POLITECNICO DI TORINO

Master degree course in Mechatronic Engineering

Master Degree Thesis

Experimental application for Bluetooth Low Energy industrial systems

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July 2022

Abstract

To face the nowadays challenges of including Internet of Things devices in production systems, to automate and simplify the collection of data, the study of transmissions and protocols is of paramount importance. By starting on two example boards and the Bluetooth Low Energy as chosen protocol, a test bench is defined to simplify and characterise the in-field system where they can be applied: a capping machine produced by AROL Closure Systems. The aim of this thesis work is to analyse and create an experiment where different boards can be used to decide which one has a better communication performance and test its limit conditions, with a structure that can be modular and adapted for different implementations.

Acknowledgements

I received a lot of support and assistance during this year, in which this thesis has taken its shape.

I would like to thank my academic supervisor, Professor Massimo Violante, whose suggestions were invaluable and let me take the right path when I was in need. Your patience and guidance brought my work to a higher level and pushed me to improve my skills.

I would like to acknowledge my colleagues from my internship at AROL S.p.A. for their wonderful collaboration. In particular, I would like to thank Denis Ruffino, who let me participate in this wonderful project, and Gianpaolo Macario, who taught me so much that he made the engineer I am today.

In addition, I would like to thank my family, who was there for me for everything I needed. You always supported me and I would be never here if it were not for you. Thanks especially to my sister Marta, who helped me even if she was overwhelmed by her commitments.

I could not have completed this dissertation without the help of my friends, especially Eleonora, Aurora, Blu, Nathalie, Luca, Caterina, Greta, Alessandra and Annalisa, with all their love, who provided stimulating discussions as well as happy distractions to rest my mind outside of my research.

