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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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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 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 its highest peaks.

Many publications have been studying the development of low-cost devices, focused on analyzing the quality of the surroundings of individual. This thesis takes a focus on a particular project, MegaSense, a personal air quality device developed by the University of Helsinki.

In this thesis, the architecture for connecting such devices is expanded with the use of LoRa and with the evaluation of other use cases.

1.1 CONTRIBUTIONS

The contributions that the work described in this thesis are multiple

1.2 DOCUMENT OUTLINE

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

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

2

Background

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

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

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

2.1 INTERNET OF THINGS

IoT, which stands for Internet of Things, has a longer history than many people think about. Its name, which is now known all around the globe, has been attributed to *Kevin Ashton*, who used it in a presentation about radio frequency identification (RFID) technology, at *Protector & Gamble*, in 1999 [5] to describe the network connecting objects in the physical world to the Internet.

This constantly expanding branch of Computer Science aims to turn physical objects, as small as they may be, into nodes of an interconnected system which opens the door to new interfaces between humans and machines and how these see the physical world. Its importance heavily relies on data gathered from these devices, since, in combination with other

paradigms such as machine learning and Artificial Intelligence, this can be transformed into valuable information. The creation of models from all these inputs has given a more efficient workflow in companies and has improved certain aspects of everyday life, with wearable technologies used to enhance quality of life.

2.1.1 UNIVERSAL PRODUCT CODE AND BARCODE

One of the first technologies that can be considered part of the IoT family, is the “*Universal Product Code*”, or *UPC*. Its first iteration is detailed in the patent issued to inventors Joseph Woodland and Bernard Silver on October 7, 1952, and can be described as a “bull’s eye” symbol, made up of a series of concentric circles [6], as can be seen in Figure 3.2.

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

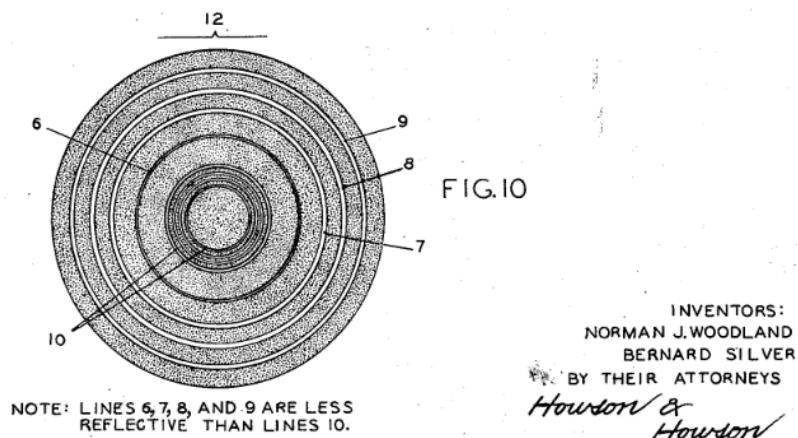


Figure 2.1: Diagrammatic view of the Universal Product Code

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

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

Only later, in

The first widespread

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

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

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

2.1.2 CMU's COKE MACHINE AND MODERN VENDING MACHINES

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



One of the most famous and most quoted as the first IoT device, is the Carnegie Mellon University (CMU) coke machine at the Computer Science Department. Communication from and to the machine, which allowed remote access, took place via Arpanet at CMU as the system predated the Internet.

Figure 2.2: CMU's “coke machine”

Various sensors were used to detect whether shelves were empty and to track status of coke bottles (warm, cold, empty).

As explained in the official 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 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 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.

