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MASTER THESIS IN COMPUTER SCIENCE

OPEN LoRA MESH NETWORK FOR IoT-BASED AIR QUALITY SENSING

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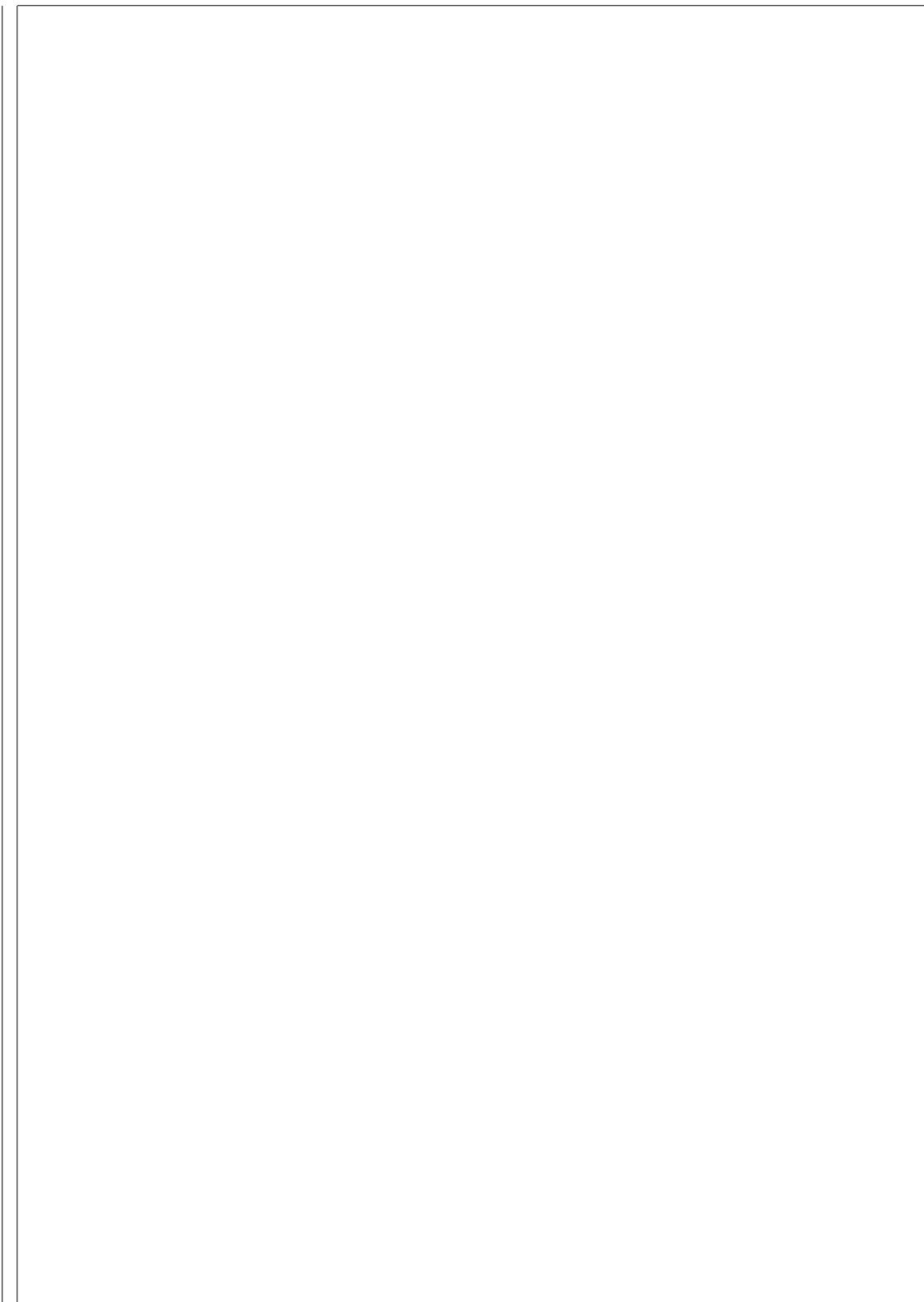
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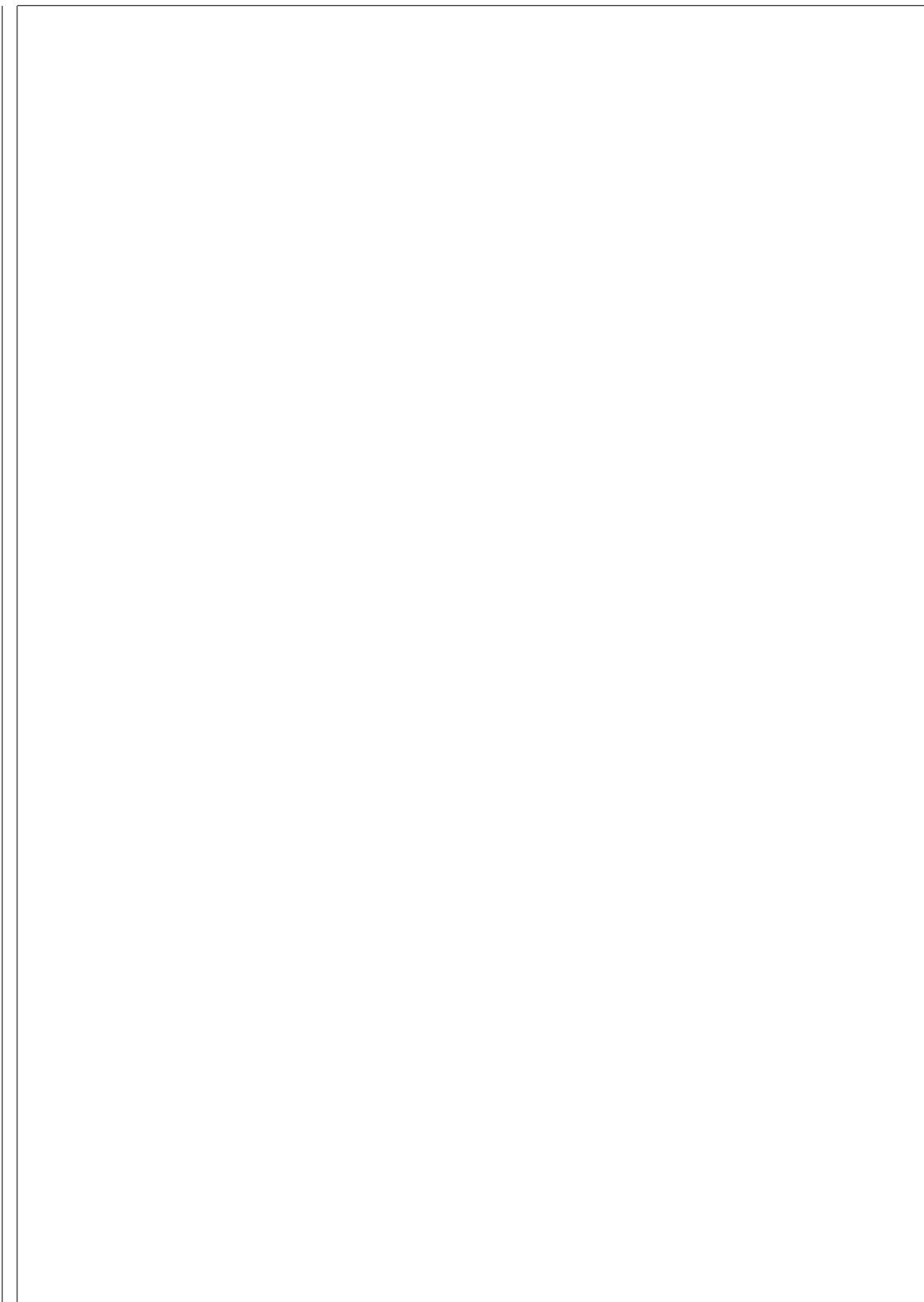
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cosmopolitan adjective

 Save Word

cos·mo·pol·i·tan | \,käz-mə-pä-lə-tən \ 

Essential Meaning of *cosmopolitan*

- 1 : showing an interest in different cultures, ideas, etc.
// cosmopolitan [=worldly, sophisticated] writers
*// Greater cultural diversity has led to a more *cosmopolitan* attitude among the town's younger generations.*
*// the *cosmopolitan* taste/sophistication of the store's customers*
- 2 : having people from many different parts of the world
*// It's one of the country's more *cosmopolitan* cities.*
*// the community's *cosmopolitan* atmosphere*

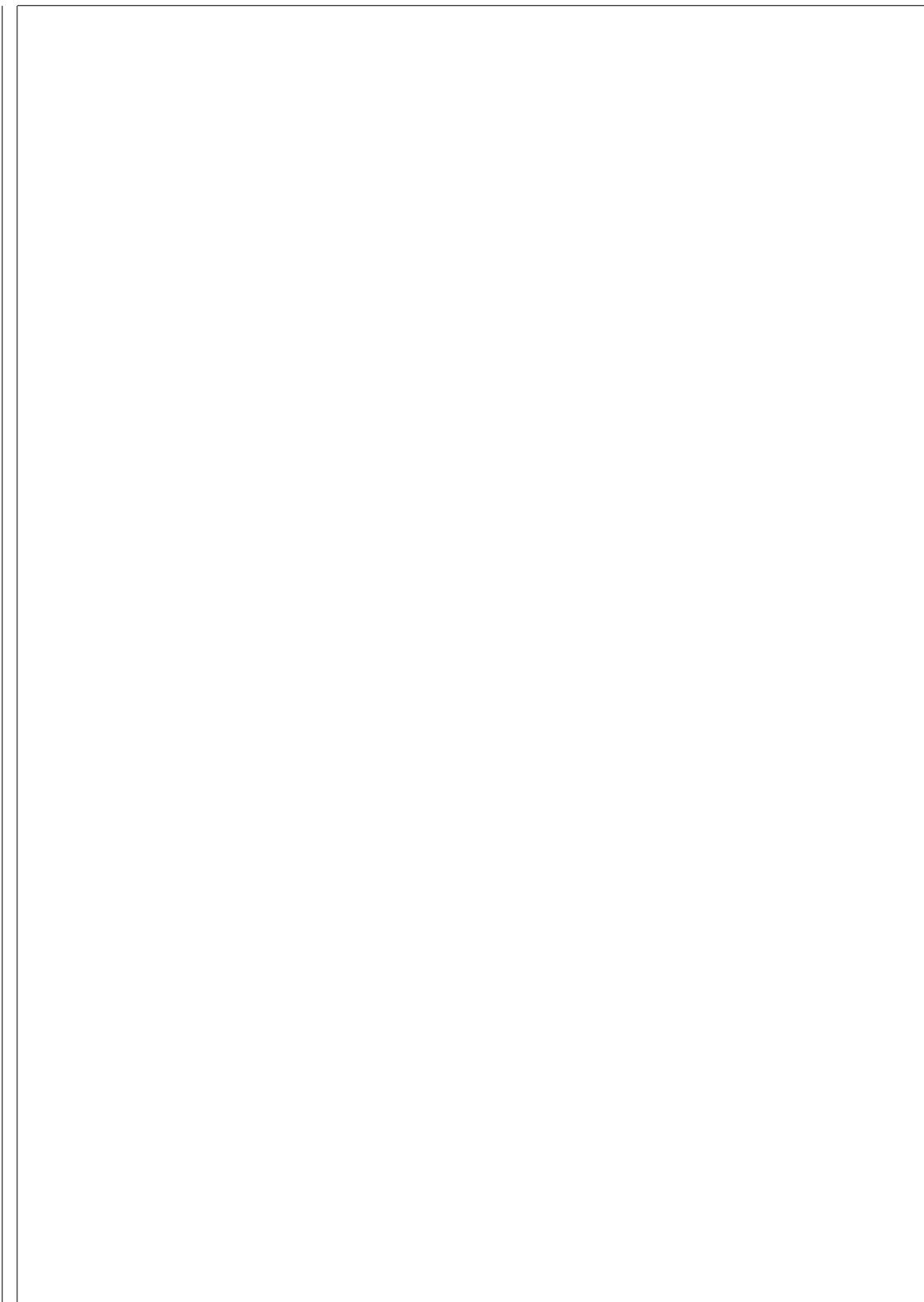
Full Definition of *cosmopolitan* (Entry 1 of 2)

- 1 : having wide international sophistication : **WORLDLY**
*// Greater cultural diversity has led to a more *cosmopolitan* attitude among the town's younger generations.*
- 2 : composed of persons, constituents, or elements from all or many parts of the world
*// a city with a *cosmopolitan* population*
- 3 : having worldwide rather than limited or provincial scope or bearing
*// ... his *cosmopolitan* benevolence, impartially extended to all races and to all creeds.*
— Thomas Babington Macaulay
- 4 : found in most parts of the world and under varied ecological conditions
*// a *cosmopolitan* herb*

cosmopolitan noun

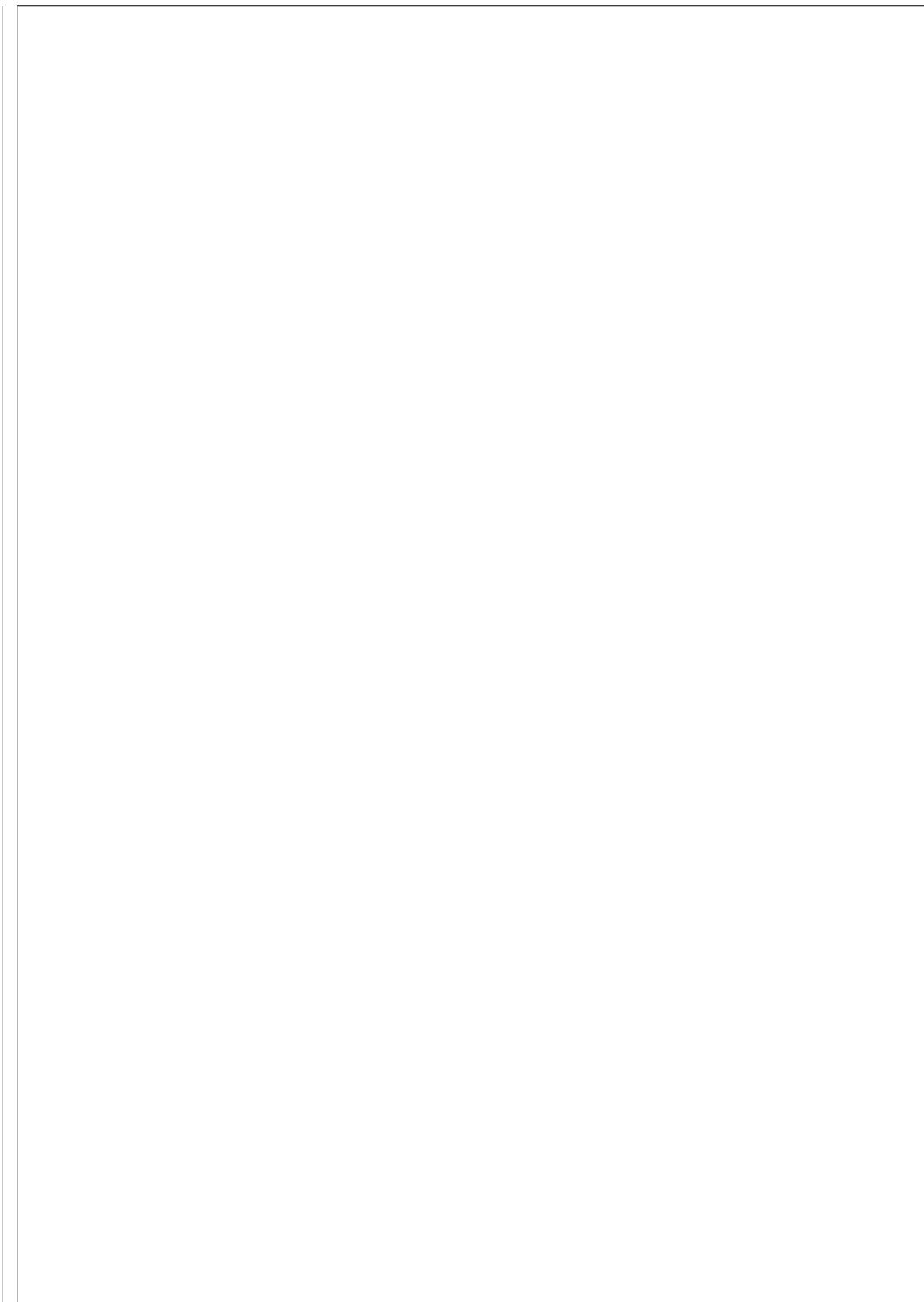
Definition of *cosmopolitan* (Entry 2 of 2)

