



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

ACCADEMIC 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

Graduation committee

Claudio Enrico Palazzi

Study programme:

E-mail:

MSc Business Information Technology

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, 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.

Sommario

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.

Preface

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.

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	11
2.3 iot for sensing of air quality	12
2.4 MegaSense	13
2.4.1 Hope	13
3 TECHNOLOGIES	15
3.1 Approaches To Network Communication	15
3.2 Radio technologies	16
3.2.1 LoRa	16
3.2.2 LoRaWAN	16
3.2.3 Bluetooth	16
3.2.4 WiFi	16
3.2.5 LTE	18
3.3 LoRa and LoRaWAN	18
3.4 Hardware (Microcontrollers)	18
3.4.1 Arduino	18
3.4.2 Raspberry Pi	18

3.4.3	Pycom	18
4	RELATED WORK	21
4.1	Solutions to detect air pollution	21
4.2	Megasense	21
5	PROPOSED SOLUTION	23
5.1	Idea	23
5.2	Architecture	23
5.3	Hardware	23
5.4	Software	23
5.5	Use cases	23
6	RESULTS AND EXPERIMENTATION	25
6.1	Experiments	25
6.2	Expected results	25
6.3	Results	25
7	CONCLUSIONS	27
7.1	Future work	27
7.2	Improvements to the hardware	27
7.3	Personal considerations	27
A	USER MANUAL	29
B	GLOSSARY OF TERMS AND ABBREVIATIONS	31
	ACKNOWLEDGMENTS	32
	REFERENCES	35
	GLOSSARY	37

List of figures

2.1	<i>“Diagrammatic view showing an embodiment of the invention”</i>	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	16
3.2	17
3.3	<i>Pycom</i> company logo	18
3.4	<i>Pycom</i> company logo	18
4.1	Circuit of the ArduECO prototype, as contained in [2]	22
4.2	ArduECO prototype	22

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 CO₂ 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 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 of 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 can be found in chapter 4, where previously made projects developed in the context of air quality monitoring 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, *Protector & Gamble*, in 1999 [5] to describe the network connecting objects in the physical world to the Internet.

This constantly expanding area of Computer Science aims to turn physical objects, as small as they may be, into nodes of an interconnected system that opens the door to new interfaces between humans and machines and how these see the physical world.

Its importance heavily relies on the data gathered from these devices, since, in combina-

tion with other paradigms such as machine learning and AI, it can be transformed into usable information. The creation of models from all these inputs have given a more efficient workflow in companies, with Industry 4.0 and IIoT, and has improved certain aspects of everyday life, with technologies such as wearables, used to enhance quality of life.

2.1.1 UNIVERSAL PRODUCT CODE AND BARCODE

One of the first technologies that can be considered as IoT, 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 the super market.

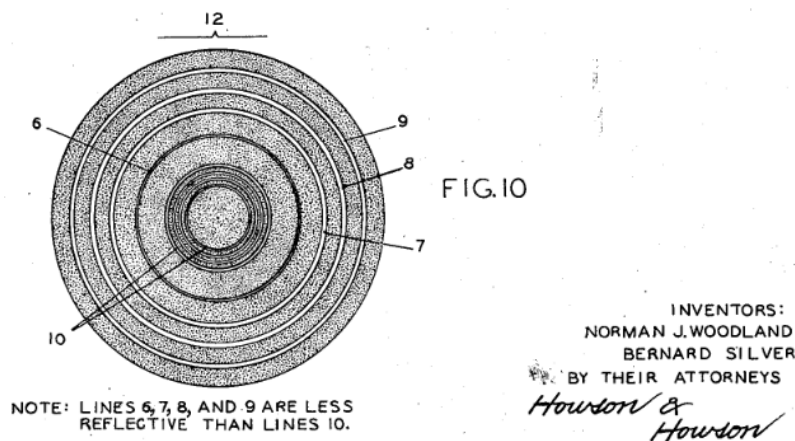


Figure 2.1: “Diagrammatic view showing an embodiment of the invention”

Although, due to the large size and low reliability of equipment, this concept has not been immediately introduced to the public.

The first widespread appearance ...

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]. Adoption relied on emergence of laser optics, developed around the same time, as these offered 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. 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 website¹ 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 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

¹https://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 Academic², 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.

