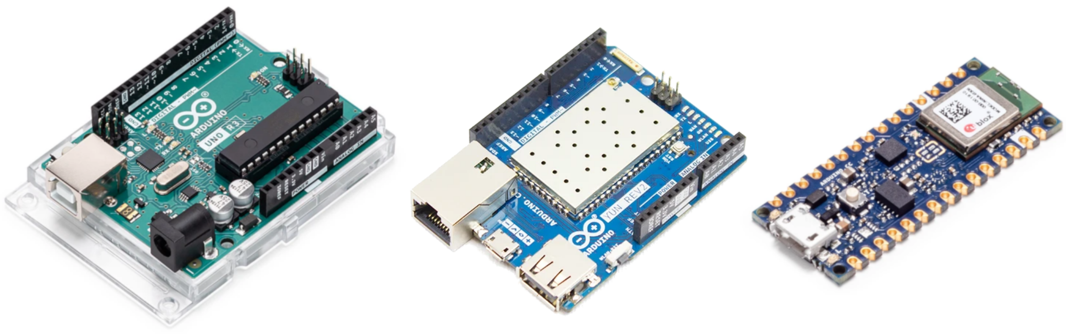

Figure 3.7: Arduino UNO Rev 3 on the left, Arduino Yun in the middle, Arduino Nano 33 BLE on the right

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 (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. 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 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:

[11] https://store.arduino.cc/products/arduino-uno-rev3

- 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.

3.3.2 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 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 [12], board makers have been able to adapt them in their own way.

[12] https://www.raspberrypi.org/documentation/computers/raspberry-pi.html

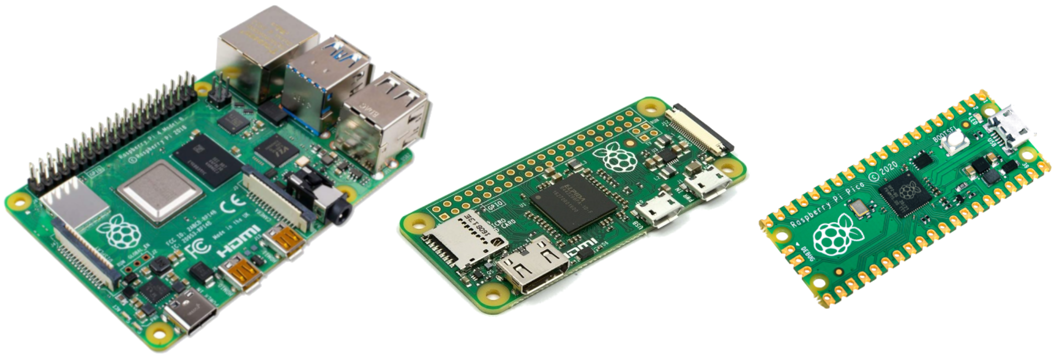

Figure 3.8: Raspberry Pi Model 3B+ on the left, Raspberry Pi Zero in the middle, Raspberry Pi Pico on the right

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" [13];
- Zero: it's the smallest form factor Raspberry Pi on the market;
- Pico: a low-cost, high-performance microcontroller board with flexible digital interfaces.

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 [14].

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.

3.3.3 Pycom

While Raspberry Pi and Arduino share a longer history, Pycom 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 Fig. 3.9, 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.

[13] https://www.raspberrypi.org/products/raspberry-pi-4-model-b/
[14] https://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. As described in the product page [15], 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. 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, the 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 are chosen for the affability 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 2x, which add accelerometer and GPS, and the pysense, which add ambient light, pressure and humidity. Both expansion boards are represented in Fig. 3.9.

As for the programming language, Pycom boards can be programmed using Mycropython 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 2.0 X €40.65
- Pysense €29.65

[15] https://pycom.io/product/fipy/

Although higher than an Arduino board, it is important to consider that these boards offer and 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 [16].

A more in depth description of how the chosen technologies interact is present in chap5.

[16] https://docs.pycom.io/

To succeed, planning alone is insufficient.
One must improvise as well.

Isaac Asimov, Foundation series

4

Related work

Internet of Things is one of the hottest topics in both industry and academia of the communication engineering world. On the other hand, wireless mesh networks, a network topology that has been discuss for decades that haven't been put into use in large scale, can make a difference when it comes to the network in the IoT world today.

This chapter anticipates the one where the actual project is described and shows some related projects from which the open mesh has drawn inspiration.

At first challenges and solutions are presented

Below are also presented some of the projects which have been made at various levels from amateurial projects, to research and to the ones already available on the market.

4.1 Challenges and solutions

The single point of failure nature of these Network 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. Besides, the capacity of the central hub/router of the network can also limit the coverage of the service provided by IoT devices, and the range is also constrained by the same factors.

Energy management

4.2 Overview of wireless mesh networks

4.2.1 Advantages of WMS

4.2.2 Disasvantages of WMS

4.3 Algorithms for Wireless Mesh networks

4.4 Projects

4.4.1 Homemade projects

4.4.2 Research projects

4.4.2.1 LORACTP

4.4.3 Market solutions

Pycom itself has an available mesh network that connects lora devices, compared to the one proposed in this paper thought

Keep
It
Simple
Stupid

5 Proposed solution

5.1 Idea

5.2 Architecture

5.3 Hardware

5.4 Software

The software for this

5.4.1 Algorithms

Finite-state machine

To better understand the algorithms, they are represented using finite state machines. For a graphical reason, each state of the automatas is abbreviated, and the full state is described in a table underneath

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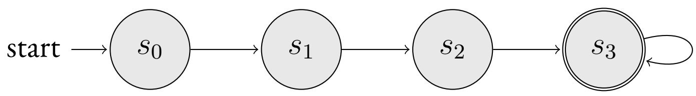
5.4.1.1 Main



State abbreviation	Full state name	State description
s_0		

Table 5.1: Main algorithm fsm description

5.4.1.2 Boot up

5.4.1.3 Mesh initiation

5.4.1.4 Broadcast mesh information

5.4.1.5 Loop

5.5 Use cases

6
Results and experimentation

6.1 Experiments

6.2 Results

7 Conclusions

7.1 Future work

7.1.1 Hardware improvements

7.1.2 Software improvements

7.2 Personal considerations

Acknowledgments

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