- 1 : **COSMOPOLITE**
*// Many *cosmopolitans* around the world now also share the English language ...*
— Robert J. Shiller
- 2 : *or less commonly* **cosmo** \ käz-(,)mō \ : a cocktail made of vodka, orange-flavored liqueur, lime juice, and cranberry juice



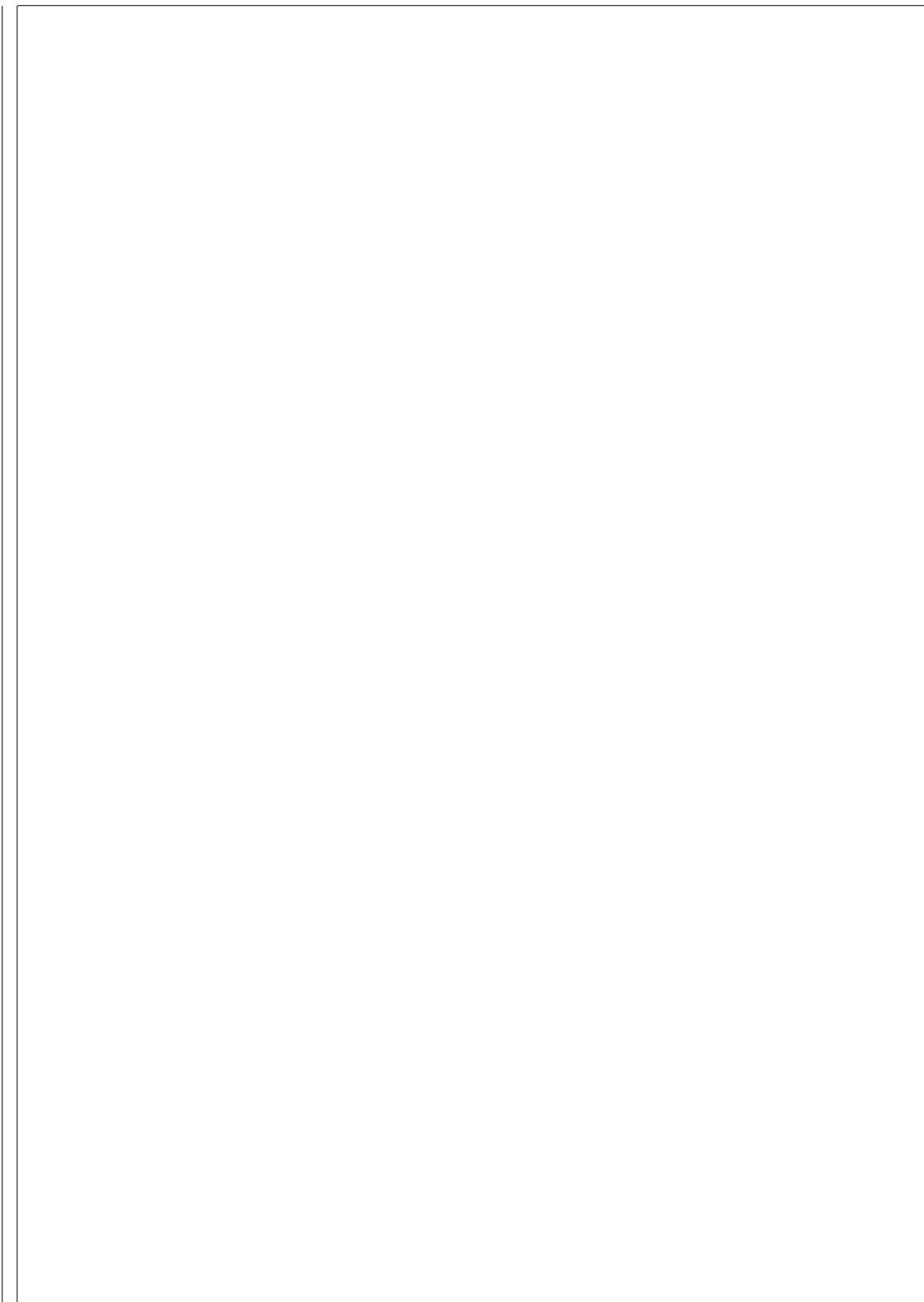
Abstract

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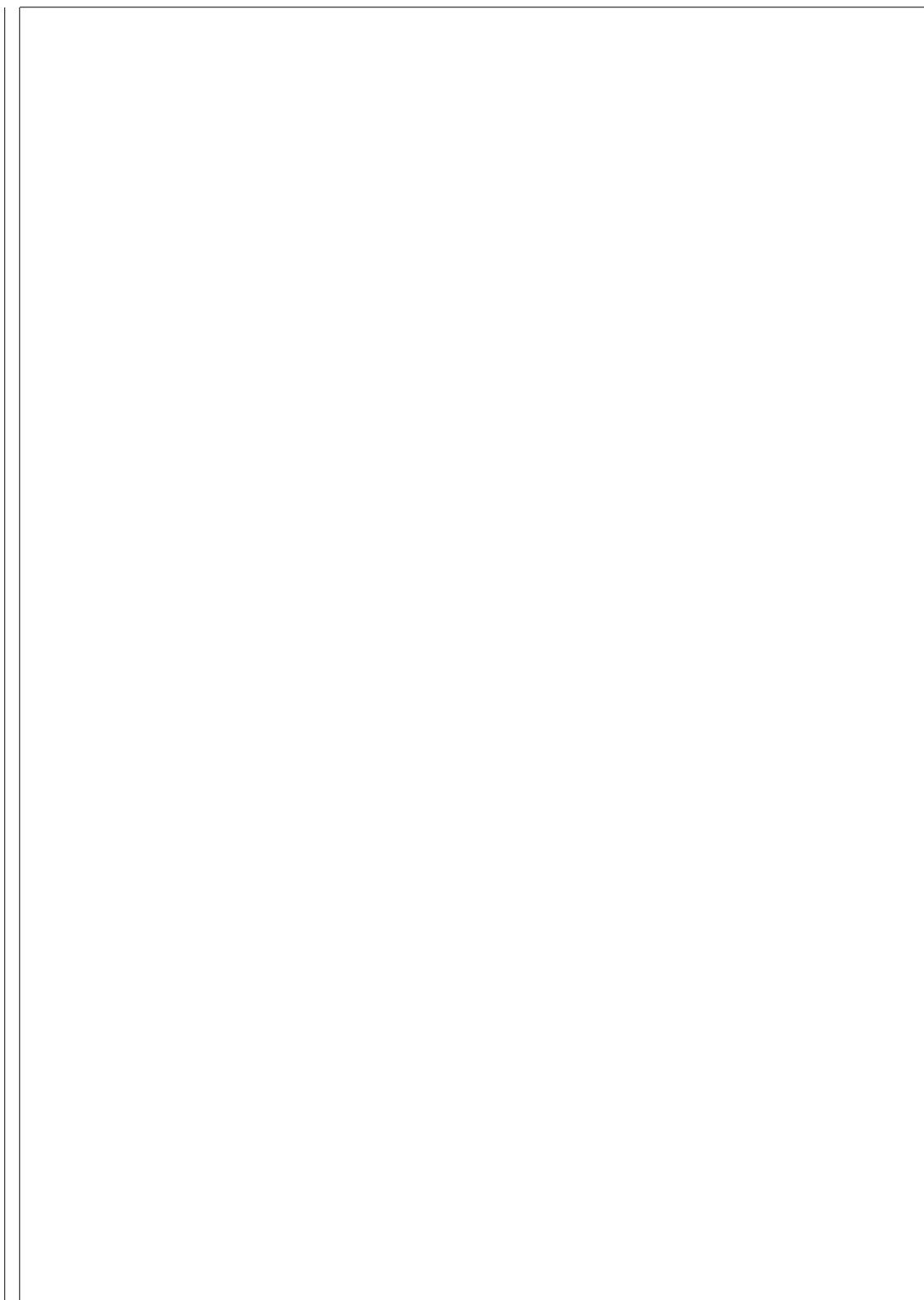
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Preface

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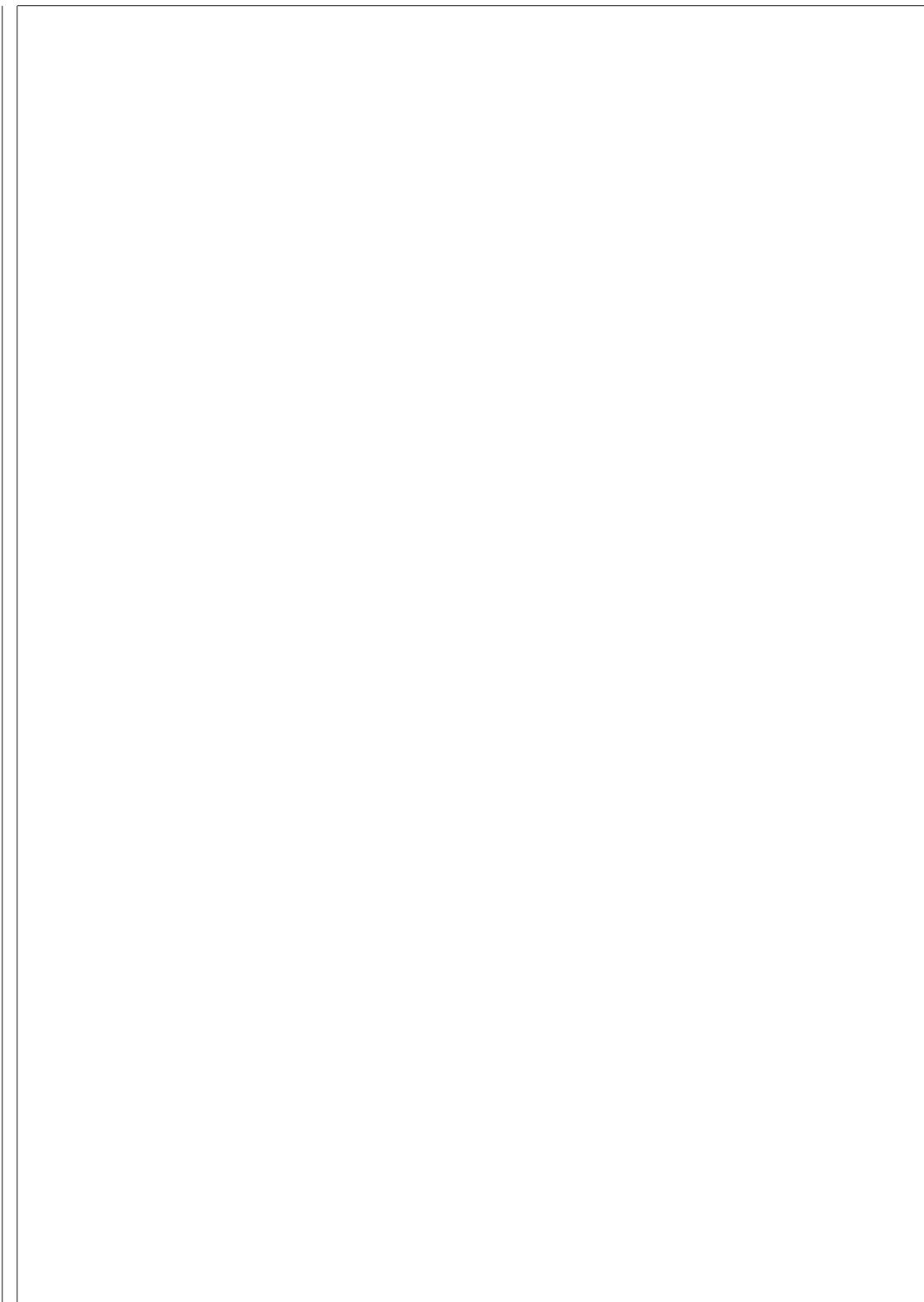
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Contents

ABSTRACT	v
SOMMARIO	vii
PREFACE	ix
LIST OF FIGURES	xiv
LIST OF TABLES	xvii
1 INTRODUCTION	1
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	6
2.2 Air quality	10
2.2.1 ArduECO	11
2.2.2 MegaSense and Hope	13
3 TECHNOLOGIES	15
3.1 Fundamentals of network communication	15
3.2 Radio technologies	20
3.2.1 LoRa and LoRaWAN	23
3.3 Hardware (Microcontrollers)	24
3.3.1 Arduino	27
3.3.2 Raspberry Pi	28
3.3.3 Pycom	30
4 RELATED WORK	33
4.1 Challenges and solutions of wireless mesh networks	33
4.2 Overview of wireless mesh networks	34
4.2.1 Advantages of WMS	36