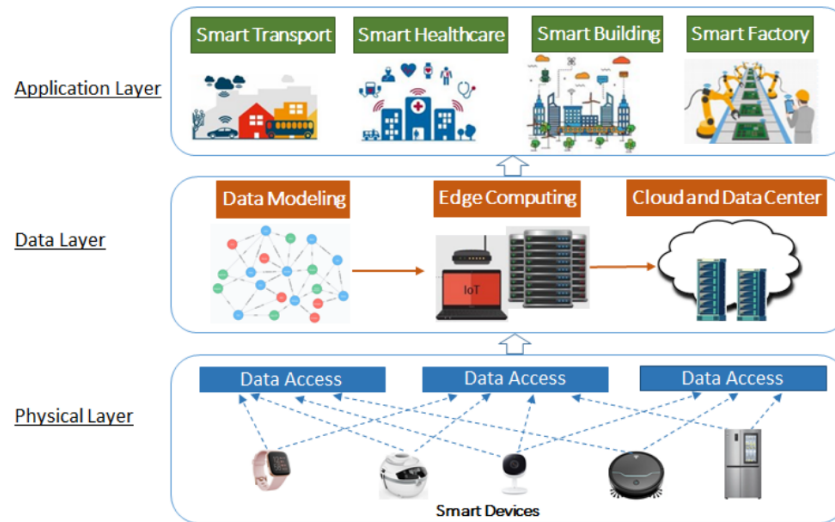


Figure 2.3: IoT research areas according to authors of [1]

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 Core³) 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.

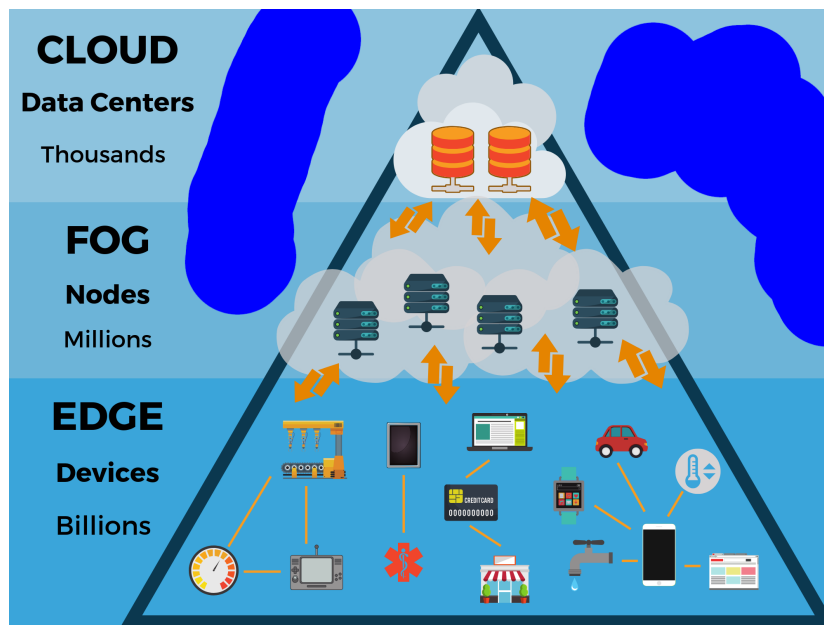


Figure 2.4: Edge, Fog and Cloud Computing

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

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 that IoT is an enabler for AI, since many companies “view IoT and AI as two components

⁴<https://www.arm.com/>

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 MEGA**SENSE**

MegaSense, developed at the University of Helsinki's department of Computer Science⁵

2.4.1 HOPE

⁵text

3

Technologies

To fully understand the project and the choices behind it, is worth taking a look at some background technology which can be useful to know before proceeding further into this thesis. In this chapter we describe DTNs, the notion of peer-to-peer and overlay networks. internetworking [14]

3.1 APPROACHES TO NETWORK COMMUNICATION

connection oriented vs connectionless

Despite the potential drawback of not being able to guarantee network capacity, connectionless networks have become extremely popular.

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.