"Cavilla sui tuoi limiti e senza dubbio ti apparterranno"
Richard Bach

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Acronyms

ATT
: Attribute Protocol

API
: Application Programming Interface

BLE
: Bluetooth Low Energy

CAD
: Computer Aided Design

CRC
: Cyclic Redundancy Check

GAP
: Generic Access Profile

GATT
: Generic Attribute Profile

IDE
: Integrated Development Environment

IoT
: Internet of Things

IRK
: Identity Resolving Key

ISM
: industrial, scientific, and medical radio band

KPI

Key Perofrmance Indicator

LL

Link Layer

L2CAP

Logical link control and adaptation protocol

MTU

Maximum Transfer Unit

PDU

Protocol Data Unit

PHY

Physical Layer

PLA

Polylactic acid

PLC

Programmable Logic Controller

PMC

Portenta Machine Control

RSSI

Received Signal Strength Indicator

SIG

(Bluetooth) Special Interest Group

SMP

Security Manager Protocol

SNR

Signal-noise ratio

SoC

System on Chip

UC

Use Case

UUID

Universally Unique Identifier

Chapter 1

Introduction

1.1 Industry 4.0

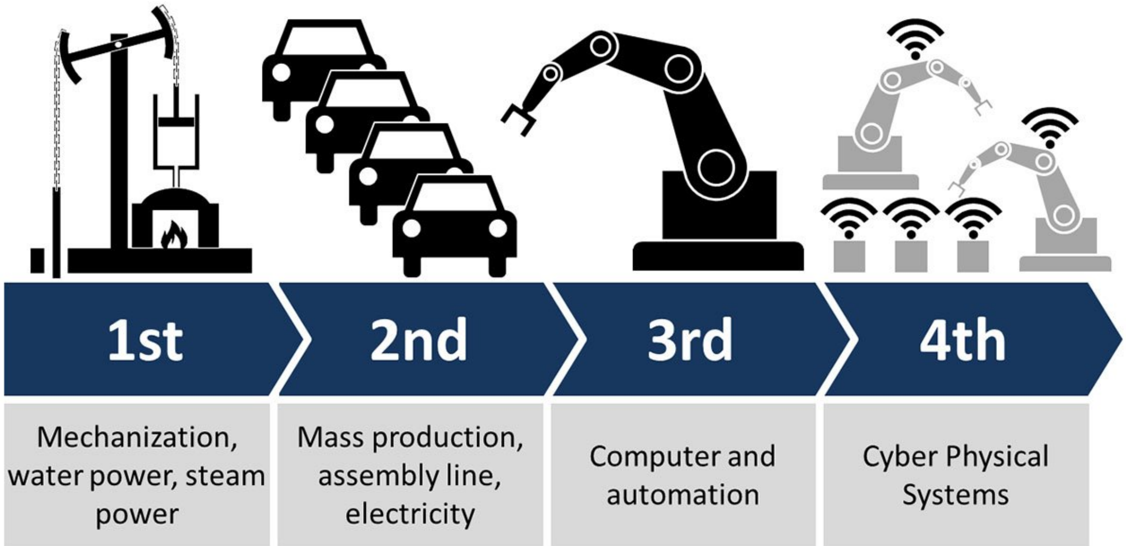


Figure 1.1: The industrial revolutions [1]

The technological advancement of the last years has shaped enormously how living beings inhabit the world: changing habits, relationships with others, but also the business world, modifying economic, social, and cultural scenarios, even though it is still too early to quantify the impact it may have in the future.

When the financial system is overwhelmed by the innovations that lead to a radical transformation, historians define that as the **industrial revolution**. There have been three main revolutions in the past and this period come to be defined as the fourth one.

The main factor triggering industrial revolutions is the role those **technological innovations** take on within the manufacturing process, the integration of which is favoured by man's ability to use them to improve production activities. Because of globalization, other similar global-scale phenomena and continuous market competition, the difference between the fourth revolution and the previous ones is that it is characterized by a **quick geographically diffusion** and a **very fast affirmation** [2].

The peculiarity is that the raw material is not something physical like it was before, but **digital**. It is based on data, connections, digital interests, and knowledge. For this reason, what is emerging is that society is not only based on objects but also people's preferences, starting the digital marketing.

The term **Industry 4.0** was born in 2011 during the Hannover Fair, where Germany, with the presentation of the Zukunftsprojekt Industry 4.02 project, decided to renew its manufacturing mechanisms, becoming one of the most important industries in the world. The experts do not think it is a proper revolution, where new machines or processes have been created, but more like an evolution of the third one. Instead of focusing on the automation of machines and their development, it tries to digitalize everything in society, from proceedings in factories to everyday objects, combining virtual and physical worlds to create a digital ecosystem. [3]

With these interconnections between systems, now data and information are used in much more efficient ways, allowing a reduction in costs and transmission times. The innovations do not include only the production but also the organization and the structure of an industry, being able to become more capable, effective, and able to modify depending on the market requests.

The digital transformation is based on some fundamentals which, if applied properly, will surely improve, and have a relevant impact on an organization, leading to higher profitability than traditional businesses. These principles are [3]:

- **Interoperability and interconnection**: the ability of machines, devices, sensors, and people to communicate with each other via the IoT.

- **Information transparency**: provides operators with comprehensive information to make decisions, by collecting immense amounts of data and information from all points in the manufacturing process, identifying key areas that can benefit from an improvement to increase functionality.

- **Technical assistance and service orientation**: the technological facility of systems to assist humans in decision-making and problem-solving, and the ability to help humans with difficult or unsafe tasks.

- **Decentralized decisions**: the ability of cyber-physical systems to make decisions on their own and to perform their tasks as autonomously as possible. Only in the case of exceptions, interference, or conflicting goals, the tasks are delegated to a higher (human) level.

- **Real-time capability**: the ability to collect data in real-time, leading to flexibility in the decision process.

- **Sustainability**: the ability to optimize the consumption of energetic resources to valorise the social and environmental aspects.

- **Virtualization**: the reproduction of a "digital copy" of the industry, through sensors applied to the physical hardware, creating an actual connection between the physical and digital world. The second one is used for augmented reality to evaluate the products, make simulations, and manage the rapid changes in the market.