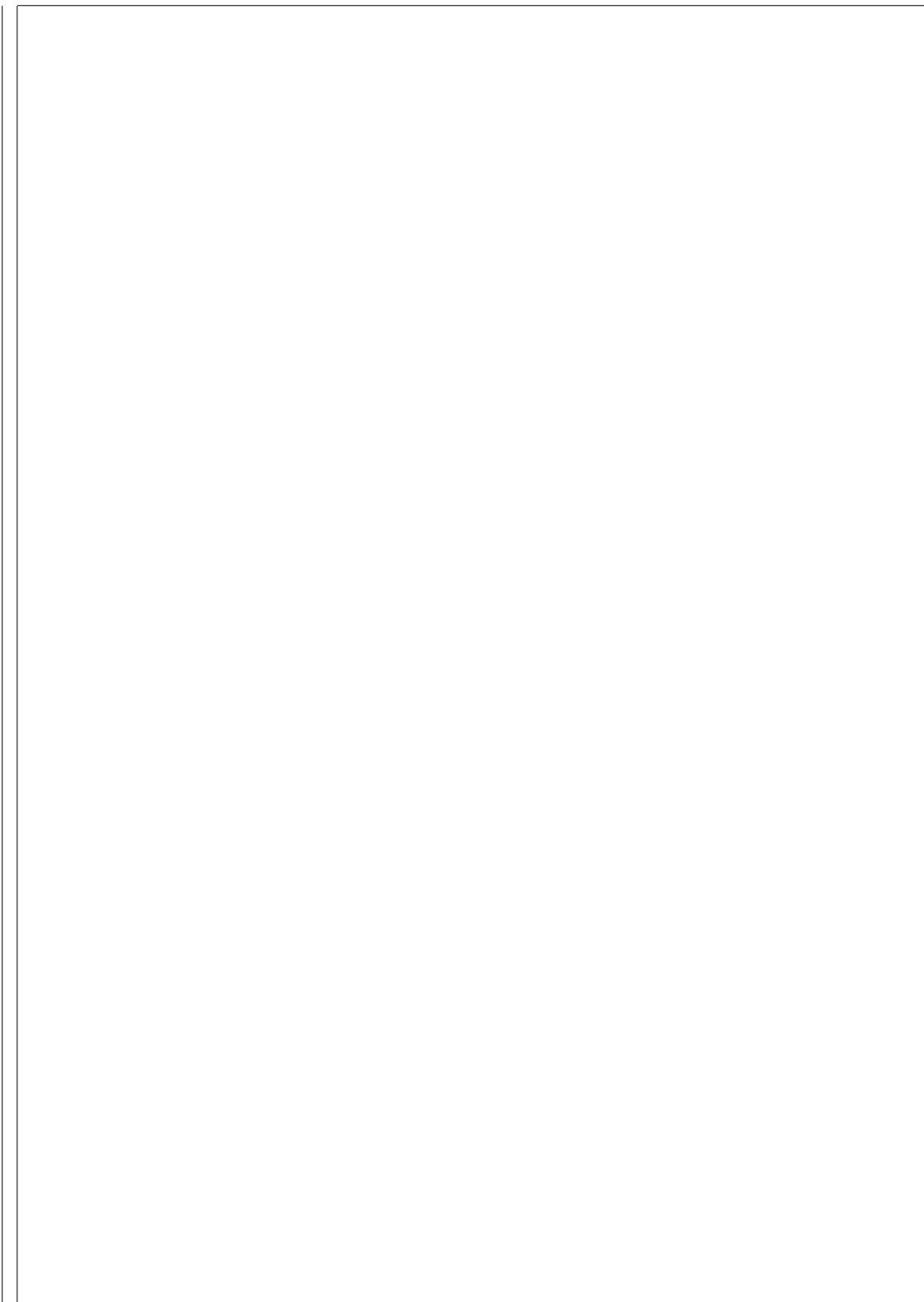
4.2.2	Disasvantages of WMS	37
4.2.3	Scalability	37
4.3	Algorithms for lora Wireless Mesh networks	37
4.4	Projects	37
4.4.1	Open source projects	37
4.4.1.1	LoRa Mesh Chat	37
4.4.1.2	Meshtastic	38
4.4.2	Research projects	39
4.4.2.1	Monitoring of Large-Area IoT Sensors Using LoRa Wire- less Mesh Network System: Design and Evaluation . . .	39
4.4.2.2	Black Powder Flow Monitoring in Pipelines by Means of Multi-Hop LoRa Networks	39
4.4.2.3	Exploring Multi-Hop LoRa for Green Smart Cities . .	39
4.4.2.4	Proposal of a Hybrid LoRa Mesh / LoRaWAN Network	39
4.4.2.5	Beyond the Star of Stars: An Introduction to Multihop and Mesh for LoRa and LoRaWAN	39
4.4.2.6	LoRa-based Mesh Network for Off-grid Emergency Com- munications	39
4.4.2.7	LoRaCTP	39
4.4.3	Commercial applications	41
4.4.3.1	Off grid mesh devices: Sonnet and goTenna	41
4.4.3.2	Mesh WiFi	42
5	PROPOSED SOLUTION	45
5.1	Idea	45
5.2	Architecture	45
5.3	Hardware	45
5.4	Software	45
5.4.1	Algorithms	45
5.4.1.1	Main	45
5.4.1.2	Boot up	46
5.4.1.3	Mesh initiation	46
5.4.1.4	Broadcast mesh information	46
5.4.1.5	Loop	46
5.4.2	Sleep cycle	46
5.4.3	Supported messages	46
5.5	Use cases	46
5.5.1	Mobile network	46
5.5.2	Fixed network	46
5.5.3	Hybrid network	46

6	RESULTS AND EXPERIMENTATION	47
6.1	Experiments	47
6.2	Results	47
7	CONCLUSIONS	49
7.1	Future work	49
7.1.1	Hardware improvements	49
7.1.2	Software improvements	49
7.2	Personal considerations	49
7.2.1	About the Pycom boards	49
7.2.2	About mesh networking	49
	ACKNOWLEDGMENTS	50
	REFERENCES	53
	GLOSSARY	57

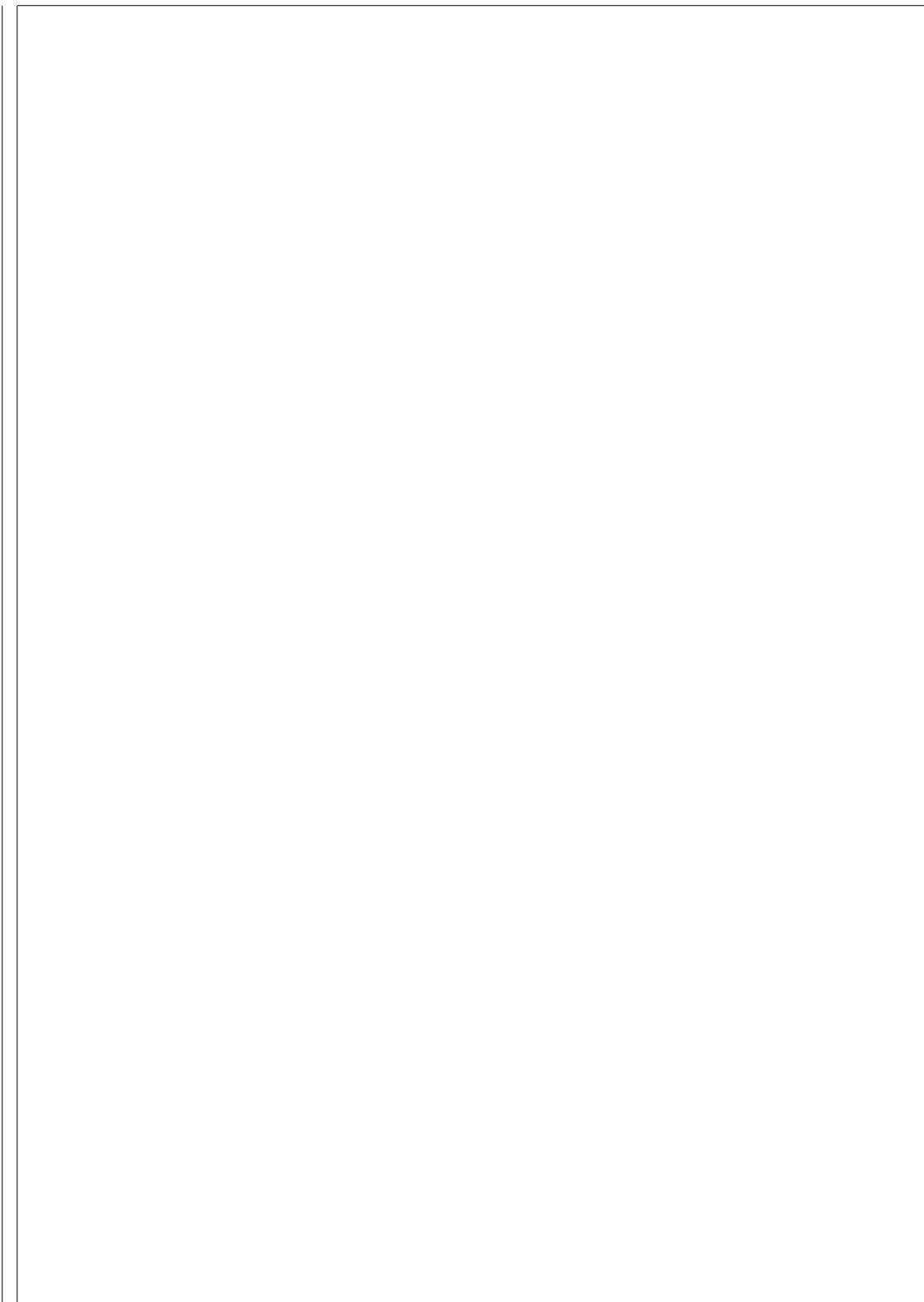


List of figures

2.1	Diagrammatic view of the Universal Product Code	5
2.2	CMU’s “coke machine”	5
2.3	Most researched areas in IoT	7
2.4	Edge, Fog and Cloud Computing	8
2.5	Full record Keeling curve until Nov. 1 2021	11
2.6	Two years Keeling curve until Nov. 2021	11
2.7	Circuit of the ArduECO prototype	12
2.8	Built ArduECO prototype	12
2.9	Megasense prototype	13
3.1	Subsea Internet backbone cables between US and Europe.	17
3.2	The ISO/OSI reference model against the TCP/IP stack	18
3.3	Common network topologies	19
3.4	Wireless access geographic coverage.	22
3.5	Range of LoRa transmission compared to Wi-Fi, BLE and Cellular	24
3.6	Attiny 85 on the left, in the middle two boards based on the ESP32, on the right the Asus Tinkerboard 2	25
3.7	Arduino UNO Rev 3 on the left, Arduino Yun in the middle, Arduino Nano 33 BLE on the right	27
3.8	Raspberry Pi Model 3B+ on the left, Raspberry Pi Zero in the middle, Raspberry Pi Pico on the right	29
3.9	fypy on the left, PyTrack 2X in the middle, pysense on the right	30
4.1	Multihop network	35
4.2	Self Organizing Wireless Mesh Networks	36
4.3	An example of a VANET	36
4.4	ESP32 Lora with OLED	38
4.5	Flow of the establishment and interchange of data in LoRaCTP	39
4.6	Flow of the establishment and interchange of data in LoRaCTP	40
4.7	Sonnet	41
4.8	goTenna Mesh	41
4.9	goTenna Pro	41
4.10	WiFi 6 mesh nodes vs WiFi range extenders performance	43



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, like the “London Fog” [1] in 1952.

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.

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, portable and per-

sonal, 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 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.

I.1 CONTRIBUTIONS

The contributions that the work described in this thesis are

I.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 two IoT devices capable of detecting such pollution. In particular, it concentrates on MegaSense, the IoT air quality sensing project that this thesis works with.

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

2.1 INTERNET OF THINGS

Internet of Things, also abbreviated with IoT, has a longer history than many people think about: its name, 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 [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. IoT's importance heavily relies on data gathered from these devices, since, in combination with other

computer science 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, from wearable technologies to Inter-Vehicular Communication (IVC). As explained in [5], the latter is a “key technology in order to increase driving efficiency and safety, as well as support autonomous driving and provide many other connectivity-based services”. The biggest challenges though are the heterogeneity and dynamicity in vehicular scenarios.

Another important application scenario of IoT is emergency situations, where it supports first responders with adequate means to perform their operations in an effective and safe way. In this case, from a networking point of view, “one of the main challenges is that of providing first responders with multimedia information about the emergency as soon as possible, even from a remote location” [6]. Projects designed to provide connectivity off-grid not only to civilians, but firefighters, military operations, local law enforcement, search and rescue, are described in 4.4.

But first, below are two important key projects in the story of IoT the UPC, or Universal Product Code, and the Carnegie Mellon University (CMU) coke machine.

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 [7], 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.

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

Thus, the ameliorated upc was vertical and came in the form of a barcode printed with strict rules in order to avoid errors in scanning due to smear or marks on the label.

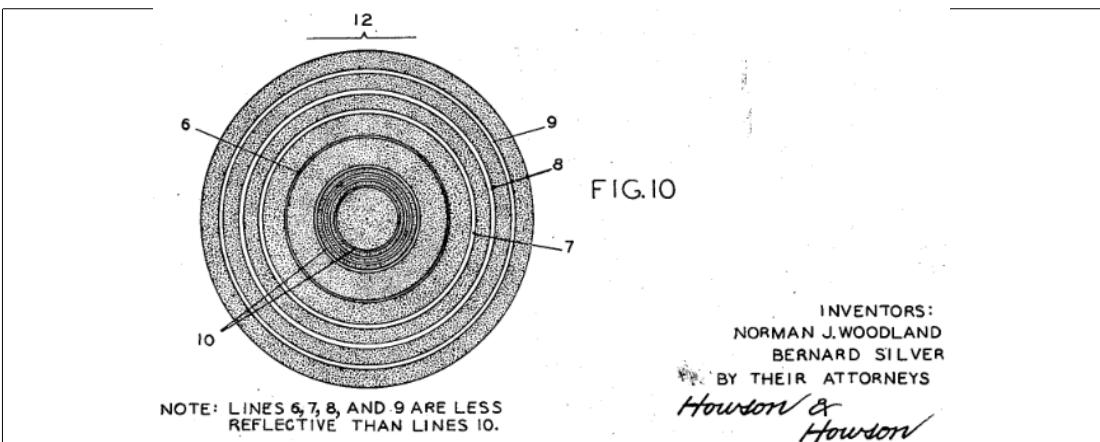


Figure 2.1: Diagrammatic view of the Universal Product Code from [7]

This version, developed in 1971 by George Laurer at IBM [8], became the first wide appearance of the upc.

A centralizes super-system that provided the code translations was used in order to standardize codes among different super markets and shopping places. Such system has been the first way to track products and address them at large scale, thus rendering a "thing" at the super market capable of providing information to a larger scale, although not directly connected.

2.1.2 CMU's COKE MACHINE AND MODERN VENDING MACHINES

It may come as a surprise, but connecting everyday "things" and for direct interaction, contrary to the previous example, 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 predicated the Internet. 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 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” [9].

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.

Such kind of smart vending machines have helped bring a step closer old “un-connected” cities to become smart cities, where these machines can be used as a mean to place devices such as routers or public wifi access points.

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, some IoT techniques can still be considered not ready and many technical difficulties and problems need to be solved.

¹ https://www.cs.cmu.edu/~coke/history_long.txt

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

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 [10] have highlighted ten particular topic areas that span across three layers of IoT architecture: Application, Data and Physical, as represented in Figure 2.3.

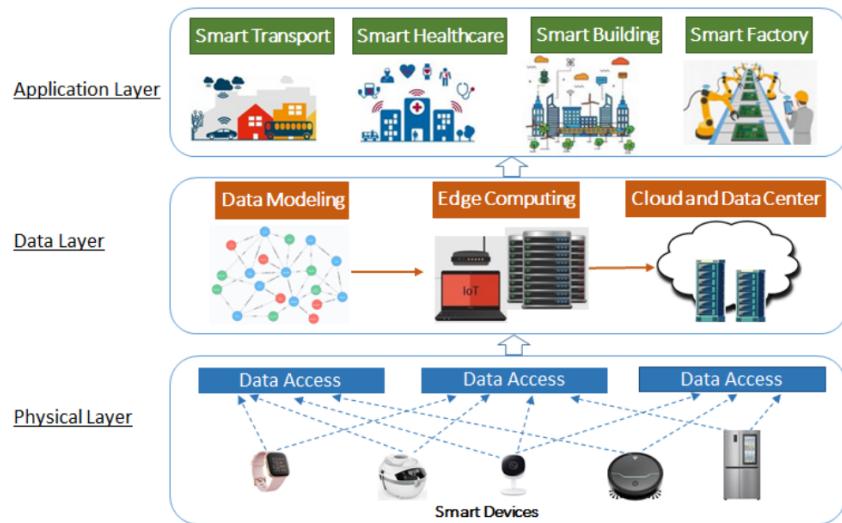


Figure 2.3: Most researched areas in IoT [10]

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 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 Computing⁴ have emerged.

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

⁴ “Edge computing does not mean computers at the edge of a table.” Alessandro Canesso

With Edge Computing, data stays where it is produced, used and where it belongs – without traversing the network unnecessarily. This way, cloud infrastructure needs are reduced in three ways: firstly, less network traffic, secondly, less central storage and thirdly less computational power. Rather, edge computing makes use of all the capable hardware already deployed, e.g., in a smart home where all the data could stay within the house and be used on site.