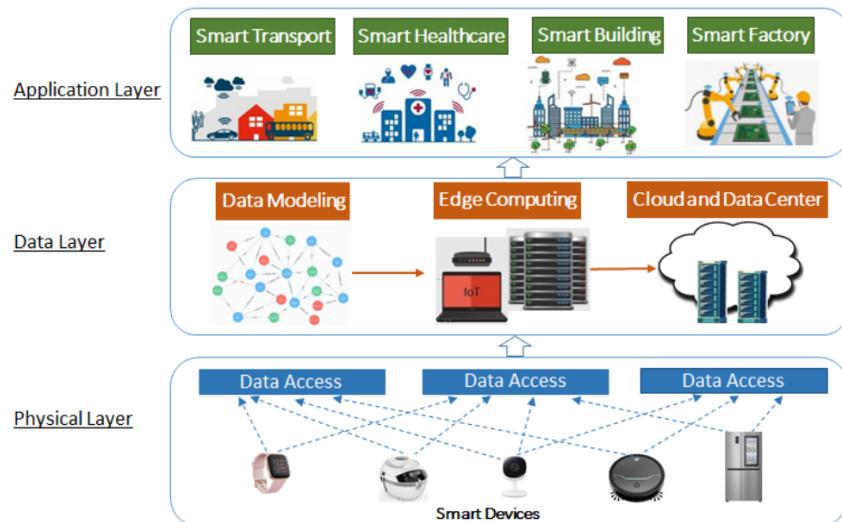


Figure 2.3: IoT research areas according to authors of [1]

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 online (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.

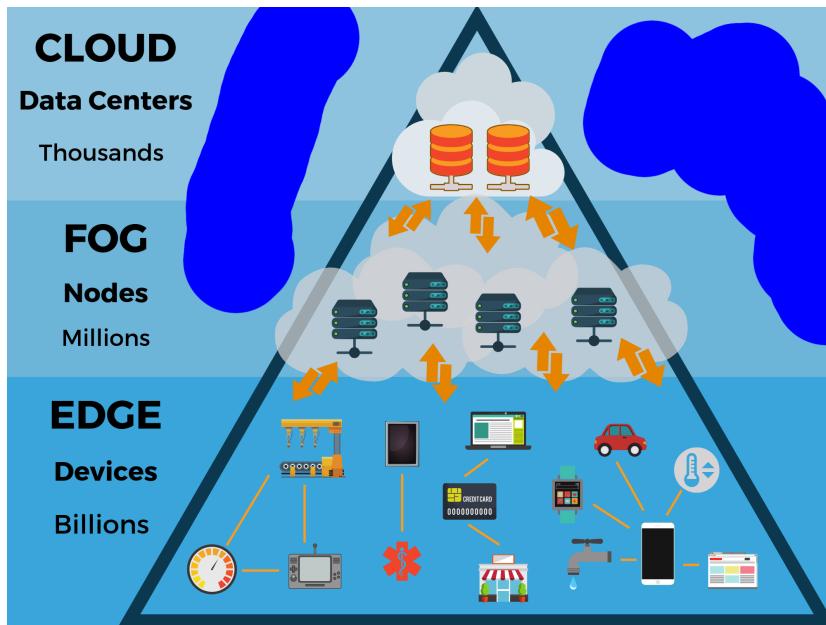


Figure 2.4: Edge, Fog and Cloud Computing

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
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 Science⁵

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 FUNDAMENTALS OF NETWORK COMMUNICATION

“A computer network is a structure that makes available to a data processing user at one place some data processing function or service performed at another place.” [14]

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

While this raw data is important for computers, people, the final users, process it to gain information, and this exchange of information from all around the world has brought radical changes many levels, from a cultural point of view to an economic point of view. The possibility of having a network of information exchange is the next step of globalization, which started with the exchange of goods among countries and now brings everyone together, allowing for a cultural exchange that lets people share and unite across the globe.

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

It is important to note that Internet, with a capital I, is a particular set of worldwide interconnected networks [15], but a common network of networks is called internetwork, shortened by internet, with a lowercase i.

Such distinction began in the 1980s and has been described in RFCs^{1,2} by computer scientists that understood how ARPANET was expanding and its dimensions were not enough anymore to accommodate the amount of data traveling from one computer to another. At that time, computers such as the IBM 5150 and the infamous Commodore 64 were starting to become more and more available, even if highly priced, not only to companies and universities, but also to consumers that brought them in their households, especially with the advent of MS-DOSs, the dominant operating system throughout the 1980s and now open source³.