So, the usage of wireless communication has become central in recent studies because it is what permits the transfer of data to control not only the product itself but also the **needs of final customers** and the **algorithms for decision-making**.

It is important to support the technological advancement of a firm with an adequate **strategic plan** for the business itself. If it is not done accordingly, the company would not be capable of modifying itself depending on the needs, with a medium-long term vision. This movement does not include only the manufacturing work but all the aspects, from the design to the commercial aspect.

The combination of digital devices and the internet with the physical world, the bringer of a new intelligent and connected reality, is what makes possible the fourth industrial revolution based on a transformation of an entire industry. The innovation of the technology developed in the last century has a fundamental role in the realization of a digital world in which every being, living or not, is connected.

These types of instruments are exactly the true pillars on which Industry 4.0 is based, which let to understand better its meaning and value. So, it is due to them that the operative chain is more efficient, and dynamic, allowing these components to elaborate expedients and refinements.

The tendency toward digitalization is by far already consolidated in the entrepreneurial universe, however, its application is still limited. It is important to focus on the **advantages** that these technologies apport, not only on their efficiency in the process systems. Thanks to the integration and the interconnection, they can be used to save resources, the enabling of new business models, a better cycle of life for products, the reduction of time-to-market, and the ability to know what the markets and the population are asking. For this reason, is important not only to "possess" these improvements but also to know how to use them, otherwise it would be useless and just a waste of money.

Industries without a strategic plan would lose the ability to create an innovative product, follow the requests from the extern, and not use at best the new channels of communication. Important is also the collection of data from the final customers, which will create a customised product for the target of the business.

The creation of a new economic ecosystem let the integration of different technologies: we can highlight principally **nine**, which are transforming not only the relationships but also how companies work. [4]

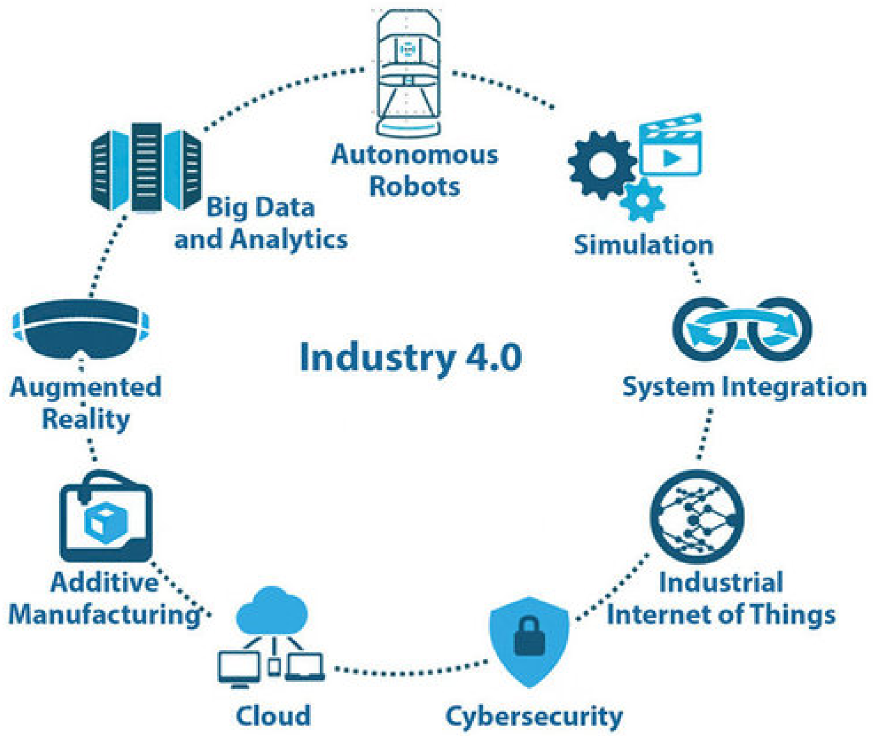


Figure 1.2: The nine pillars of Industry 4.0 [5]

