Università degli Studi di Padova

Department of Mathematics "Tullio Levi Civita"

Master Thesis in Computer Science

Open LoRa mesh network for IoT-based air quality sensing

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This is a very meaningful dedication

Abstract

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Sommario

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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*"[3]. 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"[4]. 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 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. 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 [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*. 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 [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.

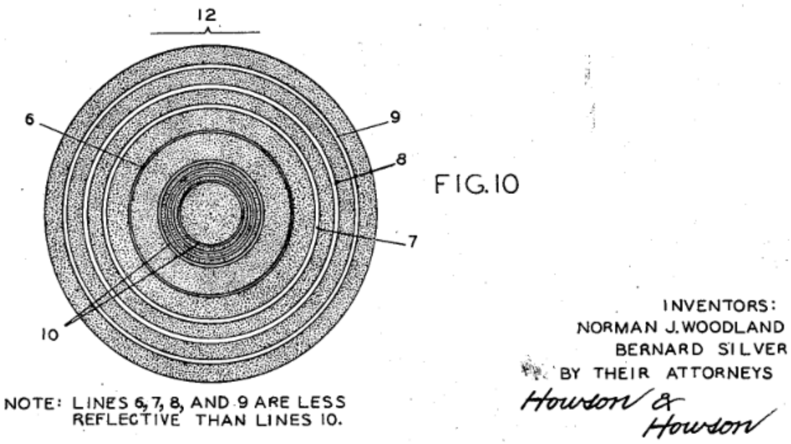


Figure 2.1: Diagrammatic view of the Universal Product Code

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.

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" [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[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.

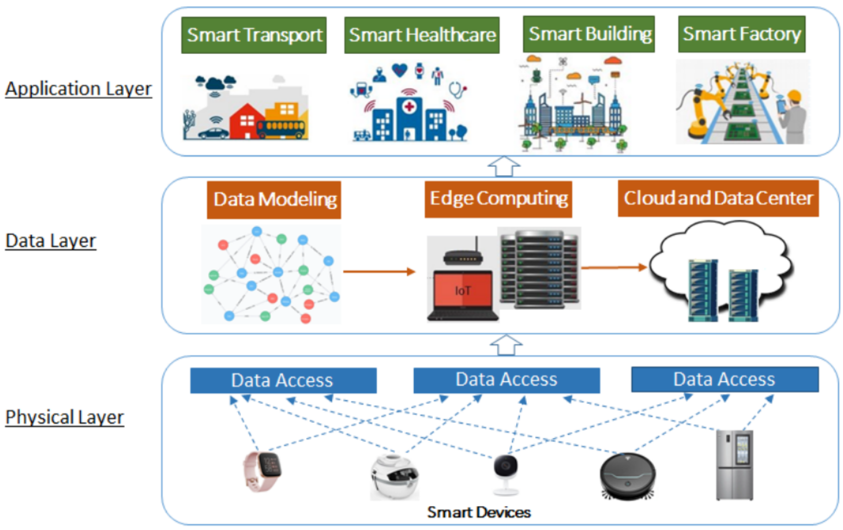


Figure 2.3: IoT research areas according to authors of [1]

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-

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

sions of these are emerging, each fitted for different scenarios, that may range from a fully on-line (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.

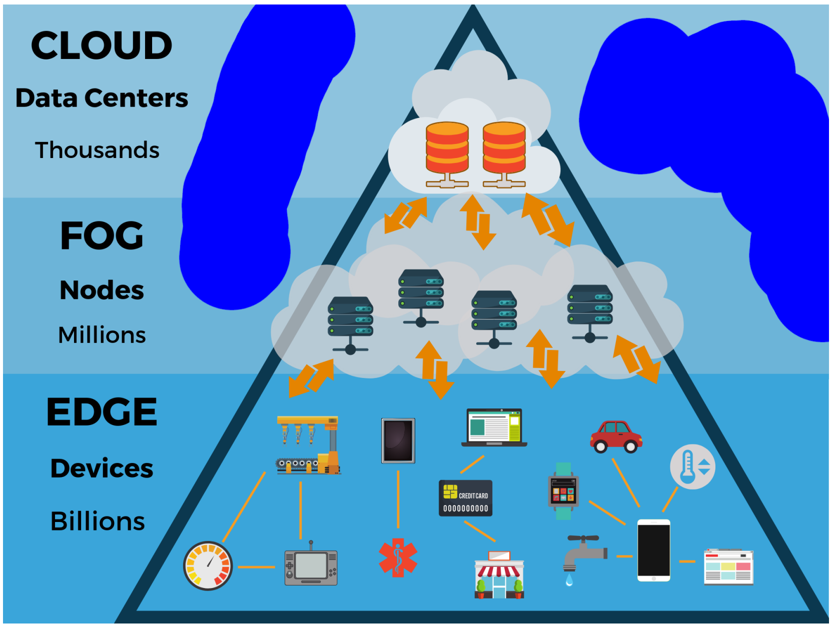


Figure 2.4: Edge, Fog and Cloud Computing

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 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.