As described by IBM in one of their technical books from the time, "it is possible to divide the Internet such as the following groups of networks" [15]:

- Backbones: large and strategical data routes among core networks and routers that compose and connect the Internet;
- Regional networks that connect large facilities such as universities and colleges to each other;
- 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>

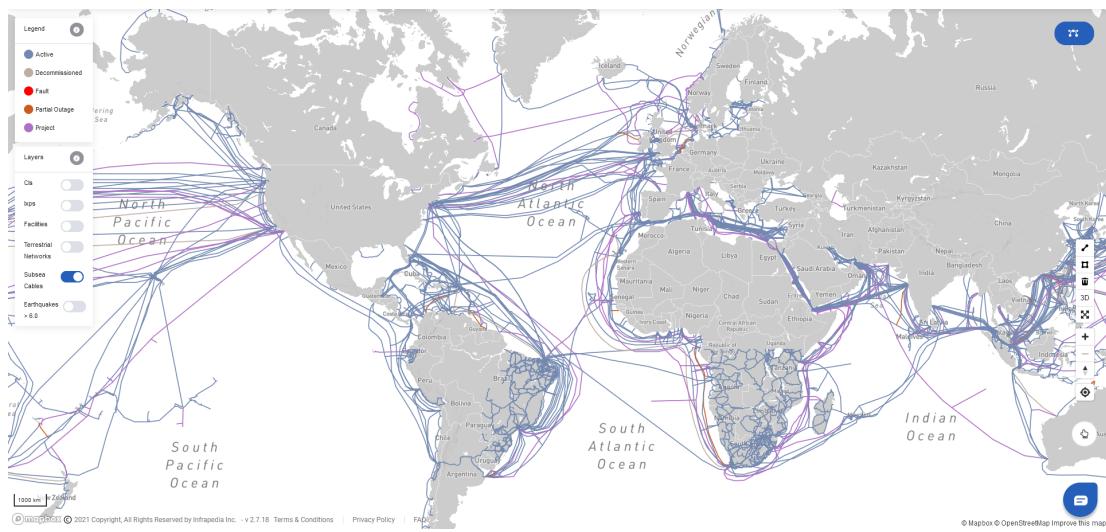


Figure 3.1: Subsea Internet backbone cables between US and Europe.⁴

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.

There is no need for the 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.

It is important to understand the difference between network architecture and network topology.

A network architecture, as described by Paul E. Green, “is a complete definition of all the layers necessary to build the network”[14]. This is focused on the network software, which needs to be highly structured in order to allow for heterogeneous systems to communi-

⁴<https://www.infrapedia.com/app>

cate with each other. One example of network architecture is the ISO/OSI reference model, 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.

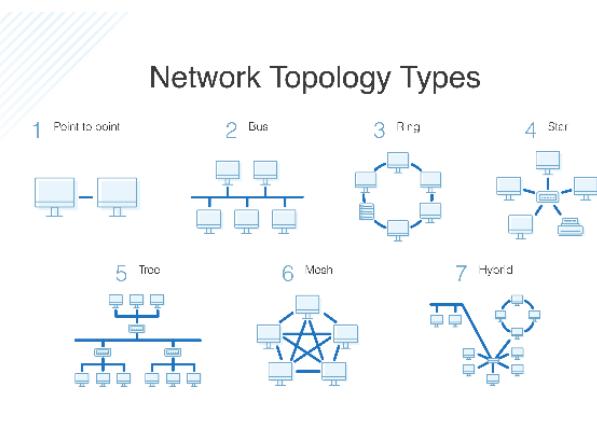


Figure 3.2: Diagrammatic view of the Universal Product Code

dot com bubble

Nowadays, the organization responsible for technical management of IETF activities and the Internet standards process is the Internet Engineering Steering Group (IESG)⁵. 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.

Networks can be categorized based on their span. Instead, vendors apply the terms loosely to help customers distinguish among technologies.

- WAN: WAN technologies, sometimes called long haul networks, provide communication over long distances.
- MAN
- LAN: LAN technologies provide the highest speed connections among computers, but sacrifice the ability to span long distances.

⁵ <https://www.ietf.org/about/groups/iesg/>

- PAN

breve definizione di cloud

In this thesis the mesh network that is described è contenuta nella categoria delle LAN / WAN in quanto

Inoltre, come verrà spiegato nel paragrafo successivo, è una rete che usa un mezzo trasmissivo radio a bassa energia, chiamata LPWAN ...

3.2 RADIO TECHNOLOGIES

Although Guglielmo Marconi is usually credited as the inventor of radio due to the creation of the first commercially successful wireless communication system, many scientists before him have studied radio waves.

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

The discovery of electromagnetic waves, including radio waves, by Heinrich Rudolf Hertz in the 1880s came after theoretical development on the connection between electricity and magnetism that started in the early 1800s.