1.1.1 Autonomous robots

Autonomous robots have become an important investment for companies since there are environments where precision and speed are essential, usually implied in the production system. In recent years robotics have made a lot of improvements in various aspects, such as flexibility, cooperation, and autonomy. Everything will bring better collaboration between humans and robots. Manufacturers in many industries have long used robots to tackle complex assignments. [6]

1.1.2 Simulation

The simulation is the implementation of instruments to create a virtual reality which simulates the physical one, to evaluate models, products, and a production process. The aim is to understand what can be changed to have the perfect design before the product itself is created and sold to the market. For now, 3D simulations are already used but, in the future, they will surely be more powerful, representing entire production plants. These simulations are used in real-time to improve machine settings, cut costs and time, and improve the efficiency and quality of the final product. [7]

1.1.3 System Integration

The system integration interconnects every phase of a productive cycle, from the design and research to the assistance of the final customer. This is **vertical integration**. However, this improvement happens also to the horizontal systems, like the connection and coordination between suppliers and clients, to have better collaboration. This leads to having a central integrated system, made by all the different departments of a firm.

This approach has mainly two benefits to the production system: the **maintenance** and the **understandability** of the machines. In fact, with the usage of sensors inside an electromechanical apparatus, it becomes easy to see when a certain device is facing troubles, or if there is a solvable issue, leading to an improvement of the action of the system and the quality of the final product. Moreover, by understanding why a certain machine encounters problems, the design department and the field service can work to not only avoid that from the beginning but also to act more effectively on the requests from the end-users. Since data are retrievable from wherever part of the world by being on the cloud, also companies that act in different countries can see what the issues of the users are and help them in a brief time. For this reason, it is very important to connect technological capability to an operational power. The difference between the two is that while the former is more focused on unifying the different parts of a company to have better efficiency and coordination, the latter is more centred on the physical work at the manufacturer level. If these two sides of a coin can be merged, the efficiency of enterprises will surely be improved, with a reduction in costs and better-quality products. [8]

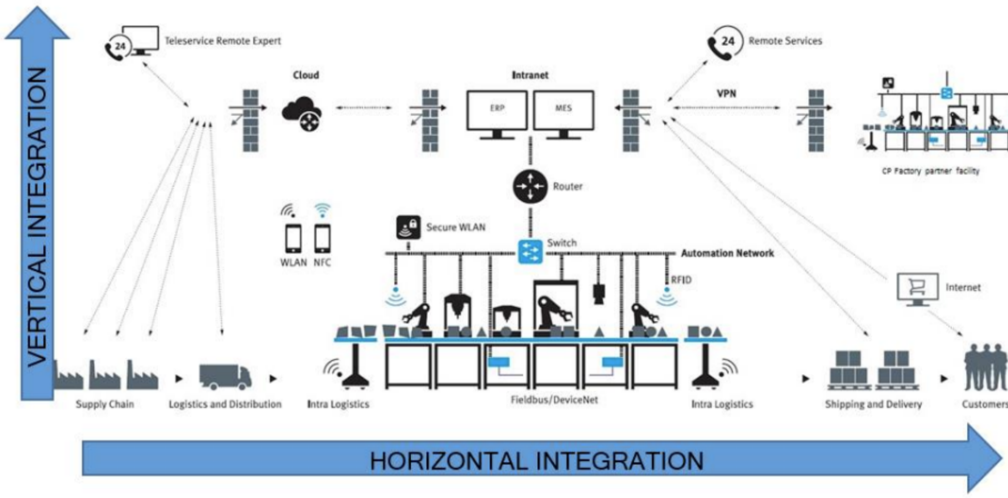


Figure 1.3: System Integration [9]

1.1.4 Internet of Things

The Internet of Things (IoT) is one of the key features of Industry 4.0. It indicates the usage of the internet to connect different devices and create an integrated digital workspace. This connection does not regard only the people but also the machinery inside of a company, to have direct control over how things are working. As more time passes, it has taken a significant role in the constant increase of the complexity of industrial systems which cannot pursue those goals of efficiency and coordination explained before if not updated on the recent technologies.