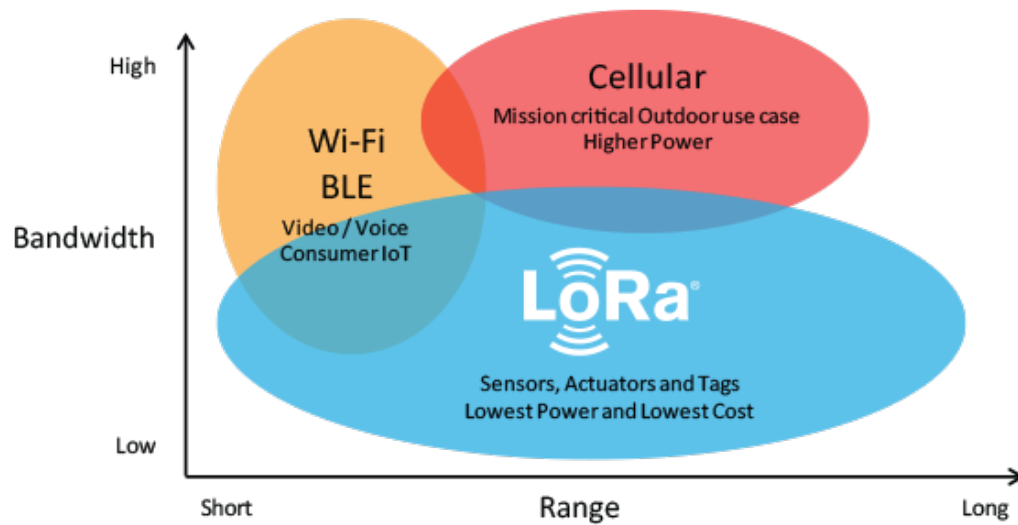


Figure 3.1

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>

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

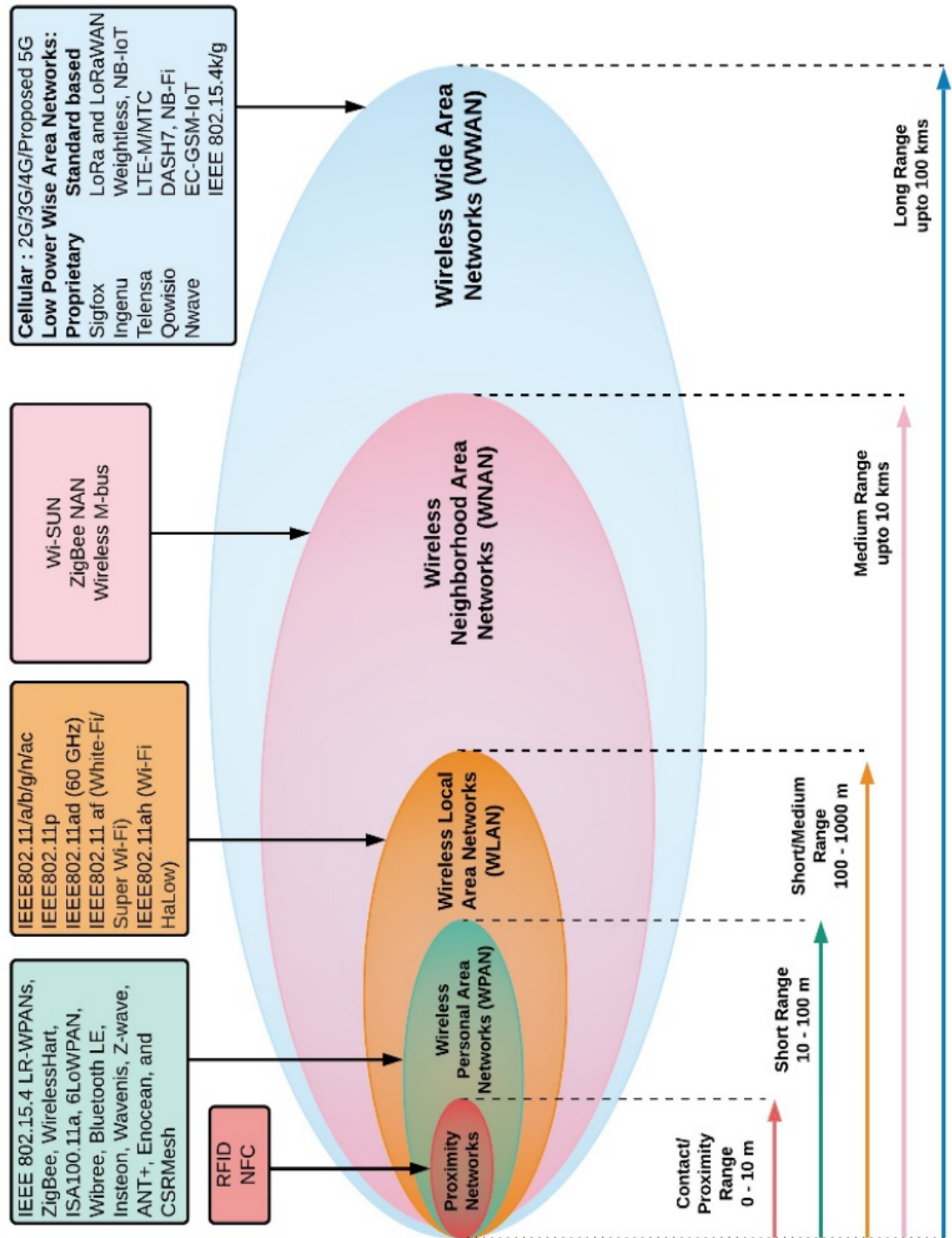


Figure 3.2

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

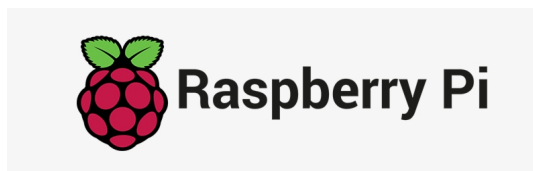


Figure 3.3: Pycom company logo

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

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 in this thesis, this chapter better 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