Other important experiments were made by Nikola Tesla

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

In order to give a complete picture of radio transmitting technologies, it is important to make a distinction among the ones that are made for internal or nearby use vs the ones that are used for longer distances.

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

With new transmission technologies, new network architectures have emerged

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

LAN MAN and WAN are not enough anymore to describe the new topologies

An important distinction is now made by other factors such as POWER, COST and RANGE of the transmitter receiver

Distinction of low cost vs higher cost

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

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

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

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

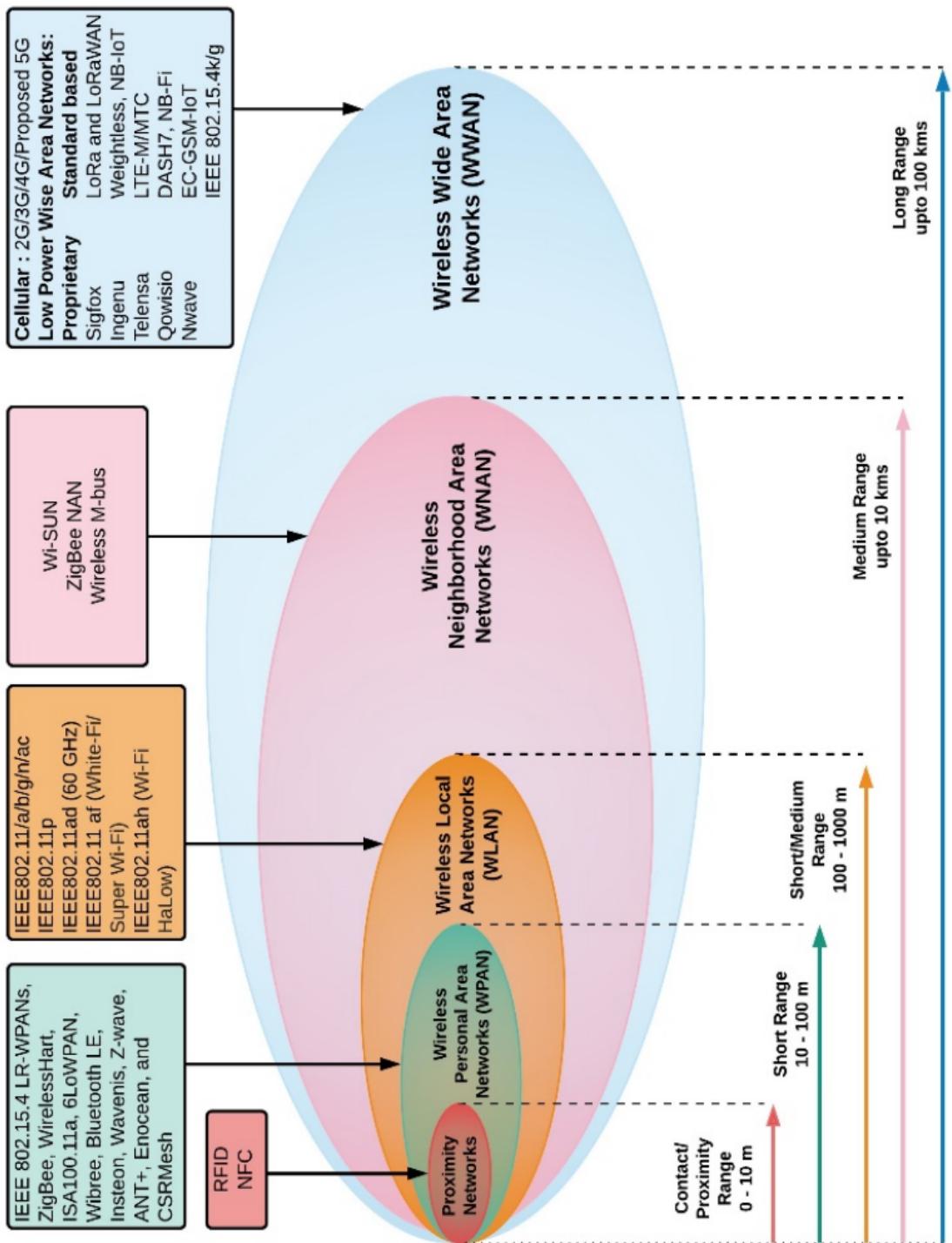


Figure 3.3

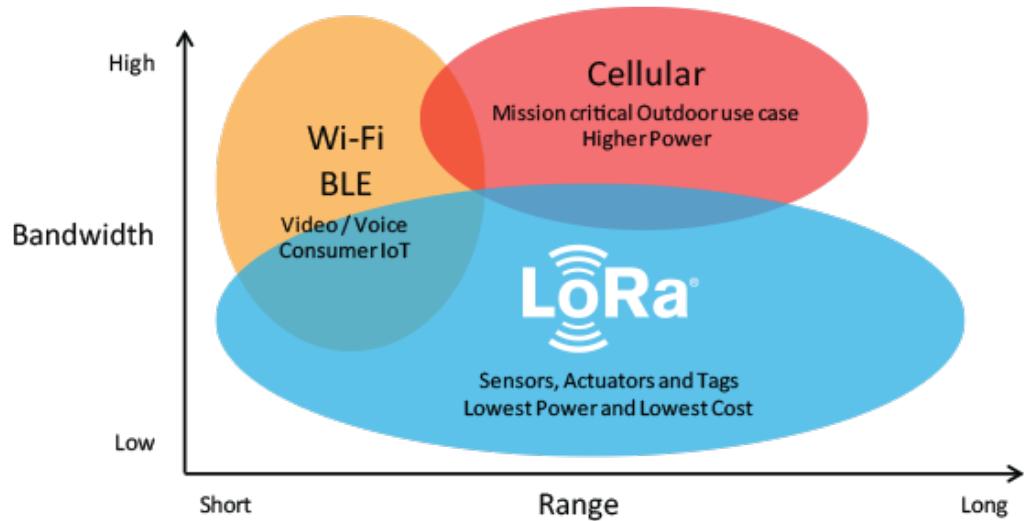


Figure 3.4

3.2.1 LoRA

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

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