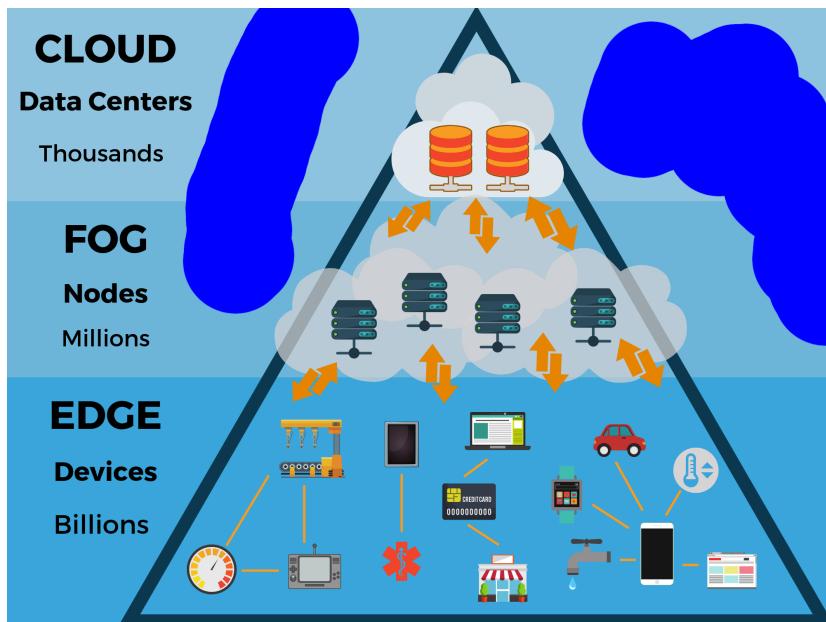


Figure 2.4: Edge, Fog and Cloud Computing

Each of these paradigms, 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.

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)”[11]. 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 [12] or other diseases, like Hyperkalemia [13]. Even now IoT devices and frameworks can be used for contact tracing in order to prevent the spread of Covid-19 [14].

Consumers want remote control of devices such as coffee pots so that they may wake up to freshly brewed coffee, or cause coffee to be prepared at a precise time after the completion of dinner preparations⁵.

On the other hand, from an industrial point of view, the demands are more focused on fast connectivity among devices to constantly improve production of goods and services in Industry 4.0 and with Industrial IoT (IIoT). The more data available, the more there are opportunities for science, services, business etc. to understand and grow. 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, that is why the goal of fifth-generation (5G) wireless networks and beyond is to realize connecting “anything, anyone, anytime, anywhere” [15].

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.

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 Arm⁶, states that “More than two-thirds of respondents agree that understanding the value of data helps them articulate the business case for IoT investments.”[16]. In the same analysis, has emerged that

⁵ *Hyper Text Coffee Pot Control Protocol:* <https://datatracker.ietf.org/doc/html/rfc2324>

⁶ <https://www.arm.com/>

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

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

The ubiquity of mobile technology has opened the door to a new era of mobile sensing.

Through this new paradigm, physical phenomena can be observed in a distributed way, crowd-sourcing the data measurement tasks to smartphones and/or other popular smart wearables. Mobile sensing and wireless communications can hence be employed to gather data and generate new information and services, benefiting our society.

Two general strategies can be used to deploy an environmental monitoring system: creating a network of fixed sensors and resorting to mobile sensors.

Air quality and the presence of tiny particular matter are crucial factors in human health, especially when considering urban scenarios. In this context, smart mobility coupled with low-cost sensors can create a distributed and sustainable platform for social sensing able to provide pervasive data to citizens and public administrations. Sustainable and eco-aware decisions can then be supported by empirical evidence, resulting in an improved life and city administration.

Some of the most harmful airborne agents are fine particles (PM_{2.5}), Sulphur dioxide (SO₂), Nitrogen dioxide (NO₂), PM₁₀, Carbon monoxide (CO), Benzene and Ozone. The maximum amount for these particulates is regulated by various authorities, for example the EU has set standards ⁷ that are reinforced by constant monitoring.

One of the most important instruments in air quality measurement is the Keeling Curve: a meticulous record of the amount of carbon dioxide in the atmosphere. The Keeling Curve tracks changes in the concentration of CO₂ in the Earth’s atmosphere using data from a research station on Mauna Loa in Hawaii. Figure 2.5 shows the result of daily readings that have continued almost uninterrupted for more than 60 years, while Figure 2.6 shows the data between October 2019 and November 2021. The importance of this instrument lies in the fact that, over those six decades, the zig-zag has trended steadily upward. Real time readings

⁷ <https://ec.europa.eu/environment/air/quality/standards.htm>

can be found on the UC San Diego, Institution of Oceanography's dedicated website⁸.

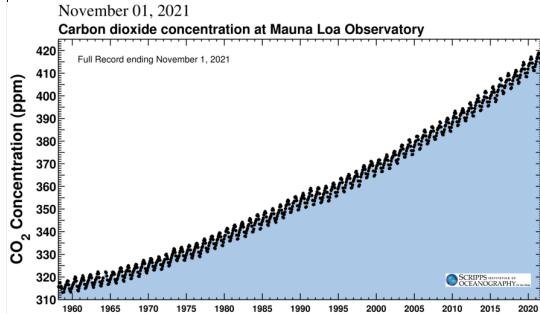


Figure 2.5: Full record Keeling curve until Nov. 1 2021

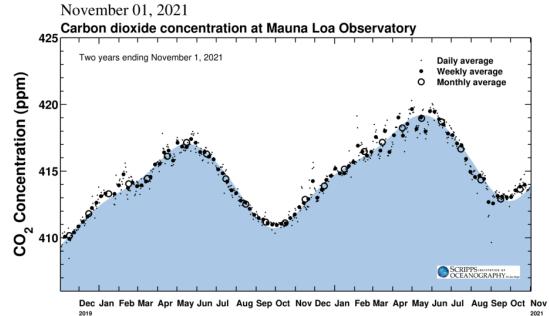


Figure 2.6: Two years Keeling curve until Nov. 2021

Many projects have been made, both for research and commercial purposes, to detect pollutants in the air and raise awareness of the conditions people are living in.

Below are two research solutions that have been made for air quality sensing with low-cost sensors.

2.2.1 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”[17].

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, which been advantaged by the COVID-19 pandemic [18]. In contrast, other approaches to shared transportation, such as car sharing, have severely suffered from the outbreak of the coronavirus.

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. 2.7 shows the full circuit of the prototype, while Fig. 2.8 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

⁸ <https://keelingcurve.ucsd.edu/>

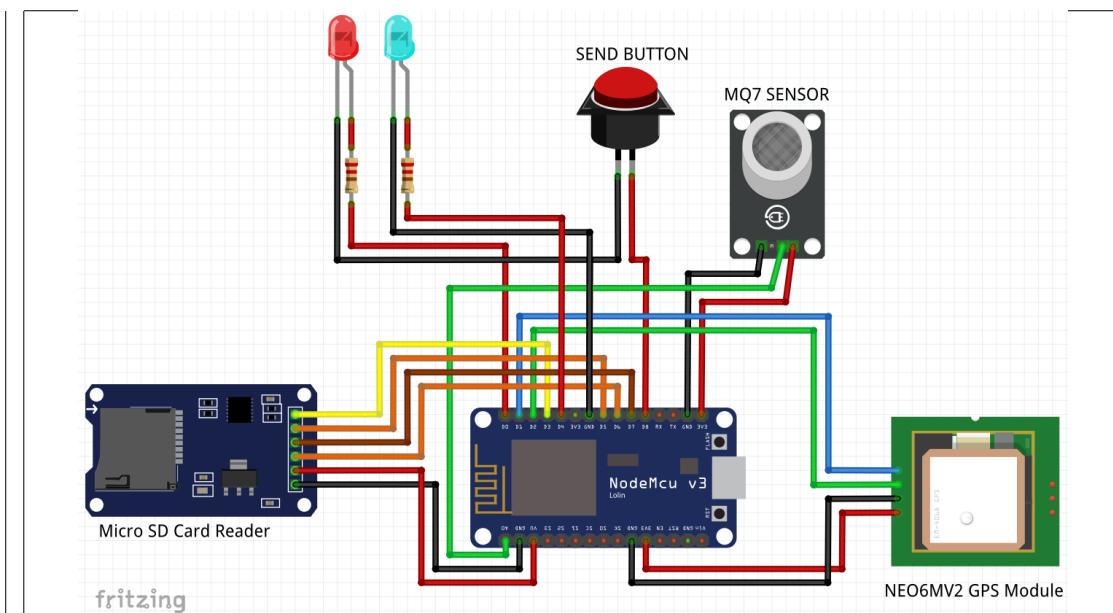
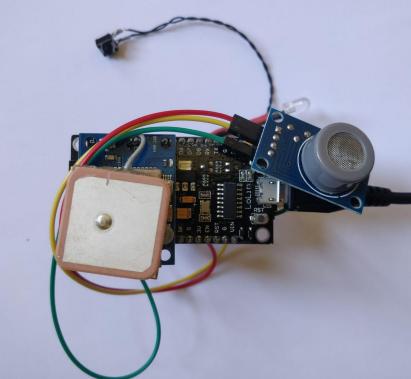


Figure 2.7: Circuit of the ArduECO prototype

an MQTT server running on Amazon Web Services IoT Core⁹. Server costs aside the sensor platform can be built in a bill of materials of around €15 (around \$18) — less, if built in bulk.



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 adding multiple sensors to detect different pollutants and tweak the software so that the board can sleep and save battery.

Figure 2.8: Built ArduECO prototype

⁹ <https://aws.amazon.com/iot-core/>

2.2.2 MEGASENSE AND HOPE

MegaSense has been developed by the Departments of Computer Science at the University of Helsinki¹⁰ 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.



Figure 2.9: Megasense prototype

The feedback loop involves the actions of individuals and the physical and chemical processes, which increase exposure duration and concentration to air pollution. Compared to the previously described ArduECO, the MegaSense is a more complete project which has been tested by citizens and companies in City of Helsinki and EU projects.

The system receives data from sensing platforms measuring local pollution exposure and other variables affecting 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 measurements in areas that have limited sensor coverage.

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 cleaning. The 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 download the HOPE Exposure App from Google play store and tether their Android smart phone to HOPE sensor. The HOPE Exposure App is preconfigured with the MegaSense server address and upon launching the app and switching on the HOPE sensor, measurement data packets including the smart-phone GPS location are routed by wireless connection via local mobile service provider to

¹⁰ <https://www.helsinki.fi/en/computer-science>

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.

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.” [19]

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 [20], 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-DOS, 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" [20]:

- 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>

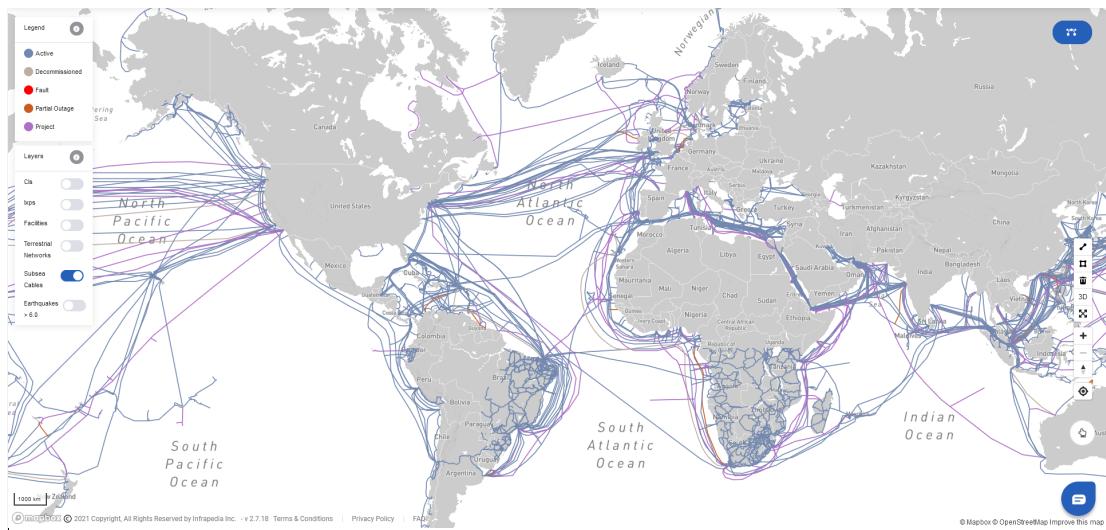


Figure 3.1: Subsea Internet backbone cables between US and Europe.⁴

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 Area Network, or PAN: connects devices within a user's immediate area.

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

⁴ <https://www.infrapedia.com/app>

Since everyone can connect to the Internet and access its services, there is no need for the average user to understand what happens between his machine and the rest of the network, which means he only sees the information that is displayed to him without knowing where it arrives from or what path it took to arrive on his monitor.

For computer scientists though, it is important to understand the difference between network architecture and network topology. A network architecture, as described by Paul E. Green, “is a complete definition of all the layers necessary to build the network”^[19]. This is focused on the network software, which needs to be highly structured in order to allow for heterogeneous systems to communicate with each other. One example of network architecture is the ISO/OSI reference model⁵, which is implemented by the TCP/IP stack of protocols.

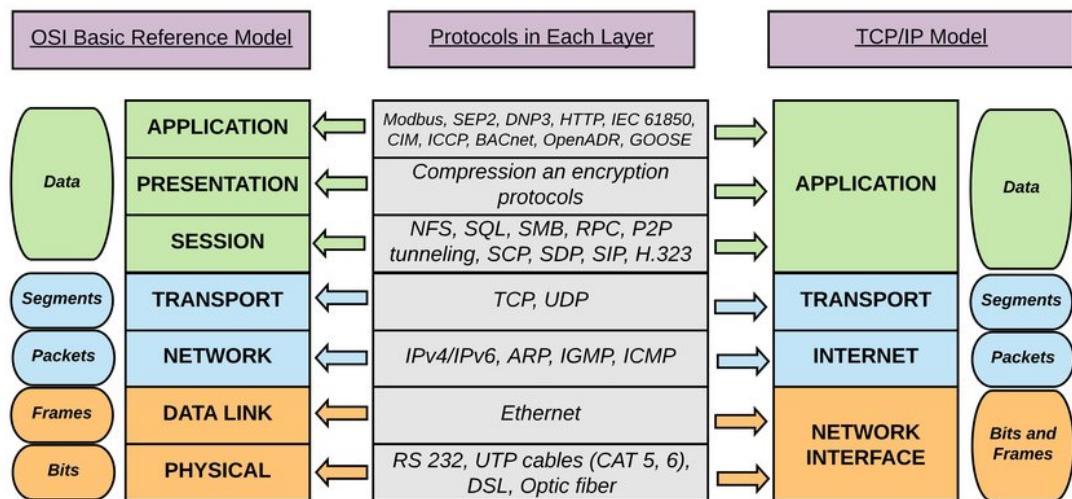


Figure 3.2: The ISO/OSI reference model against the TCP/IP stack

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.”^[19]. 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>

Network Topology Types

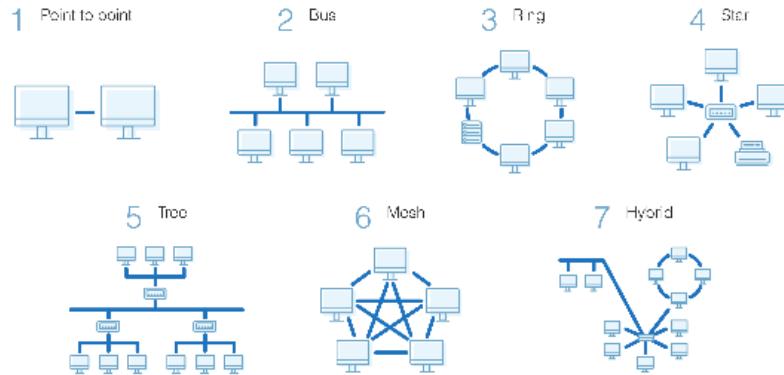


Figure 3.3: Common network topologies

As shown in Fig. 3.3, some of the most common network topologies are:

- Point-to-Point: in which devices are connected directly;
- Bus: devices are connected to each other via a backbone cable;
- Ring: two dedicated point-to-point links connect a device to the two devices located on either side of it, creating a ring of devices through which data is forwarded via repeaters until it reaches the target device;
- Star: connects each device in the network to a central hub. Devices can only communicate with each other indirectly through the central hub;
- Tree: parent-child hierarchy in which star networks are interconnected via bus networks;
- Mesh: a dedicated point-to-point link connects each device on the network to another device on the network, only carrying data between two device;
- Hybrid: any combination of two or more topologies.