The IoT has economic advantages since it improves the operational efficiency and the production, since there is a saving in time and costs, having better coordination and autonomous decisions since they are all decentralized. It has a new modus operandi because it let the production change depending on the requests of the market, having also better quality on the final product since it is more personalized for the customers. [10]

1.1.5 Cybersecurity

The augment of connectivity between devices also means an increase in security to protect the systems from external threats and data thieves.

Cybersecurity brings together all those technologies that help a computer system to prevent or defend itself from attacks which can cause the loss or compromission of sensible data. The frequency of those threats increased over time since hackers try to obtain information to damage the privacy and the security not only of companies but also at the government level.

Since in a technological transformation the industry must renew completely its infrastructures, it put on the risk its computer security. These problems are taken care of by specialists on these matters, who are continuously put on the edge with new challenges since the hacker attacks are always more ingenious. However, the digital transformation is still an opportunity to be more competitive, also from this point of view. Companies are investing in automation technologies which assist with security to have more rapid response times and better coordination with those who oversee these matters. [11]

1.1.6 Cloud

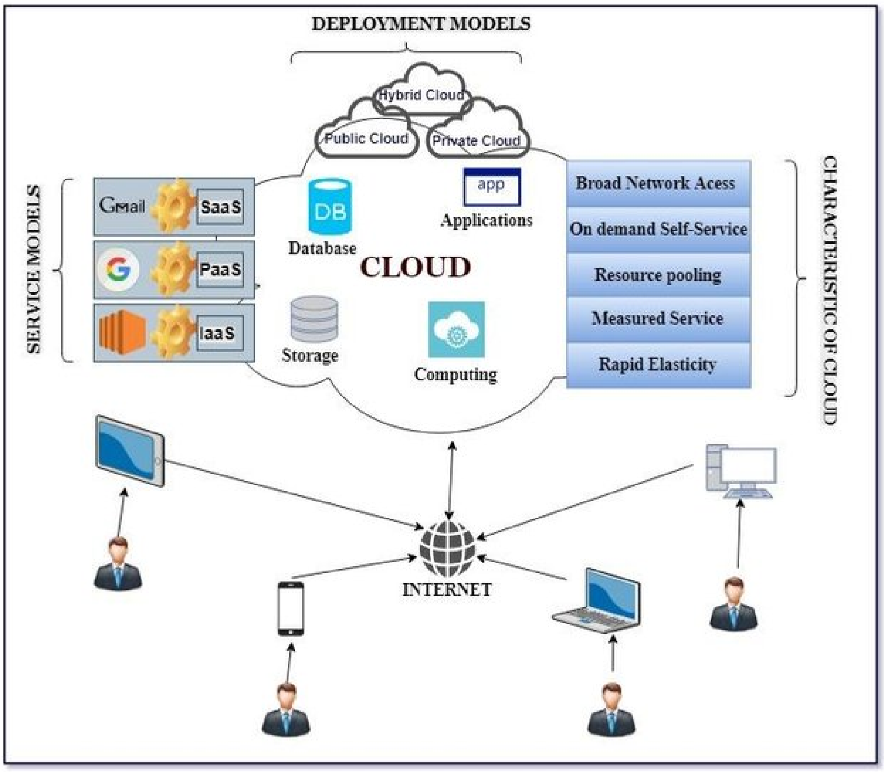


Figure 1.4: Cloud computing [12]

Following the birth of the technologies described above, cloud computing has taken place. It is the gathering of information and data inside industries' storage centres.

With the development of the internet and the capability of collecting different types of data in short times, the ability to store massive volumes of data in servers was needed. Usually, these were locally inside the headquarters buildings of companies, now instead the need of having them everywhere around the world and in real-time is essential, so the cloud has been born, which indicates the ensemble of utilities offered by a third party by using servers and internet services.