[3] 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 [4], 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

[4] 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[5]

2.4.1 Hope

[5] 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 Approaches To 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]

Given the definition of computer network by Paul E. Green, it is easy to understand its importance in today's society. A network of networks is called internetwork, shortened by internet; however, the Internet, with a capital I, is a set of worldwide interconnected networks [15]. Questa distinzione è stata cominciata ad essere fatta / proposta in the beginning of the 1980s[1,2], when computers were becoming more and more accessible not only to to companies and universities, but also in households with the advent of MS-DOS[3], thus ARPANET was expanding and LANs were not enough anymore to accomodate the amount of data travelling from one place to another.

Although from the 1980s, As described in [15], it is possible to divide the Internet such as the following groups of networks:

[1] RFC 871 (1982): A PERSPECTIVE ON THE ARPANET REFERENCE MODEL

[2] RFC 872 (1982): TCP-ON-A-LAN

[3] MS-DOS source code on GitHub

- Backbones: Large networks that exist primarily to interconnect other networks. Also known as network access points (NAPs) or Internet Exchange
- Regional networks connecting, for example, universities and colleges.
- Commercial networks providing access to the backbones to subscribers, and networks owned by commercial organizations for internal use that also have connections to the Internet.
- Local networks, such as campus-wide university networks

Thus came the need for a better structure that could organize at best these components in a more robust, but also flexible, large network.

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"[14]. 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 stack, which is implemented by the TCP/IP stack of protocols. "A protocol is 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."[14]. 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.

Nowadays, the organization responsible for technical management of IETF activities and the Internet standards process is the Internet Engineering Steering Group (IESG)[4].

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

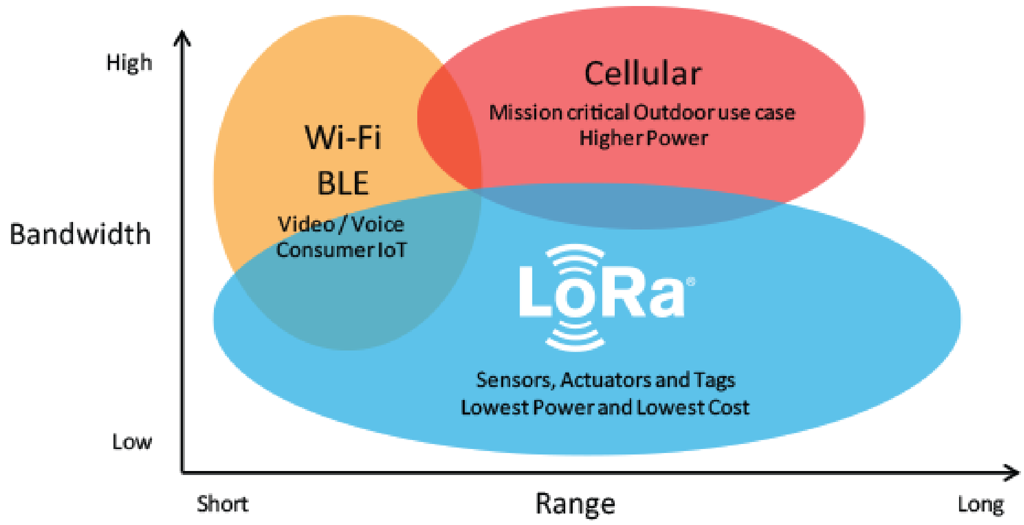


Figure 3.1

WAN vs LAN

WAN technologies, sometimes called long haul networks, provide communication over long distances.

LAN technologies provide the highest speed connections among computers, but sacrifice the ability to span long distances.

Instead, vendors apply the terms loosely to help customers distinguish among technologies.

TCP / IP

3.2 Radio technologies

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.