The project presented in this thesis regards a network with a mesh topology, which can be considered a multi-hop network, since data passes from node to node until it reaches its destination. This is better described in 5 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.

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 [21], 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 have 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 transmitter and receiver.

The most important new category of wireless communication, that interests IoT and represents 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 [22], 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 [22].

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

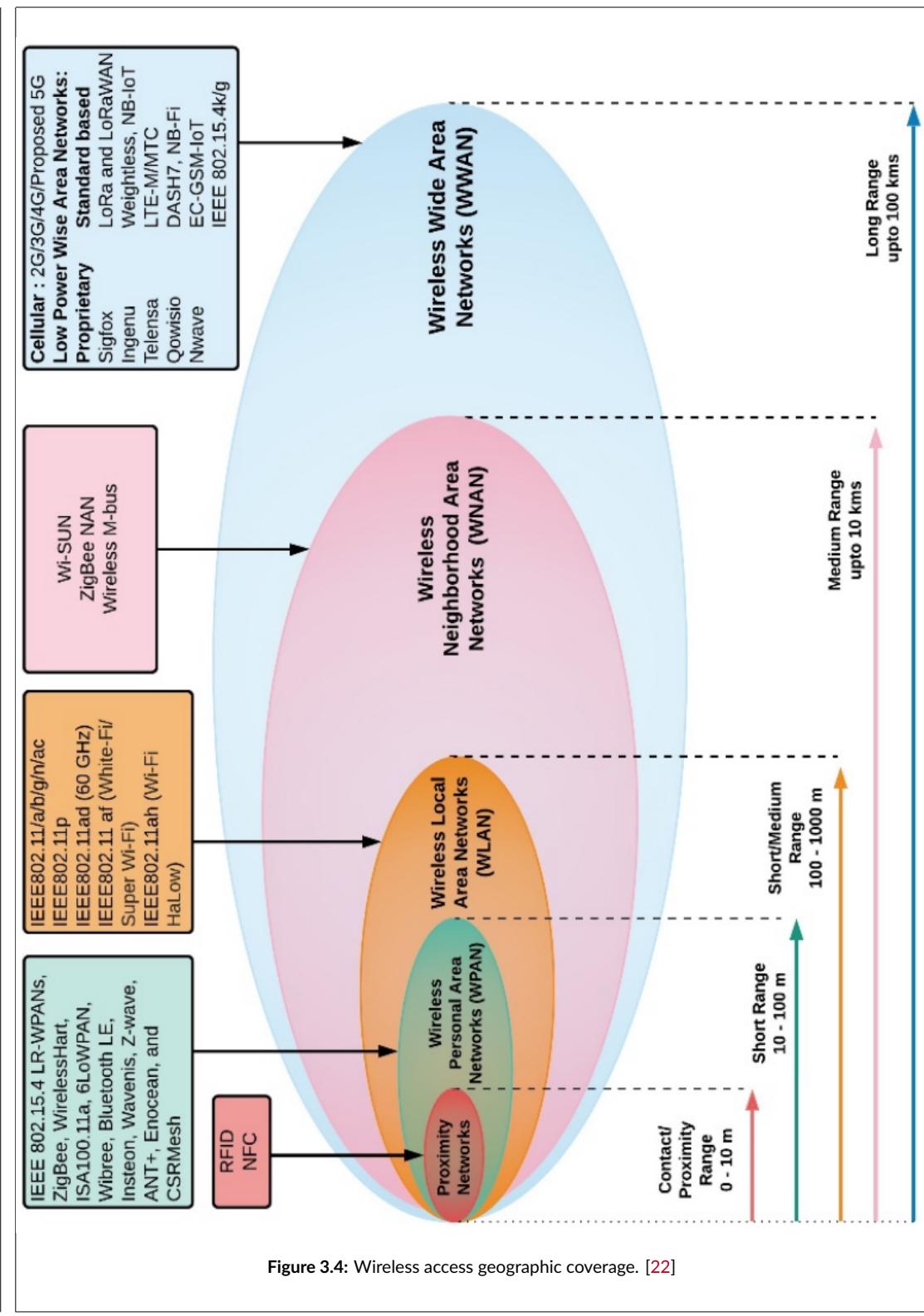


Figure 3.4: Wireless access geographic coverage. [22]

The latter was used in the ArduEco project, described in Sec. 2.2.1. 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 the chirp spread spectrum (CSS) technology. LoRa devices provide a long range, low power wireless platform that is being widely adopted for the Internet of Things (IoT) networks worldwide. LoRa devices and the open LoRaWAN protocol enable smart IoT applications in various context, like: energy management, natural resource reduction, pollution control, infrastructure efficiency, disaster prevention, and more.

LoRaWAN is a comprehensive network architecture that details a Low Power, Wide Area (LPWA) networking technology. It was designed to interconnect battery operated “things” and provides a bi-directional communication service with end-to-end security features. The architecture is based on a star-of-stars topology in which specific devices called gateways relay messages between end-devices and a central network server. The wireless communication takes place through a single-hop link between the end-device and one or many gateways. The specification defines the device-to-infrastructure physical layer parameters (LoRa) and the specific LoRaWAN protocol to allow for full interoperability among manufacturers. It defines the technical implementation but it does not define any commercial model or type of deployment, e.g., public, shared, private, enterprise. The LoRaWAN specification is developed and maintained by the LoRa Alliance, an open association of collaborating members. With LoRa and LoRaWAN the intention was to provide the possibility to deploy Internet of Things applications fast in areas where large distances are involved, yet low bandwidth is needed. Low bandwidth makes it ideal for practical IoT deployments with less data or where data transmissions are not constant, for example with waste management where the information that is required is whether a waste bin is full or not. Moreover, the end-to-end delay (or the RTT) can be relatively high, with values below one second being acceptable.

Conversely, packet loss is a more crucial factor. In LoRaWAN, once a message has been delivered, there is no acknowledgement of receipt. However, nodes can request acknowledgements. In this case, if many gateways receive the same packet, the cloud has to choose one gateway to respond at a fixed time, usually a couple of seconds later. The problem is that when a gateway is transmitting back to the node, it stops listening to everything else. So, if an application needs a lot of acknowledgements, the gateway will very likely spend more

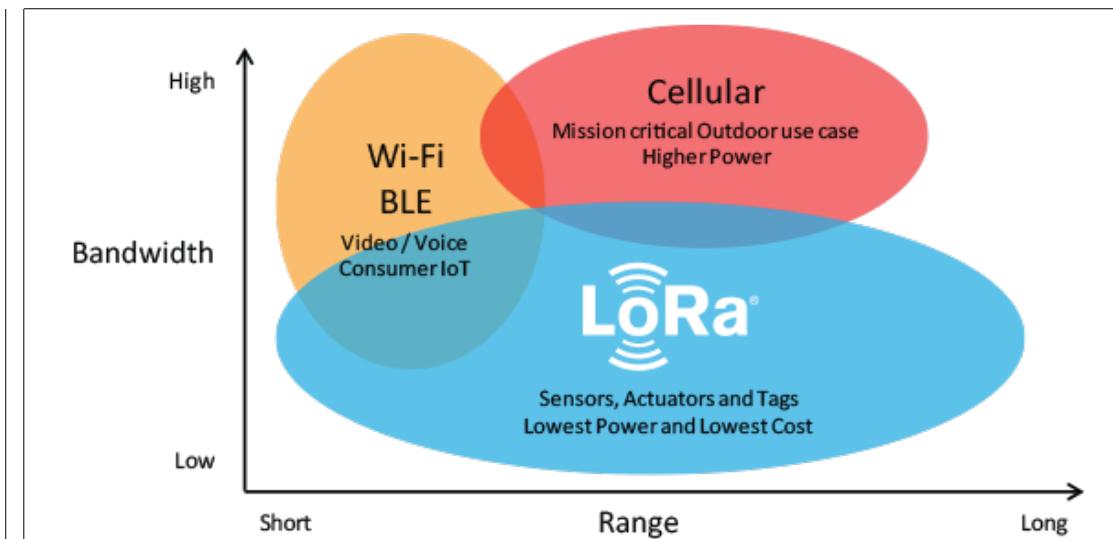


Figure 3.5: Range of LoRa transmission compared to Wi-Fi, BLE and Cellular

time transmitting acknowledgements than listening, which will eventually lead to a network saturation. Therefore, classical applications do not require acknowledgments and that's why having a reliable network with very small packet loss rate is crucial if we don't want to lose relevant information.

Chirp spread spectrum has been used in military and space communication for decades due to the long communication distances that can be achieved and robustness to interference, but LoRa is the first low cost implementation for commercial usage. The advantage of LoRa is in the technology's long range capability. Range highly depends on the environment or obstructions in a given location, but LoRa and LoRaWAN have a link budget greater than any other standardized communication technology.

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 heart of IoT devices, described in Chap.

2, and they require long-lasting, low-cost, and sustainable batteries.

The number of IoT connected devices is expected to grow up to 75 billion worldwide by 2025 [23], and connection density is expected to be one million devices per square km [24]. 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 85⁷, 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 2⁸, 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€.

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

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

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

Table 3.1: Specifications of Arduino, Raspberry Pi and Pycom microcontrollers

It is important to note though that using a generic board in a production environment might not be ideal, since it might lack of support and documentation. The boards described subsequently are from three of the major MCU producers, Arduino, Raspberry Pi and Pycom, which have built hardware that is well documented and suited for many different environments, from hobbyists to industrial use.

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 microcontroller company, Arduino, have developed a version of C++ specific for their boards, but given the simplicity 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 MicroPython. 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"⁹. 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.

⁹ <https://micropython.org/>

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

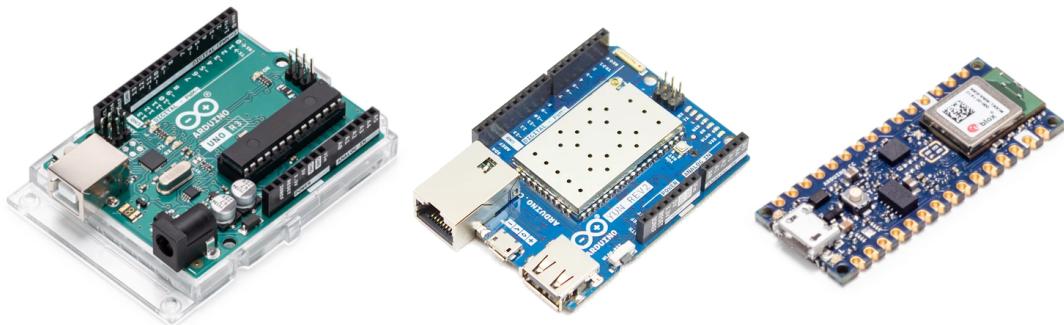


Figure 3.7: Arduino UNO Rev 3 on the left, Arduino Yun in the middle, Arduino Nano 33 BLE on the right

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.

¹⁰ <https://store.arduino.cc/products/arduino-uno-rev3>

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:

- 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 Raspbian OS

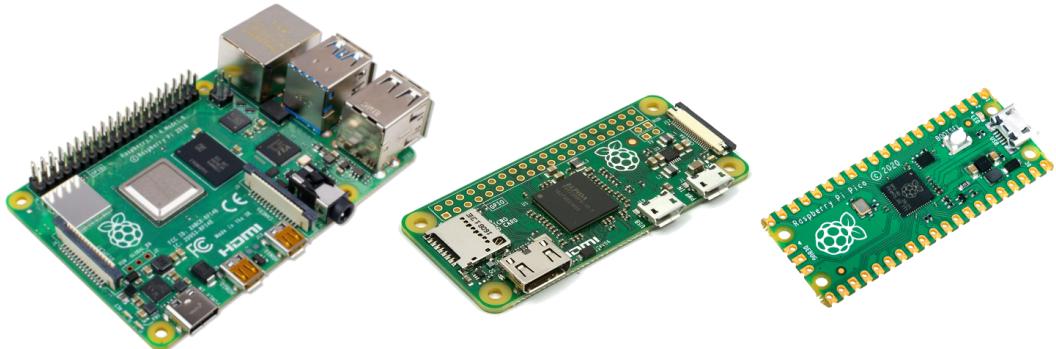


Figure 3.8: Raspberry Pi Model 3B+ on the left, Raspberry Pi Zero in the middle, Raspberry Pi Pico on the right

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 online¹¹, board makers have been able to adapt them in their own way.

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

- 3 B+ / 4: the model 3B+ and 4 are their most selling products, they are marketed as a "tiny, dual-display, desktop computer"¹²;
- 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 store¹³.

¹¹ <https://www.raspberrypi.org/documentation/computers/raspberry-pi.html>

¹² <https://www.raspberrypi.org/products/raspberry-pi-4-model-b/>

¹³ <https://www.raspberrypi.org/products/>

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.



Figure 3.9: fipy 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 page¹⁴, 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 affordability of the company producing them, also because of their high density of hardware on a board with a small footprint.

¹⁴ <https://pycom.io/product/fipy/>

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.

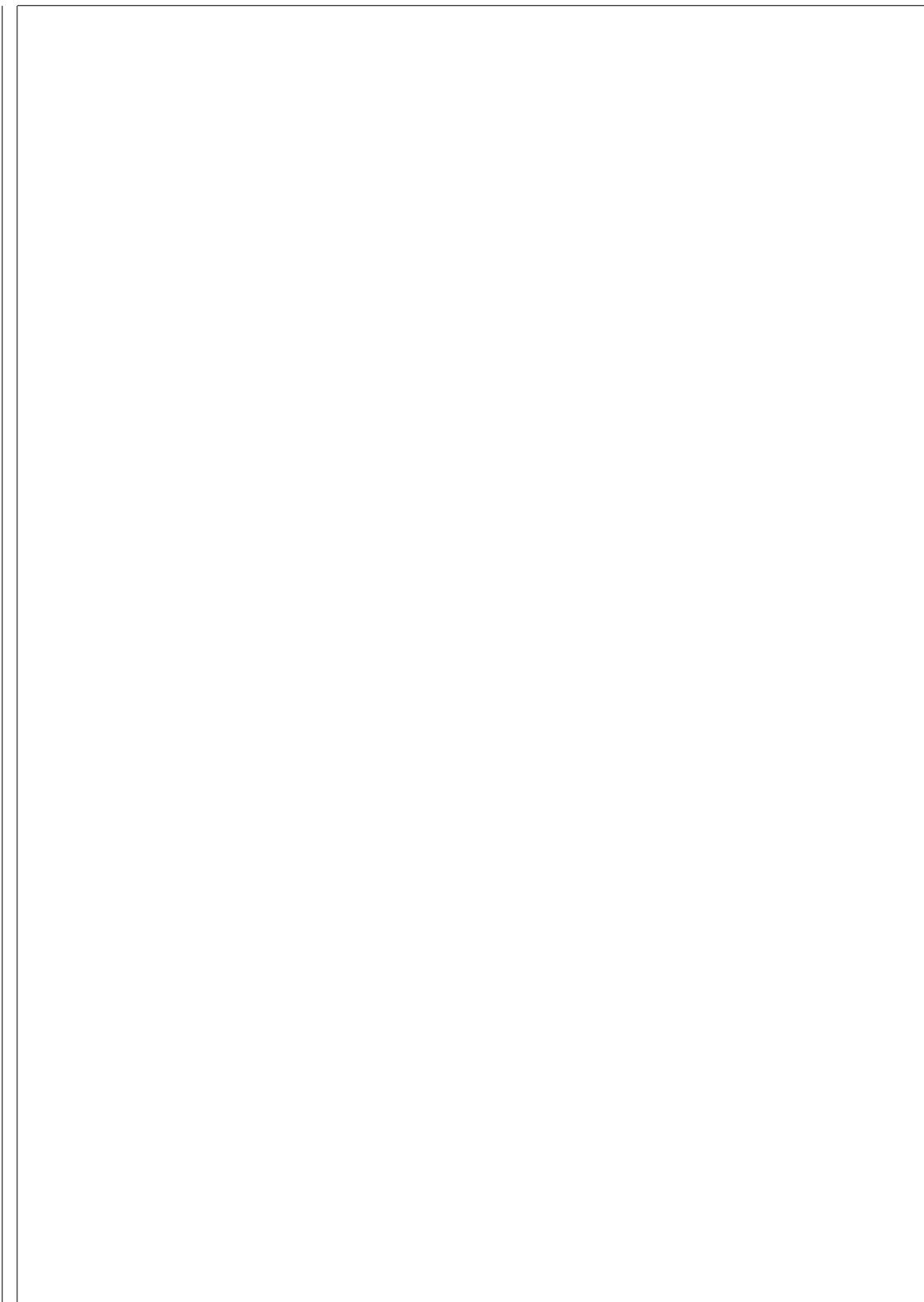
About the cost of the boards, the price of the single major components used for this project are, at the time of writing:

- FiPy €59.40
- Pytrack 2.0 X €40.65
- Pysense €29.65

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 website¹⁵.