Cloud computing is a product offered by some companies where the users decide to abandon the needed hardware and software to store their data, entrusting these external resources, where they can retrieve their information with decided a-priori time and costs. In this way, the companies reduce the price of storage and have a very flexible ability to retrieve their data from everywhere in the world.

The issue is about the security of these data because of not only the risk to lose them but also having to stock them in a remote part of the world. For this reason, is up to the client to use these kinds of facilities with awareness of the risks.

In a cloud system the involved figures are:

- **Service provider**: it provides one or more services for the storage of data and transmission over the internet. Usually, they use a pay-per-use system, to make payments only for the effective utilisation of the product.
- **Administrator**: it is the figure who manages the correct integration between the cloud and the already implemented systems in a company.
- **Client**: it is the final customer, the one who uses the services from the provider with the help of the administrator.

Cloud computing is divided principally into two parts: the Front-End and Back-End, interconnected by the internet.

The first one is constituted by the architecture that is interfaced with the client and is composed of the principal elements which influence the utilisation of the customer. It is what the client uses, the application or web interface, which helps the interaction of the user with the cloud system. Usually, it is implemented in the software itself and in the hardware that the client employs to access the service. In this way, the device used does not need a high computational power since most of the operations are done in the cloud.

The back-end architecture instead is made of all those elements that allow a fluid and non-buggy usage of the resources. The application is the first element of the back end, which manages the interface used by the customer and solves any kind of issue.

The service represents what is offered to the client and can comprehend different tasks: storage, the availability of utilisation of development environments for applications and web solutions, the management of data etc. Depending on the utilisation, the service can vary in its configuration, while the management software is the one that is responsible for the allocation of resources depending on the requested activities.

The principal disadvantage of cloud systems is given by the low availability of resources with respect to the physical servers. For this reason, bad management can cause trouble in the service provision.

Companies are already using cloud-based software for some industrial and analysis applications, but with the advent of Industry 4.0, a major number of data will be stored, needing more interconnection and sharing between sites. At the same time, the cloud services will improve, reaching shorter reaction times. Data and functionalities will always be more distributed in the cloud, consenting more services based on production systems. [12]

1.1.7 Additive manufacturing

Additive manufacturing, called colloquially 3D printing, regroups all those processes which produce a three-dimensional object by a succession of addiction of material on layers.

This technology has been already used in the past, anyway, the improvement in the digital world led to a significant reduction in costs, waste management and variety of the materials/design that can be printed. 3D printers are now accessible by the public, realizing not only complex forms but also unconventional materials, not only PLA (Polylactic acid) and ABS (Acrylonitrile butadiene styrene) anymore. This customization in industrial production, after all, has to encounter some issues, like the costs for the modifications to the product for every customer. For this reason, it is not utilised for mass production.

The fact that objects are created as unique pieces and not assembled by hand increases the quality and the precision, allowing to have a better product, with less cost and time than an assembled one. However, before a purchase of a 3D printer from a company, one must apply a strategy to be effective and use this kind of technology in the most efficient way possible. By being quite expensive and difficult to handle, it may be more useful to contact a company that produces pieces for third parts rather than produce the pieces for an entire production. [13]

1.1.8 Augmented reality

Augmented reality (AR) is the enhancement of sensorial perception through information, manipulated and transformed into electric output, not perceived by human senses. The continuous research on digital transformation has brought these drivers into positive results for the industrial sector.

The environments where this technology can be implemented are various, starting from the building industry [14], where structures can be seen and designed even before their actual construction to avoid the highest number of errors, to the emergency one [15], where sensors can transmit real-time data and advise the right department (police, firefighter, hospitals) to save people' lives. The sanitary sector [16] and the educational one are already using it, to improve the preparation of their students through the observation, integrating the theoretical study with a practical one.

This technology is not already well spread, but it will be used at every level in most sectors to improve their activities.