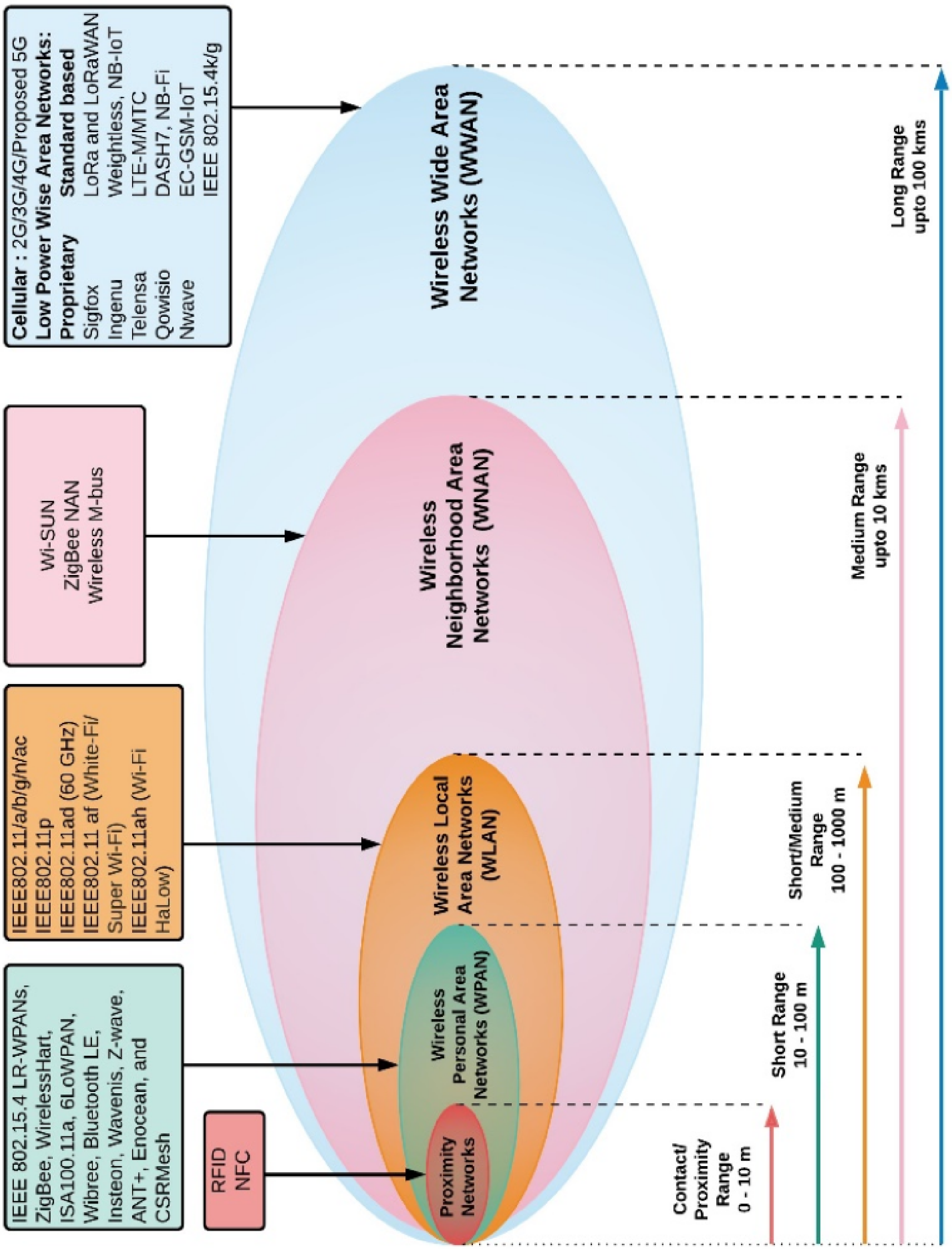
With new transmission technologies, new network architectures have emerged

Distinction of low cost vs higher cost

3.2.1 LoRa

https://lora-alliance.org/

https://www.semtech.com/lora



Cellular : 2G/3G/4G/Proposed 5G
Low Power Wise Area Networks:
Proprietary
Sigfox
Ingenu
Telensa
Qowisio
Nwave
Standard based
LoRa and LoRaWAN
Weightless, NB-IoT
LTE-M/MTC
DASH7, NB-Fi
EC-GSM-IoT
IEEE 802.15.4k/g
Wi-SUN
ZigBee NAN
Wireless M-bus
IEEE802.11/a/b/g/n/ac
IEEE802.11p
IEEE802.11ad (60 GHz)
IEEE802.11 af (White-Fi/ Super Wi-Fi)
IEEE802.11ah (Wi-Fi HaLow)
IEEE 802.15.4 LR-WPANs, ZigBee, WirelessHart, ISA100.11a, 6LoWPAN, Wibree, Bluetooth LE, Insteon, Wavenis, Z-wave, ANT+, Enocean, and CSRMesh
RFID
NFC
Wireless Wide Area Networks (WWAN)
Wireless Neighborhood Area Networks (WNAN)
Wireless Local Area Networks (WLAN)
Wireless Personal Area Networks (WPAN)
Proximity Networks
Long Range upto 100 kms
Medium Range upto 10 kms
Short/Medium Range 100 - 1000 m
Short Range 10 - 100 m
Contact/ Proximity Range 0 - 10 m

Figure 3.2

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 LTE

3.3 LoRa and LoRaWAN

3.4 Hardware (Microcontrollers)

Microcontrollers (or MCUs) are compact integrated circuits designed to govern a specific operation in an embedded system.