A more in depth description of the chosen technologies is described in Chap. 5.

¹⁵ <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.

Future IoT deployments need to focus on sustainability since huge centralized data centers (cloud computing) have become a critical part of the infrastructure.

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

A wireless mesh network (WMN) is a communications network made up of radio nodes organized in a mesh topology instead of star topology [25].

At first challenges and solutions are presented for these WMS. Below are also presented some of the projects which have been made at various levels from homemade projects, to research and to the ones already available on the market.

4.1 CHALLENGES AND SOLUTIONS OF WIRELESS MESH NETWORKS

With new technologies, wireless mesh networking has reached a point of maturity and become ideal for IoT app developers. Besides, the elevation of connected homes and industry support on open-source resources has made mesh truly accessible and low-cost. They are also regarded as much more viable and real choice for commercial as well as industrial IoT

apps. At the same time, it can render extra services in a system where extending a two-node connection is limited.

There are various applications for this network topology

- Smart Cities: extending radio signals through campus grounds, business parks, parking garages, and other outdoor facilities Healthcare Equipment: monitoring and locating medical equipment. It can also serve as a backup for medical devices that always require to stay online. Thus, if one node crashes and loses connectivity, another node can step in to maintain the connection.
- Smart Home: You can track and manage temperature across your home using a wireless mesh network. You can also capture live data and adjust settings automatically by setting up one powered gateway, sensors, and mesh-enabled nodes in each room.
- Farming: Mesh networking is the best way to track sun exposure and water levels across the crops and fields. Additionally, you can create a cellular-connected IoT platform by building a mesh network across a whole acreage with the help of an IoT app development company.

Before choosing a mesh network topology it is important to evaluate aspects such as installation, device management and support.

Energy management is an important factor as well, since the connected devices might not have a constant source of power. Efficient transmission techniques and protocols that consider the amount of energy used, must be developed in order to optimally use the batteries on the devices That is why there is a particular network topology, Low Power Wireless Area Network, which is focused on the interconnection of these devices

Solutions to optimize the networks are being implemented both via hardware and software Spiegare le varie soluzioni hw, dalle board migliori, e le soluzioni sw, implementazione dell'intelligenza artificiale, fare alcuni esempi e magari citare progetti presentati successivamente.

4.2 OVERVIEW OF WIRELESS MESH NETWORKS

A WMS is a particular multihop network where data is sent from a node to another until it reaches its destination.

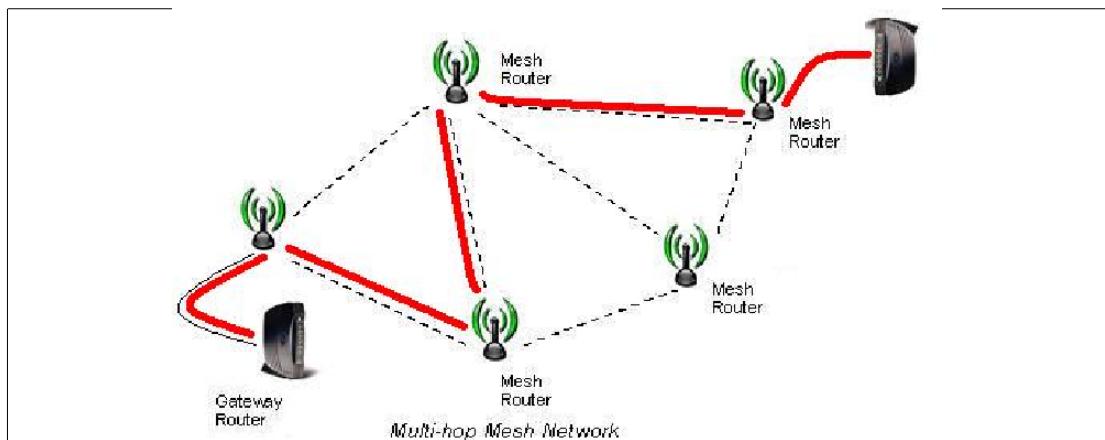


Figure 4.1: Multi-hop network

Classic network topologies, such as the ones in Fig. 3.3, are not designed for IoT networks and might not be able to meet the requirements for more dynamic devices. These computer networks are not designed for low-powered devices such as remote sensors even these IoT devices are considered to be mini computers. The single point of failure nature of these networks 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.

An example of a multi hop wireless mesh network is VANET, a particular case of wireless multihop network, which has the constraint of fast topology changes due to the high node mobility. With the increasing number of vehicles equipped with computing technologies and wireless communication devices, intervehicle communication is becoming a promising field of research, standardization, and development. VANETs enable a wide range of applications, such as prevention of collisions, safety, blind crossing, dynamic route scheduling, real-time traffic condition monitoring, etc. [26].

Microsoft has also tried to apply mesh networking to normal internet household use [27], however, given the improvements in telecom infrastructures and the advancement of fiber optics and internet via cable, the project has been abandoned. This shows how each network topology is better suited for particular scenarios.

Compared to the example of Microsoft's project, a vanet is more suited for a WMS since the data transferred among cars is less than the one transferred among houses.

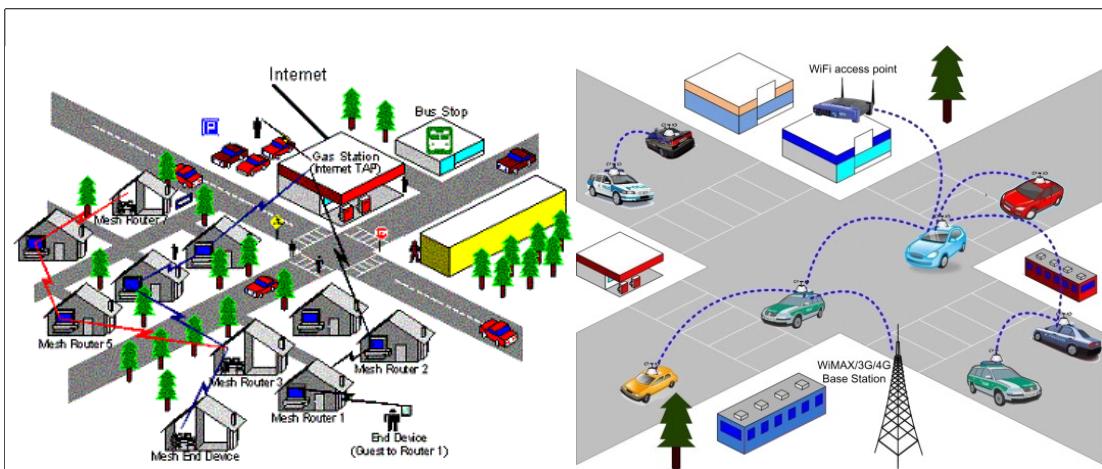


Figure 4.2: Self Organizing Wireless Mesh Networks [27]

Figure 4.3: An example of a VANET [26]

4.2.1 ADVANTAGES OF WMS

Mesh Network for IoT devices offers enormous benefits that make it sought-after in enterprises and significant in an IoT app development company. Self-healing

Like Shortest Path Bridging, Self-healing algorithm automatically chooses the best path to transfer data even if a few nodes lose connection. Specifically, it uses only those connections that are available and working to maintain the task. Self-configuring

Due to auto-discovery, mesh networks are self-configuring in nature. Hence, the new nodes calibrate automatically and connect to the network without any previous setup. Consequently, network administration and expansion become easier in mesh networking. Scalability and Reliability

In a mesh network, it is way easy to add or remove nodes without any efficiency issue. Usually, issues are in proportion to the devices. However, it is quite the opposite in the case of a mesh network. Adding nodes in a mesh network provides more routes in which data package can travel, which makes the network faster, reliable, and error-resistant. Cost Reduction

Since mesh networks don't require internet connection, it consumes ultra-little energy. Meanwhile, sensors are pocket-friendly and long-lasting.

Besides, IoT implementation reduces expenses in many other ways like better management, optimization of resources usage, and more.

4.2.2 DISAVANTAGES OF WMS

Drawbacks of Mesh Network in IoT

Though there are ample benefits of a mesh network, it also comes with a few drawbacks. So, it is essential to gain in-depth knowledge of this network before deciding whether a mesh network is a perfect fit for you. Low Capacity

Mesh network is the best way of sending small data packages. Unfortunately, it doesn't perform well while transferring video file sized data.

Still, if transferring a large amount of data is compulsory, then the wifi mesh network would be a better option. Latency

Actively switching from one node to another can decelerate the data receiving process. However, it is not an issue when your system requires a package every few minutes or so. But, it might be not enough for a few systems.

Conversely, a full mesh network can accelerate the data transfer by connecting every node to one another. Maintenance

Due to the self-healing ability of the mesh network, finding a non-working node might be time-consuming. Also, we won't come to know if a node is having an issue.

On the other hand, mesh networks for IoT devices are established to make the IoT system smarter and more efficient. So, the nodes are less prone to crash.

4.2.3 SCALABILITY

4.3 ALGORITHMS FOR LORA WIRELESS MESH NETWORKS

4.4 PROJECTS

Here are three categories of projects:

4.4.1 OPEN SOURCE PROJECTS

4.4.1.1 LoRA MESH CHAT

This project consist in an add-on for mobile phones that enable text messaging in a group when outside cellular and Internet coverage.



As explained on the project's webpage¹, an ESP32 microcontroller with a LoRa antenna and an OLED display is programmed to connect to the phone either via an OTG cable or BLE. By using an application on the phone, the user is capable of sending text messages in a group.

Figure 4.4: ESP32 Lora with OLED

4.4.1.2 MESHTASTIC

Meshtastic is an open-source hiking, pilot, skiing, Signal app-extending GPS mesh communicator.

Meshtastic is a project that lets you use inexpensive (\$30-ish) GPS radios as an extensible, super long battery life mesh GPS communicator. These radios are great for hiking, skiing, paragliding - essentially any hobby where you don't have reliable internet access. Each member of your private mesh can always see the location and distance of all other members and any text messages sent to your group chat.

The radios automatically create a mesh to forward packets as needed, so everyone in the group can receive messages from even the furthest member. The radios will optionally work with your phone, but no phone is required. Our device code is here, our optional Android app is here.

Prebuilt binaries are included on the GitHub sites, but it is quite easy to build from source. Instructions are included in the README. No soldering is required, essentially - buy a \$30 radio and go. We'd love to have your help extending the project - it has been super fun to work on.

¹ www.hackster.io/scottpowell69/lora-mesh-chat-5267d9

4.4.2 RESEARCH PROJECTS

- 4.4.2.1 MONITORING OF LARGE-AREA IoT SENSORS USING LoRa WIRELESS MESH NETWORK SYSTEM: DESIGN AND EVALUATION
- 4.4.2.2 BLACK POWDER FLOW MONITORING IN PIPELINES BY MEANS OF MULTI-HOP LoRa NETWORKS
- 4.4.2.3 EXPLORING MULTI-HOP LoRa FOR GREEN SMART CITIES
- 4.4.2.4 PROPOSAL OF A HYBRID LoRa MESH / LoRaWAN NETWORK
- 4.4.2.5 BEYOND THE STAR OF STARS: AN INTRODUCTION TO MULTIHOOP AND MESH FOR LoRa AND LoRaWAN
- 4.4.2.6 LoRa-BASED MESH NETWORK FOR OFF-GRID EMERGENCY COMMUNICATIONS
- 4.4.2.7 LoRaCTP

a flexible protocol based on LoRa technology that allows for the transfer of “content” to large distances with very low energy. LoRaCTP provides all the necessary mechanisms to make LoRa reliable, by introducing a lightweight connection set-up and ideally allowing the sending of an as-long-as necessary data message.

source addr. (8 bytes)		
dest addr. (8 bytes)		
flags (1 byte)	checksum (3 bytes)	data
:		
data		

Figure 4.5: Structure of the packet used by the stop-and-wait ARQ. [28]

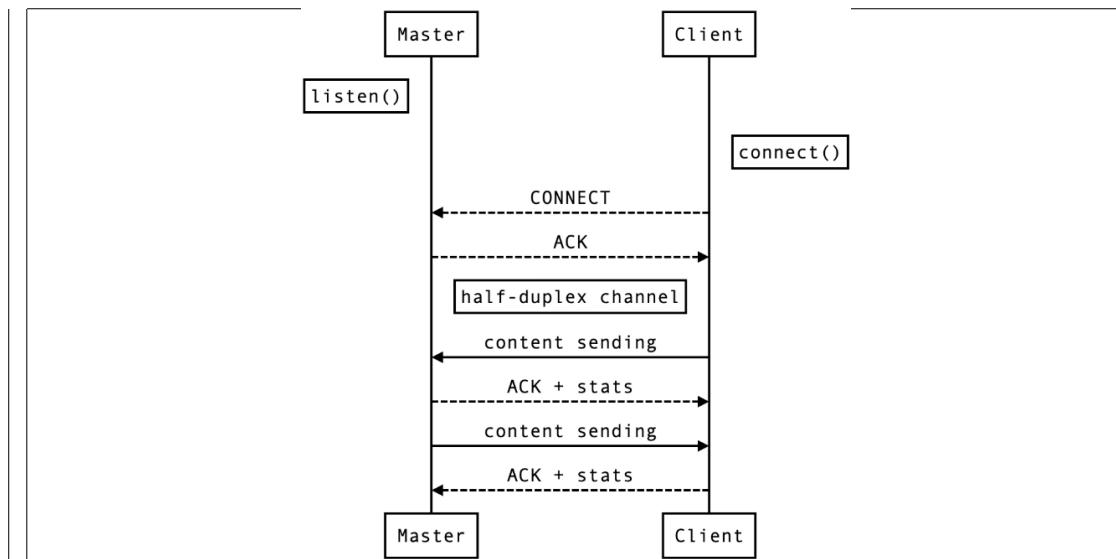


Figure 4.6: Flow of the establishment and interchange of data in LoRaCTP [28]

By content we refer to a self-contained piece of data, like a JSON encoded message whose length is in principle unlimited. We tested our library with messages of up to 150 kbytes, as indicated in Section V. LoRaCTP is based on a unicast protocol adopting a classical stop-and-wait ARQ approach with a dynamic and adaptive value for the retransmission delay. The protocol ensures that information is not lost due to dropped packets and that packets are received in the correct order.