1.1.9 Big data and analytics

What is different between the fourth industrial revolution and the others is the usage of information, collected at every moment from everything. How to utilize this material is one of the main challenges for analysts and managers who are in charge of creating strategic assets for their own companies.

The name "Big data" in fact is given for the elevated quantity of data, which is not related to only one argument, coming from various sources other than the traditional ones, managed by different databases of a business. These are used for different purposes: from the design to the services offered to the public.

All of this must be managed by an appropriate usage of technology, adopted, and optimized to gather and evaluate an abnormous number of data, creating a standard procedure for real-time decisional processes. In this way, productions can be modified real-time, depending on the market requests. Usually, wireless communications and cloud services are utilized, due to the unlimited stocking space, and open-source programs, which guarantee that every data is taken and analysed. [17]

1.2 Application examples

	Bluetooth Mesh	Zigbee	Matter w/ Thread	Wi-SUN	Z-Wave
Market Focus	Lighting, Building Automation	Home Automation, Lighting, Building Automation, Metering	Lighting, Home Security, Home & Building Automation, Appliances	Metering, Street Lighting, Smart Cities	Home Security & Automation, Building Automation
Frequency Bands	2.4GHz	2.4GHz	2.4GHz	2.4GHz & Sub-GHz	Sub-GHz
IPv6 Connectivity	No	No	Yes	Yes	No
Cloud Connectivity	n/a, Gateway, Phones	Gateway	Border Router	Border Router	Gateway
Application Layer	Native Mesh Model	Zigbee Cluster Library	Matter (ZCL/ZAP)	n/a (DLSM, DALI, BacNet,..)	Device Command Class
Promoter Ecosystems	Amazon, Leedarson, Alibaba, Xiaomi,...	Amazon, IKEA, Signify, Somfy, Legrand, Tuya, Landis+Gyr...	Amazon, Apple, Google, Comcast, SmartThings, IKEA,...	Itron, Landis+Gyr, Cisco, Omron, Trilliant,...	Alarm.com, Ring, ADT, Leedarson, Assa Abloy,...
Mesh Forwarding	Managed Flooding	Directed Forwarding	Directed Forwarding	Directed Forwarding	Directed Forwarding
Routing Algorithm	n/a	Source Routing & AoDV (Ad-hoc On-demand Distance Vector)	Optimized RIPng (Routing IP Next Gen)	RPL (Routing for Low Power and Lossy Networks)	DSR (Dynamic Source Routing)
Additional Notes	Location services, Direct phone connectivity	Mature technology, 4000+ certified devices, Battery-less ZGP	Self-healing (Thread), State of art security, Large ecosystems interest	Large Networks, Long Range w/ OFDM	Mature technology, 3500+ certified devices, new Long Range in NA

Figure 1.5: Comparison of some relevant wireless standards [18]

The transfer of data can be actuated by using different protocols of communication, depending on what is the purpose of the application. Each one of them has a "preferential" utilization, like the Zigbee for smart homes or automation, Wi-SUN for smart cities, and others that are shown in the image above.

An interesting protocol, which is turning into the basis of the future interconnection, is **Bluetooth**, which has become much more famous due to its application on portable devices like mobile phones or smartwatches. Different studies allowed the creation of the Bluetooth 4, which introduces Bluetooth Low Energy, designed for very low power operation. The new features that this kind of protocol has are: transmits data over 40 channels in the 2.4GHz unlicensed ISM (industrial, scientific, and medical radio band) frequency band, supports multiple communication topologies, expands from point-to-point to broadcast. It is now also widely used as a device positioning technology, due to the capability to determine the presence, distance, and direction of another instrument. [19]

Interesting is also the improvement in the communication between these sensors, creating a **mesh network**, which means that every component transfers data to the other, ensuring a general idea of the system. Recent studies showed how not only to build these types of structures but also their scalability, design, and configuration. [18]

This technology is widely used in different areas, like smart homes [20] [21], cities [22] and personal applications [23]. Industrial automation is still a new territory where engineers are trying to implement sensors for computerization purposes [24] [25].