Devices and CPUs have become smaller and more granular, allowing to have simple micro computers that need very little power resources, both computational and battery, that they can be used for very specific functions.

Some examples can be:

- smog detector, which sounds an alarm when excess smog is sensed
- car range detector, that sends an alarm to the car's braking system when there is an object in front of it
- etc.

3.4.1 Arduino

3.4.2 Raspberry Pi

Figure 3.3: *Pycom* company logo

Yesterday,
all my troubles seemed so far away
Now it looks as though they're here to stay
Oh, I believe in yesterday. Yesterday,
all my troubles seemed so far away
Now it looks as though they're here to stay

3.4.3 Pycom

Figure 3.4: *Pycom* company logo

Yesterday,
all my troubles seemed so far away
Now it looks as though they're here to stay
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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).

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

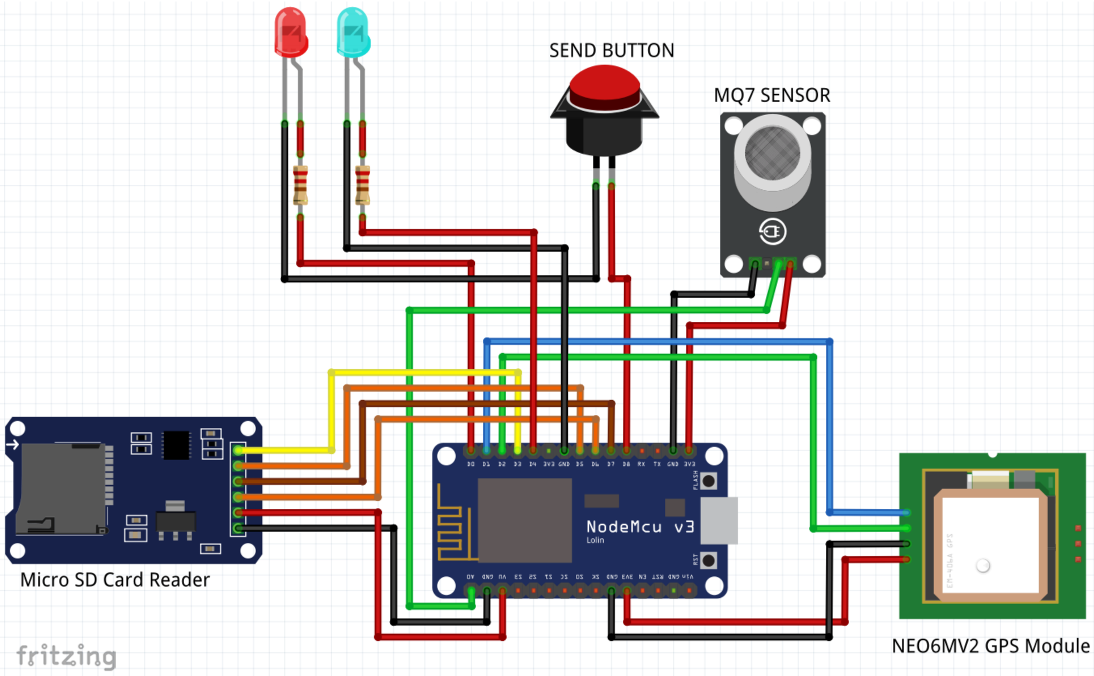

Figure 4.1: Circuit of the ArduECO prototype, as contained in [2]

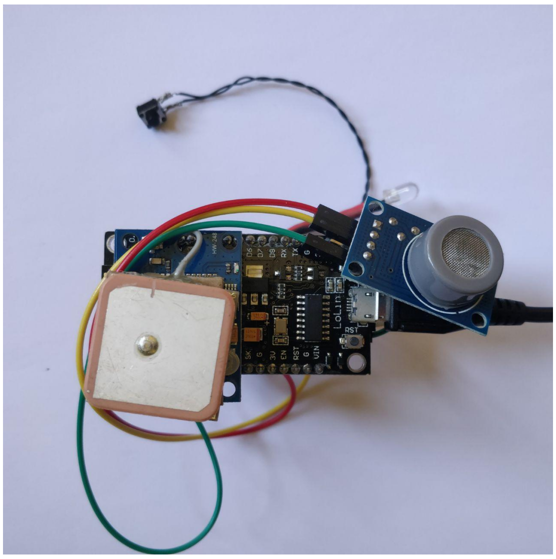

Figure 4.2: ArduECO prototype

5
Proposed solution

5.1 Idea

5.2 Architecture

Describe sensing pipeline

5.3 Hardware

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

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