Each packet is sent by using a three attempts scheme. That is, if after three attempts no ACK is received, we suppose that the channel is currently busy or too noisy and the content sending is dropped.

On top of this flow-control protocol there is a lightweight transport protocol that is used to establish a connection between a master node, and a client node. Figure 3 shows a simple sequence example. Basically the master device “listens” to incoming connections. Connections can be established in a unicast manner, by providing the address of the master device, or using an anycast approach, thus sending to the generic “oooooooo” address and thus receiving the reply from the close-by listening device. This possibility allows for a greater flexibility in establishing dynamic topologies in rural areas, for example.

4.4.3 COMMERCIAL APPLICATIONS

4.4.3.1 OFF GRID MESH DEVICES: SONNET AND goTENNA

Both of the following devices use LoRa to create a mesh network and have been designed for Emergency Off-Grid Communication, where cellular towers or land-line phones are not physically reachable.

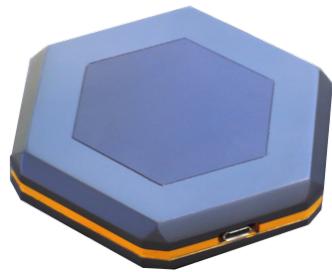


Figure 4.7: Sonnet

Sonnet², in Fig. 4.7, connects to the smartphone via WiFi allowing the user to send texts, voice messages, images, data, files and share GPS locations to any other Sonnet users up to several kilometers away, thanks to LoRa. This completely removes smartphones' dependency on cellular grid and other network infrastructure, and allows Sonnet to be used even when there is no cellular connectivity or Internet access.

According to the product's Kickstarter page³ "Sonnet's mesh network dramatically increases the effective range beyond point-to-point range by relaying data through other deices. With Sonnet, data can be relayed up to 16 times to achieve a maximum range of 80 km (50 miles)".



Figure 4.8: goTenna Mesh



Figure 4.9: goTenna Pro

²www.sonnettech.com

³www.kickstarter.com/profile/sonnet/created

The goTenna⁴, in Fig. 4.8, offers similar functions as the Sonnet, allowing to send text & GPS locations without a cellphone with Internet connection. Mesh-networking allows to relay messages from a node to another until they reach destination.

A compact and ruggedized network management kit, the goTenna Pro X, in Fig. 4.9, allows control for larger teams that operate in complex environments where no service is not an option.

As Sonnet, goTenna has raised the funds necessary to enter the market as a crowdfunded project on Kickstarter⁵.

Compared to the projects in 4.4.1.1 and 4.4.1.2, Sonnet and goTenna are more complete and offer a more stable network, thanks to the fact that these products have been thoroughly tested and produced on a bigger scale.

4.4.3.2 MESH WiFi

Mesh WiFi, or Whole Home WiFi systems, consists of a main router that connects directly to the main modem, and a series of satellite modules, or nodes, placed around the house for full WiFi coverage. Each node serves as a hop point for other nodes in the system and are all part of a single wireless network and share the same SSID and password, unlike traditional WiFi routers. Weakened signal or WiFi dead spots of the latter are the result of physical obstructions (floor, doors, and walls).

A modular mesh whole home WiFi system is flexible and scalable, giving a customizable method of expanding WiFi coverage without the need to add range extenders, which are certainly effective when it comes to increasing the router range, but they do so at the expense of WiFi performance, which gets cut in half.

It's just like installing lighting fixtures to illuminate your home; you can place your nodes anywhere in your home. You choose which rooms need the coverage, and when it's time to add more to extend the signal even further.

Wi-Fi 6 is an evolution of 802.11ac technology that promises increased throughput speeds (up to 9.6Gbps), less network congestion, greater client capacity, and better range performance thanks to the new and improved wireless technologies, including Orthogonal Frequency-Division Multiple Access (OFDMA). OFDMA improves overall throughput by breaking Wi-Fi channels into sub-channels, allowing up to 30 users to share a channel at the same

⁴ www.gotenna.com/

⁵ www.kickstarter.com/profile/gotenna/created

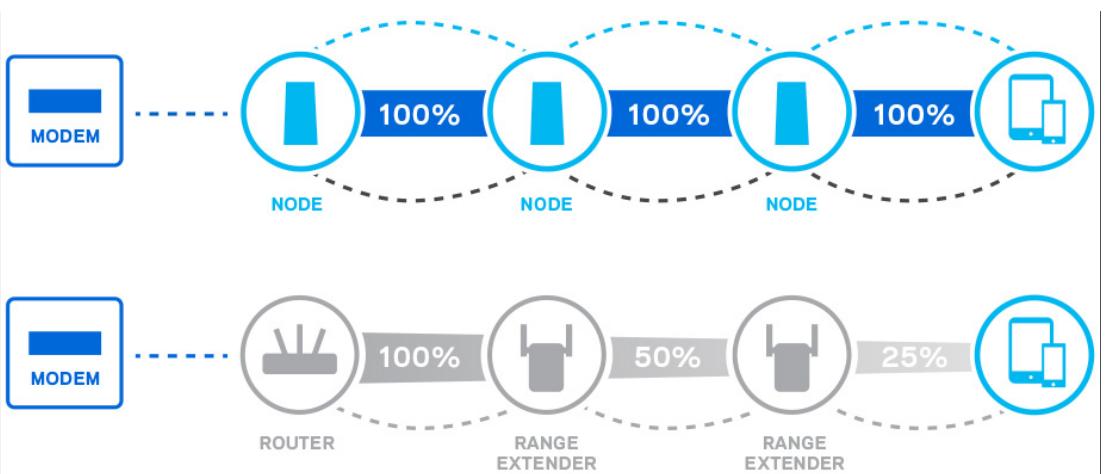
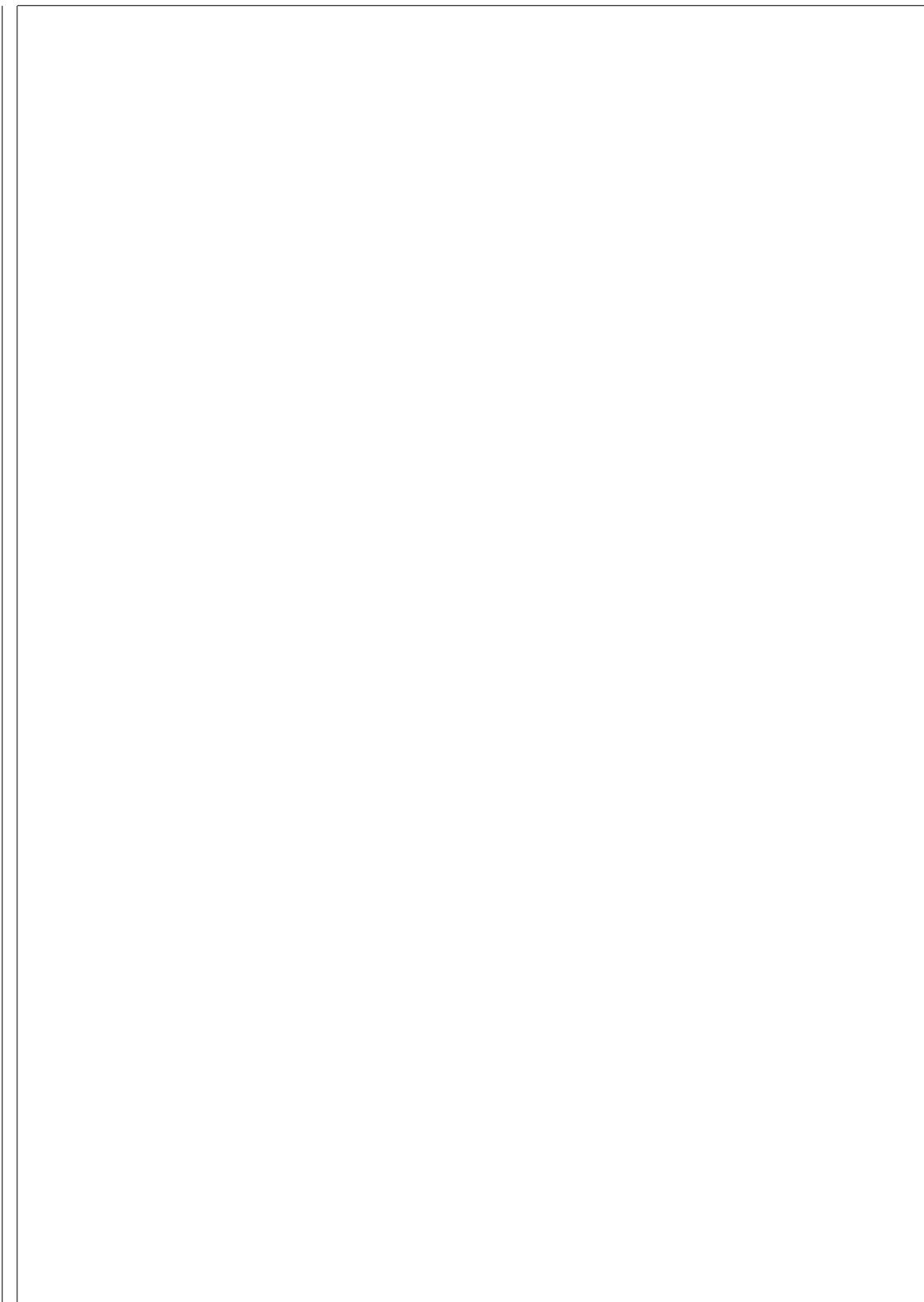


Figure 4.10: WiFi 6 mesh nodes vs WiFi range extenders performance

time. Additionally, 802.11ax takes advantage of previously unused radio frequencies to provide faster 2.4GHz performance and uses MU-MIMO streaming, too. Some Wi-Fi 6 devices can also communicate on the less-crowded 6GHz band, which was recently opened for Wi-Fi and is known as Wi-Fi 6E.

Many important manufacturers for network hardware, like Netgear and Cisco, have already implemented such technology and functions in their products.



*Keep
It
Simple
Stupid*

Kelly Johnson

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

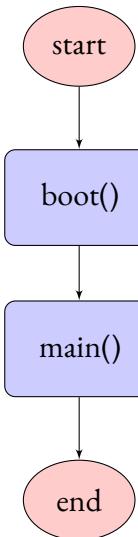
Visione da generale a specifica di ciasun componente

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

5.4.2 SLEEP CYCLE

5.4.3 SUPPORTED MESSAGES

5.5 USE CASES

5.5.1 MOBILE NETWORK

5.5.2 FIXED NETWORK

5.5.3 HYBRID NETWORK

There's no reason to have a plan B because it distracts from plan A.

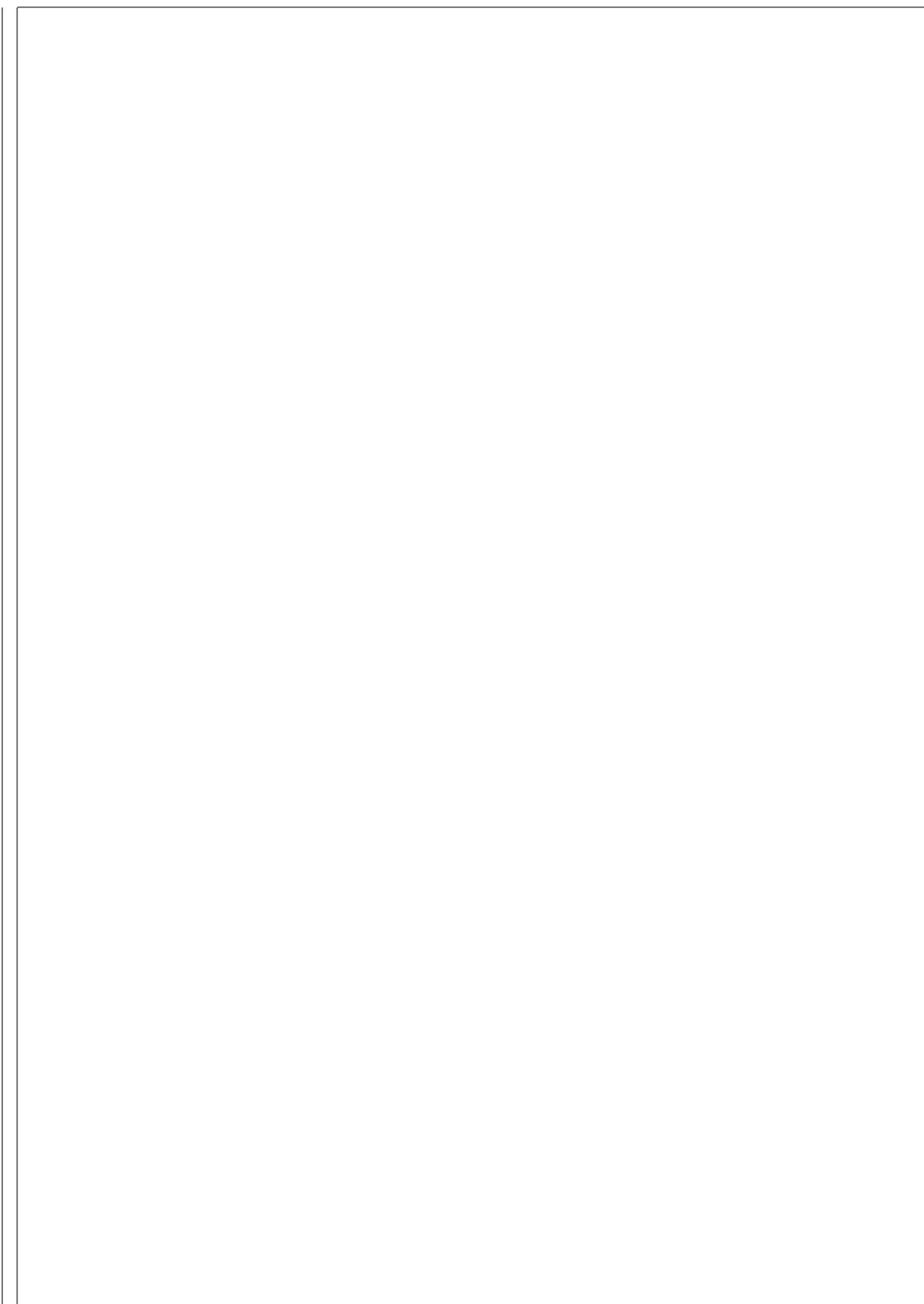
Will Smith

6

Results and experimentation

6.1 EXPERIMENTS

6.2 RESULTS



Be fearful when others are greedy, and greedy when others are fearful.