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

3.2.2 LoRAWAN

3.2.3 BLUETOOTH

3.2.4 WiFi

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

3.2.5 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.

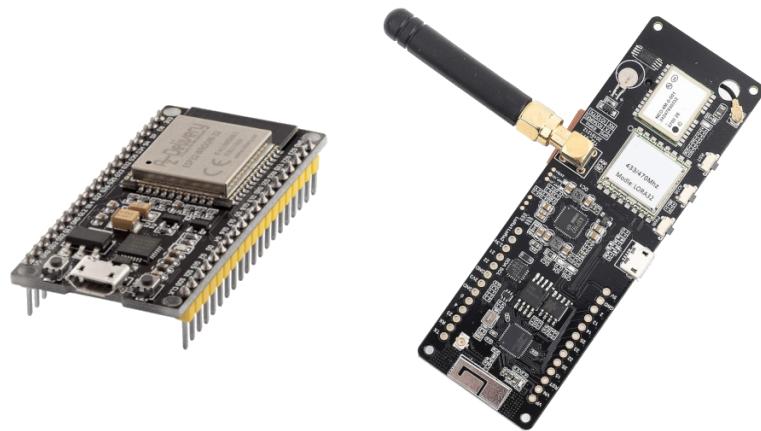


Figure 3.5

(MCU for microcontroller unit)

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

First commercially available microcontroller

In 2005, was developed by Massimo Banzi Et Al. in Ivrea, Italy.

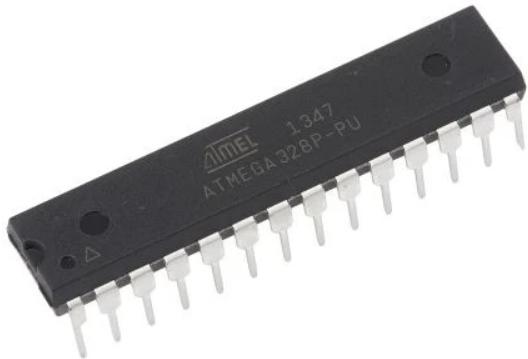
They wanted a device that was simple, easy to connect to various things (such as relays, motors, and sensors), and easy to program. It also needed to be inexpensive, as students and artists aren't known for having lots of spare cash.

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." The result was the Arduino.

The most famous version is the UNO, The UNO is the most used and documented board of the whole Arduino family.

This board does not provide any sensors or ports for external connectivities. The current revision of the board provides

Arduino Uno is based on the ATmega328 by Atmel. The Arduino Uno pinout consists of 14 digital pins, 6 analog inputs, a power jack, USB connection and ICSP header.