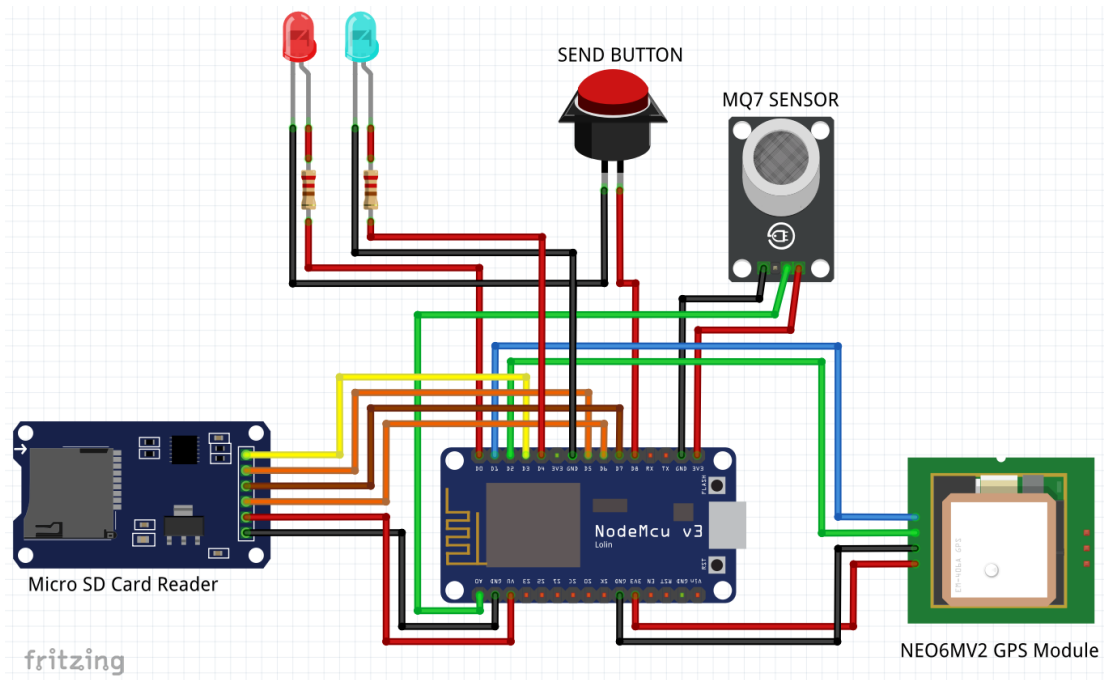


Figure 4.1: Circuit of the ArduECO prototype, as contained in [2]

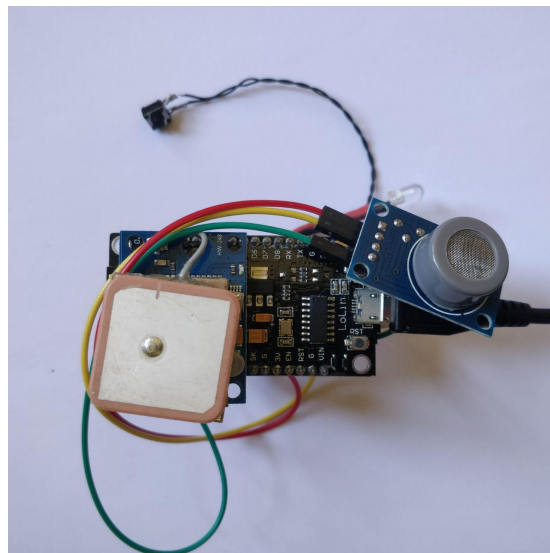


Figure 4.2: ArduECO prototype

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 EXPECTED RESULTS

6.3 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



User Manual

B

Glossary of terms and abbreviations

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.

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 smart-phone 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] D. E. Comer and D. L. Stevens, *Internetworking with TCP/IP: Principles, Protocols, and Architecture*, 3rd ed. USA: Prentice Hall PTR, 1995.

THIS THESIS WAS TYPESET using \LaTeX , originally developed by Leslie Lamport and based on Donald Knuth's \TeX . 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 or from its lead author, Jordan Suchow, at suchow@post.harvard.edu.