Warren Buffet

7

Conclusions

7.1 FUTURE WORK

7.1.1 HARDWARE IMPROVEMENTS

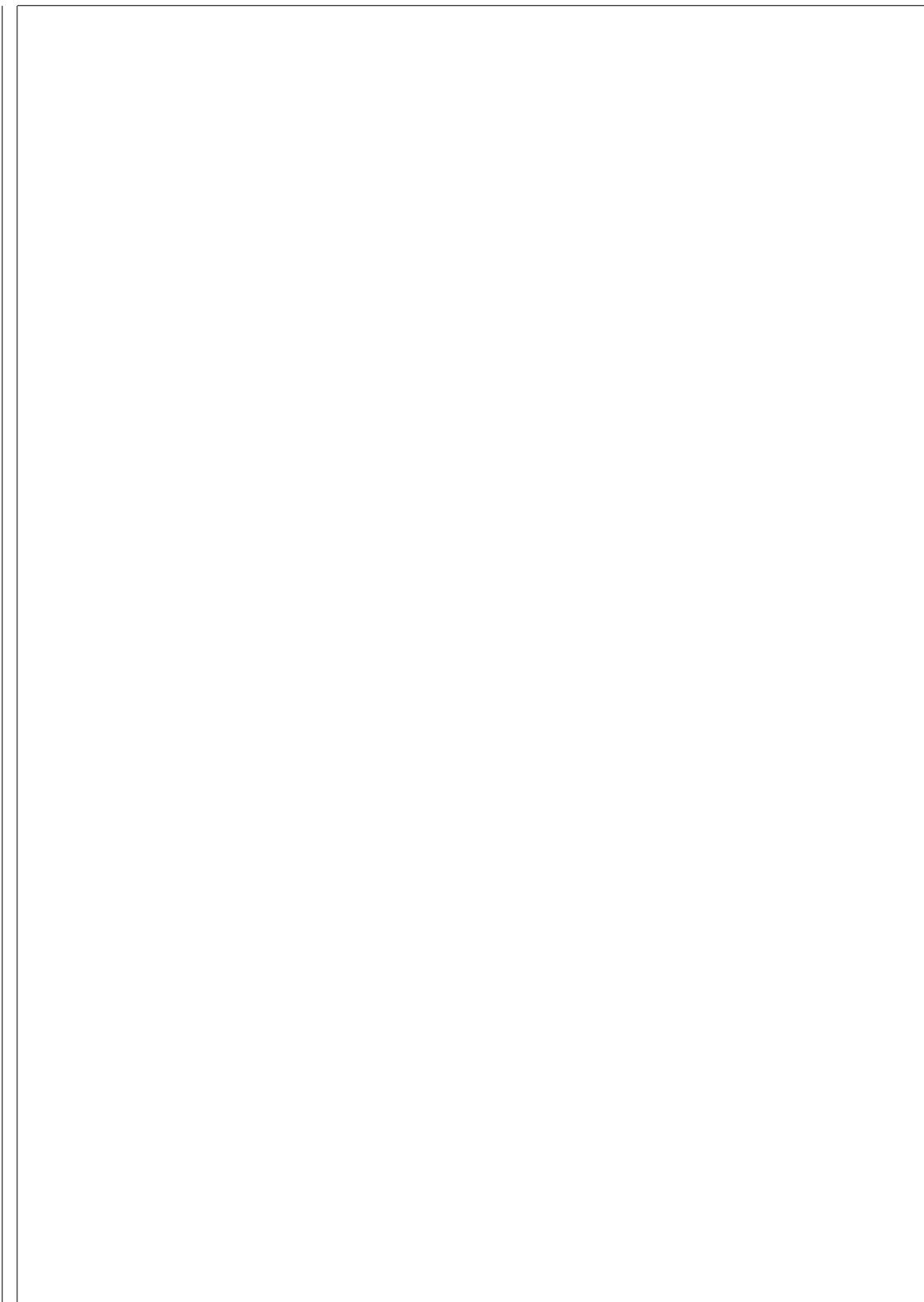
7.1.2 SOFTWARE IMPROVEMENTS

7.2 PERSONAL CONSIDERATIONS

7.2.1 ABOUT THE PYCOM BOARDS

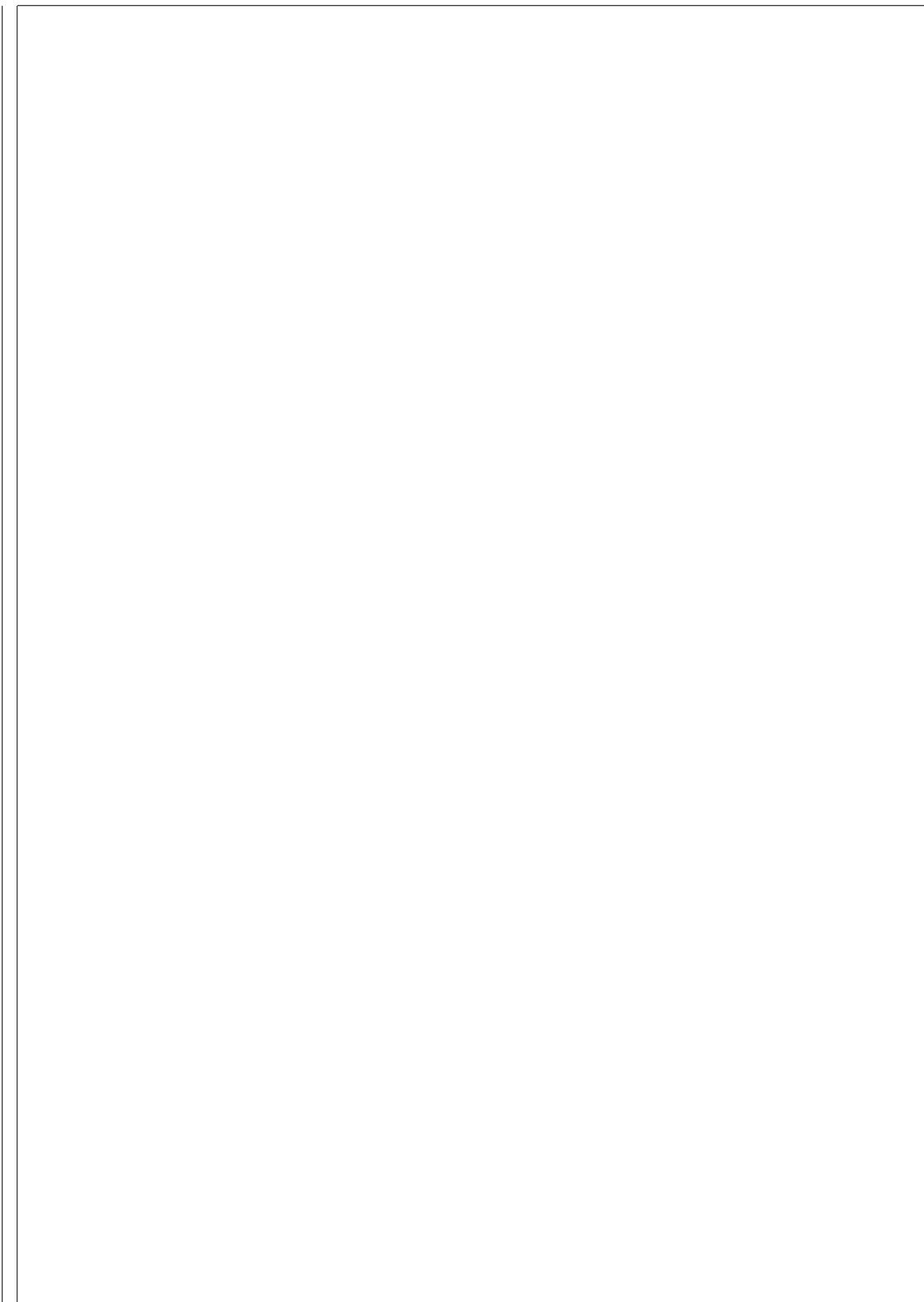
Compared to working with other boards

7.2.2 ABOUT MESH NETWORKING



Acknowledgments

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References

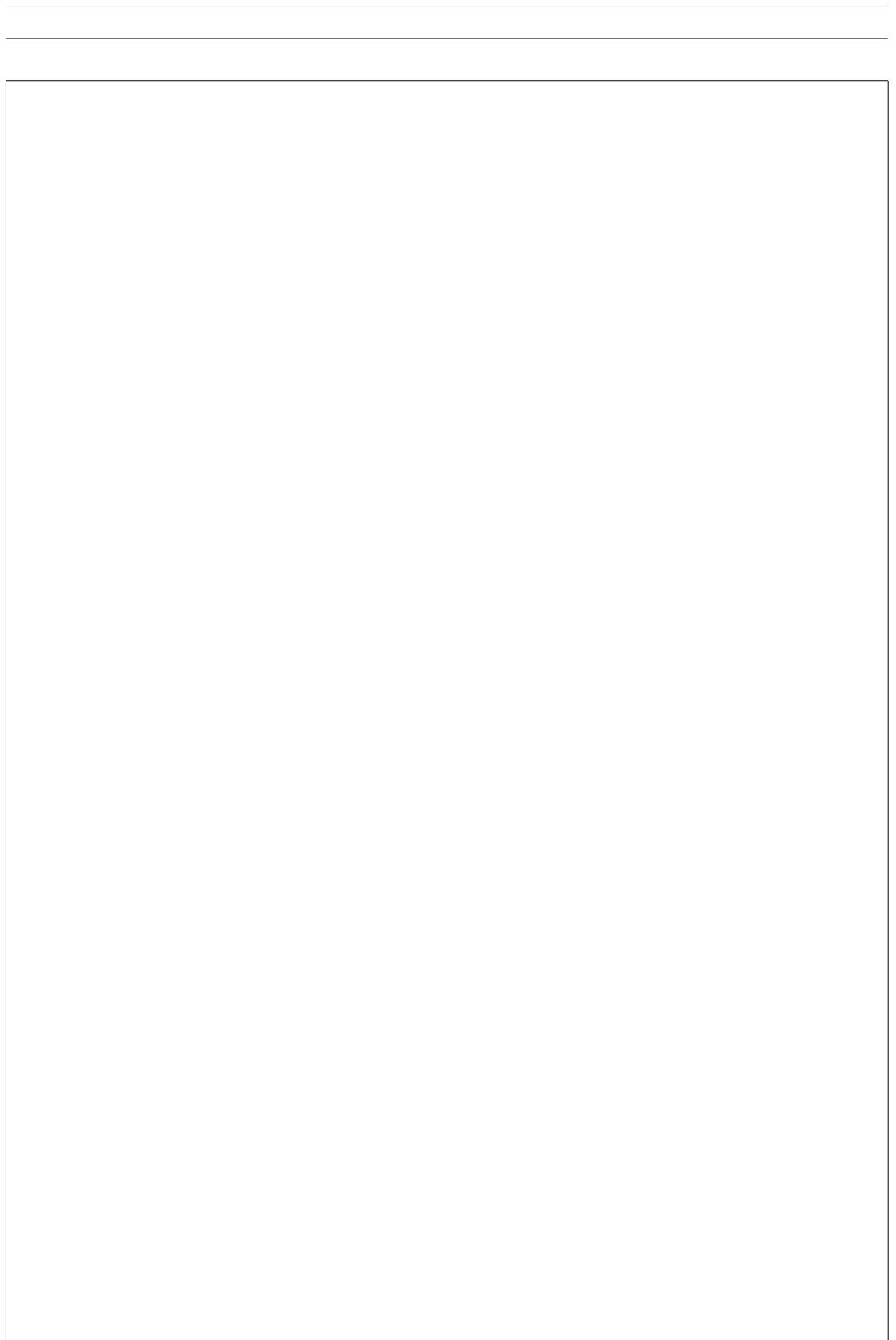
- [1] A look back at the london smog of 1952 and the half century since. [Online]. Available: <https://ehp.niehs.nih.gov/doi/abs/10.1289/ehp.110-a734>
- [2] R. E. Munn, “The design of air quality monitoring networks,” *Palgrave Macmillan, London*, pp. XIII, 109, 1981.
- [3] Intelligent world: the state of iot.
- [4] K. Ashton. That ‘internet of things’ thing. [Online]. Available: <https://www.rfidjournal.com/that-internet-of-things-thing>
- [5] A. Bujari, O. Gaggi, and C. E. Palazzi, “A mobile sensing and visualization platform for environmental data,” *Pervasive and Mobile Computing*, vol. 66, p. 101204, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1574119220300705>
- [6] M. Roccetti, M. Gerla, C. E. Palazzi, S. Ferretti, and G. Pau, “First responders’ crystal ball: How to scry the emergency from a remote vehicle,” in *2007 IEEE International Performance, Computing, and Communications Conference*, 2007, pp. 556–561.
- [7] W. E. A. N. J., “Classifying apparatus and method,” Patent US2 612 994A. [Online]. Available: <https://patents.google.com/patent/US2612994A/en>
- [8] 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.
- [9] “Verizon data breach digest.” [Online]. Available: <https://enterprise.verizon.com/resources/reports/data-breach-digest-2017-perspective-is-reality.pdf>
- [10] 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.

- [ii] “Internet of things in the 5g era - opportunities and benefits for enterprises and consumers.”
- [i2] 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.
- [i3] 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.
- [i4] 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.
- [i5] M. Agiwal, A. Roy, and N. Saxena, “Next generation 5g wireless networks: A comprehensive survey,” *IEEE Communications Surveys Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.
- [i6] “The iot business index 2020: a step change in adoption.”
- [i7] 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>
- [i8] S. Hu, C. Xiong, Z. Liu, and L. Zhang, “Examining spatiotemporal changing patterns of bike-sharing usage during covid-19 pandemic,” *Journal of Transport Geography*, vol. 91, p. 102997, 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S096692321000508>
- [i9] P. E. Green, *Computer network architectures and protocols / edited by Paul E. Green, Jr.* Plenum Press New York, 1982.
- [20] *TCP/IP Tutorial and Technical Overview. An IBM Redbooks publication.*
- [21] P. K. Bondyopadhyay, “Guglielmo marconi - the father of long distance radio communication - an engineer’s tribute,” in *1995 25th European Microwave Conference*, vol. 2, 1995, pp. 879–885.

-
-
- [22] B. S. Chaudhari, M. Zennaro, and S. Borkar, “Lpwan technologies: Emerging application characteristics, requirements, and design considerations,” *Future Internet*, vol. 12, no. 3, 2020. [Online]. Available: <https://www.mdpi.com/1999-5903/12/3/46>
- [23] “test.” [Online]. Available: <https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/>
- [24] *noma*. [Online]. Available: <https://arxiv.org/abs/1504.07751>
- [25] *Wireless Mesh Networks*. [Online]. Available: https://books.google.it/books/about/Wireless_Mesh_Networks.html?id=utTrj26vayoC
- [26] H. Badis and A. Rachedi, “Chapter 23 - modeling tools to evaluate the performance of wireless multi-hop networks,” in *Modeling and Simulation of Computer Networks and Systems*, M. S. Obaidat, P. Nicopolitidis, and F. Zarai, Eds. Boston: Morgan Kaufmann, 2015, pp. 653–682. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/B9780128008874000237>
- [27] V. Bahl, R. Chandra, P. Lee, V. Mishra, J. Padhye, D. Rubenstein, and Y. Yu, “Opportunistic use of client repeaters to improve performance of wlans,” *IEEE/ACM Transaction on Networking*, vol. 17, no. 4, pp. 1160–1171, August 2009, currently deployed IEEE 802.11 WLANs (Wi-Fi networks) share access point (AP) bandwidth on a per-packet basis. However, the various stations communicating with the AP often have different signal qualities, resulting in different transmission rates. This induces a phenomenon known as the rate anomaly problem, in which stations with lower signal quality transmit at lower rates and consume a significant majority of airtime, thereby dramatically reducing the throughput of stations transmitting at high rates. We propose a practical, deployable system, called SoftRepeater, in which stations cooperatively address the rate anomaly problem. Specifically, higher-rate Wi-Fi stations opportunistically transform themselves into repeaters for stations with low data-rates when transmitting to/from the AP. The key challenge is to determine when it is beneficial to enable the repeater functionality. In this paper, we propose an initiation protocol that ensures that repeater functionality is enabled only when appropriate. Also, our system can run directly on top of today’s 802.11 infrastructure networks. We evaluate our system using simulation and testbed implementation, and find that SoftRepeater can improve cumulative throughput by up to 200[Online].

Available: <https://www.microsoft.com/en-us/research/publication/opportunistic-use-of-client-repeaters-to-improve-performance-of-wlans-3/>

- [28] K. Nakamura, P. Manzoni, M. Zennaro, J.-C. Cano, and C. T. Calafate, “[invited] loractp: a lora based content transfer protocol for sustainable edge computing,” in *2020 16th International Conference on Mobility, Sensing and Networking (MSN)*, 2020, pp. 539–545.



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