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

Figure 3.6: company logo

Per quanto riguarda il linguaggio di programmazione... be programmed in C and C++ programming languages using a special software called Arduino IDE

Many shields that add various functionalities have been developed for this board, some examples are : motor shield, ecc.

La scelta di rendere le schematiche di arduino open source ha favorito la nascita di nuove board con capacità simili ma da produttori diversi Inoltre i maker sono stati in grado di strip down to the single components when needed Questa scelta è rimasta nel tempo in quanto anche per i nuovi prodotti è possibile scaricare il datasheet con le specifiche di come sono legati i componenti tra di loro

Newer arduino boards offrono queste funzionalità integrate, ad esempio Arduino MKR NB 1500 contiene Arduino WiFi 1010 Arduino Nano 33 BLE Sense

In particolare quest'ultimo è stato considerato per il progetto, tuttavia è stato scartato in quanto

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

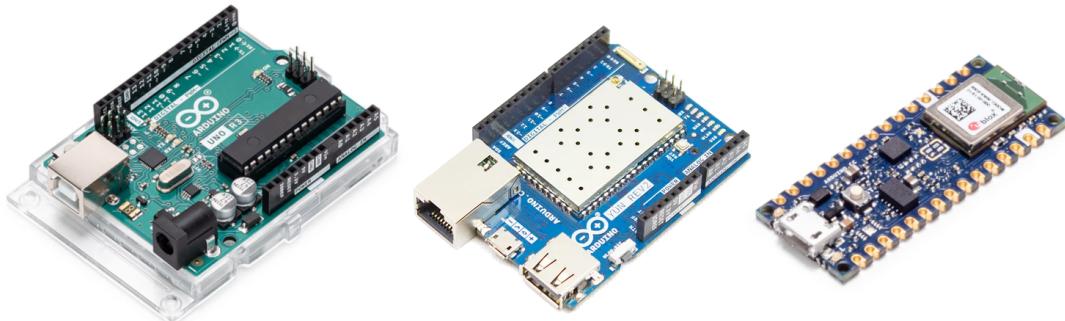


Figure 3.7

3.4.2 RASPBERRY PI

The Raspberry Pi is a tiny and affordable computer that you can use to learn programming through fun, practical projects

When compared to the Arduino, the Raspberry pi offers more functionalities, since it's architecture

Raspberry Pi and Arduino are two very popular boards among electronics DIY builders, hobbyists and even professionals. Raspberry Pi and Arduino are quite different boards. While Arduino is aimed at quick programming and circuit prototyping, Raspberry Pi acts as a learning tool for Computer Programming

The Raspberry Pi was 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. While Arduino is a Microcontroller based development board, the Raspberry Pi is a Microprocessor (usually an ARM Cortex A Series) based board that acts as a computer.

You can connect several peripherals like a Monitor (through HDMI or AV Port), Mouse and Keyboard (through USB), connect to internet (through Ethernet or Wi-Fi), add a Camera (through the dedicated Camera Interface), just like we do to our desktop computer.

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.

Another important thing about Raspberry Pi is, as it is a Linux based Computer, you can develop software using several Programming Languages like C, C++, Python, Java, HTML, etc.

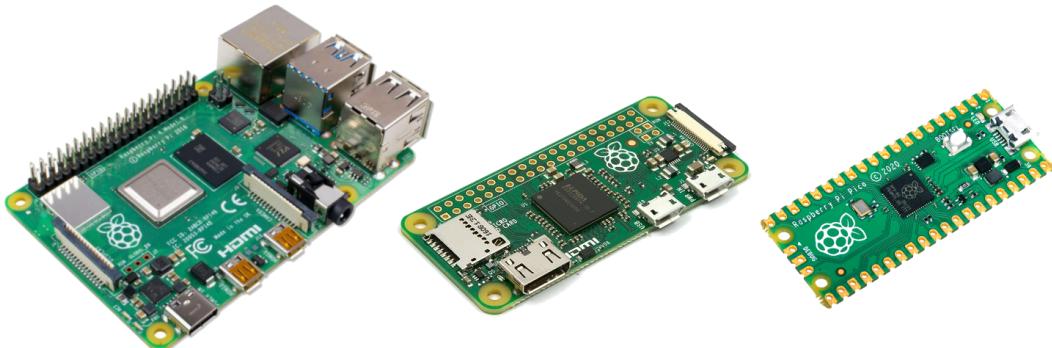


Figure 3.8

As the Arduino, there are different versions of raspberry pi, each one serving different scopes

spiegare quali sono

Come mai non è stato scelto raspberry pi

3.4.3 PYCOM

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

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

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

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

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

4

Related work

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

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

4.1 SOLUTIONS TO DETECT AIR POLLUTION

ArduECO

4.2 MEGASENSE

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

Describe the consortium

HOPE and Megasense

The calibration of the megasense device is made via

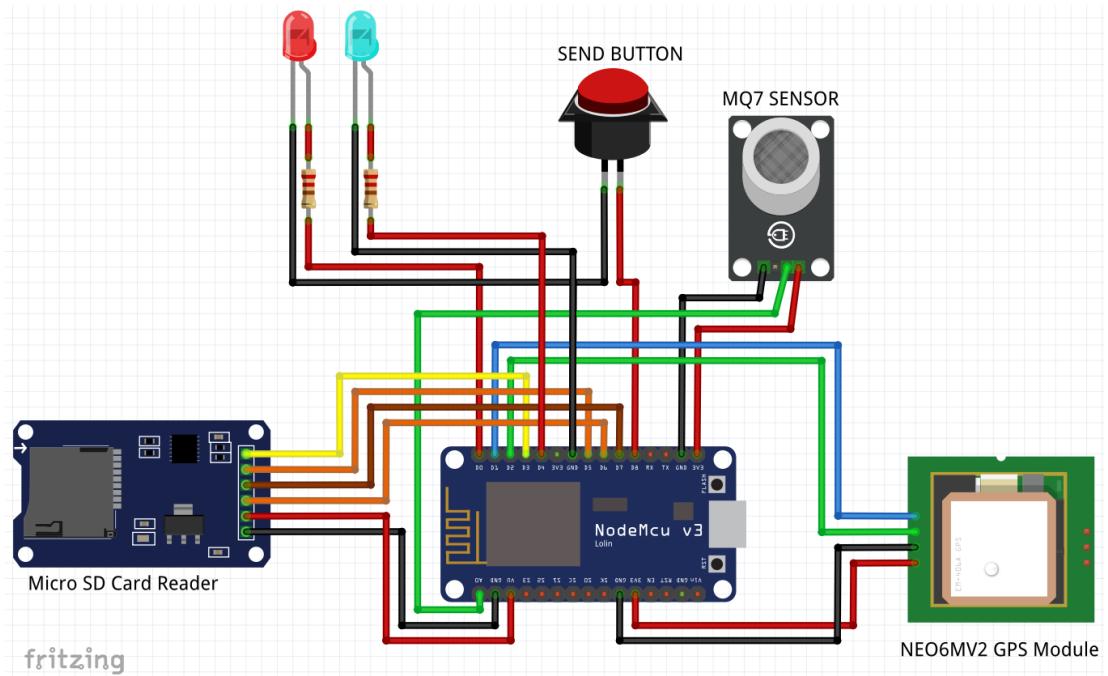


Figure 4.1: Circuit of the ArduECO prototype, as contained in [2]

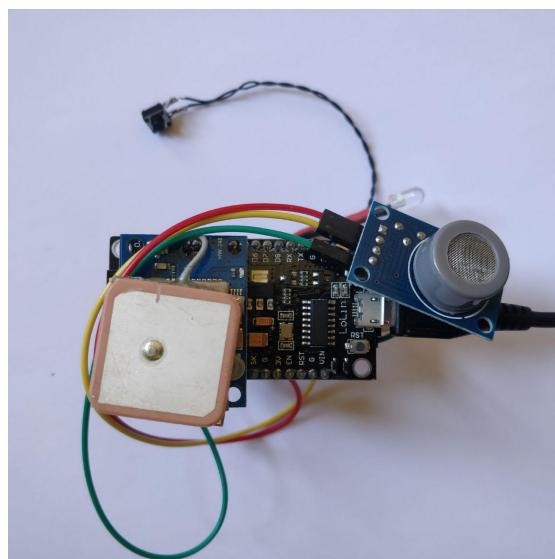


Figure 4.2: ArduECO prototype

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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