An example is *"Design and Implementation of Bluetooth Based Industrial Automation"* [26] which proposes a security industrial automation system that can be scalable and transferable also to an Android setup protected by passwords in case of a private application (smart homes). The authors focused principally on the following features: easy setup, easy to control and monitor, low cost, and efficient communication. They realized a system with flame and LDR (Light-Dependant Resistor) sensors to detect a fire inside a building, with the usage of Bluetooth to exchange data between the devices. Their experiment concludes that the system can work within a short-range, since they used a Bluetooth modem, even by using the Android operating system.

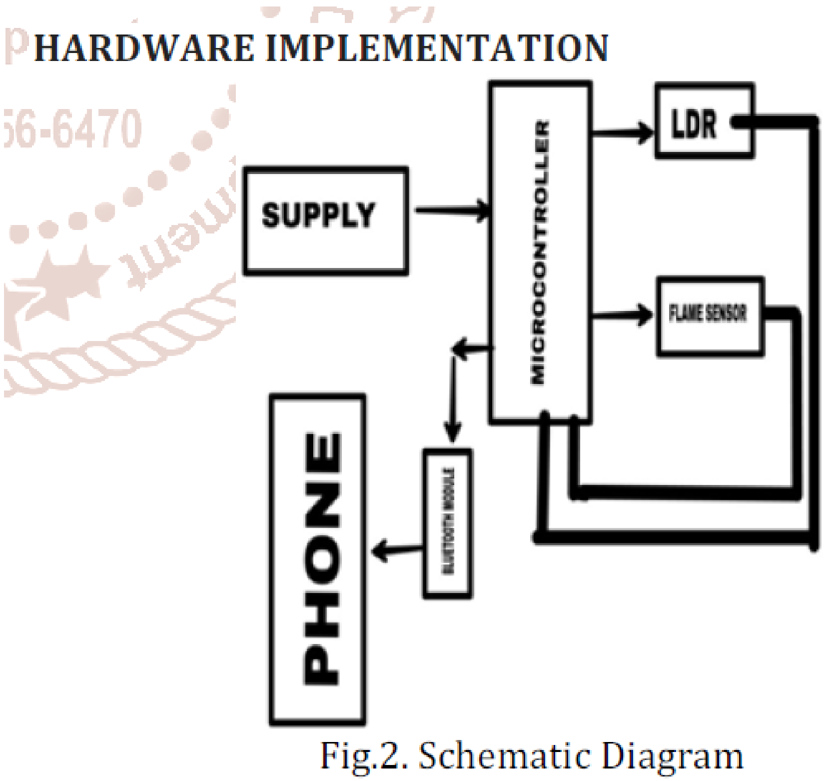


Figure 1.6: Block scheme of the experiment [26]

Another example is *"Bluetooth in Industrial Environment"* [27] which is an article about an initial study of how to implement Bluetooth communication in an office or establishment. The authors focused on the study of wireless communication and applied the usage of the Bluetooth transmission in a paper mill, which represents a complex process industry. To develop their project, they used an Ericsson Bluetooth Development Kit (EBDK). In each test position, 200.000 bits have been transmitted with AUXl packets, which have no CRC (Cyclic redundancy check) or FEC (Forward Error Correction). A restriction (apart from the 20.000 bits instead of the 1.6 bits that should be transmitted) is that only the payload has been studied and not the header errors. They concluded that since there is no FEC, the throughput is not high as the standard promoted if the distance is higher than four meters. Another thing regards the LOS (Line Of Sight) tests where they had to use the dynamic usage of FEC, which is not provided by the standard, which would also improve the safety of the data and reduce the need for re-transmissions. As a last concluding remark, they said that the Bluetooth could have the potential to offer a wireless transmission link even in quite harsh industrial environments, but additional error correction schemes and more adaptive error correction protocols would increase its applicability.

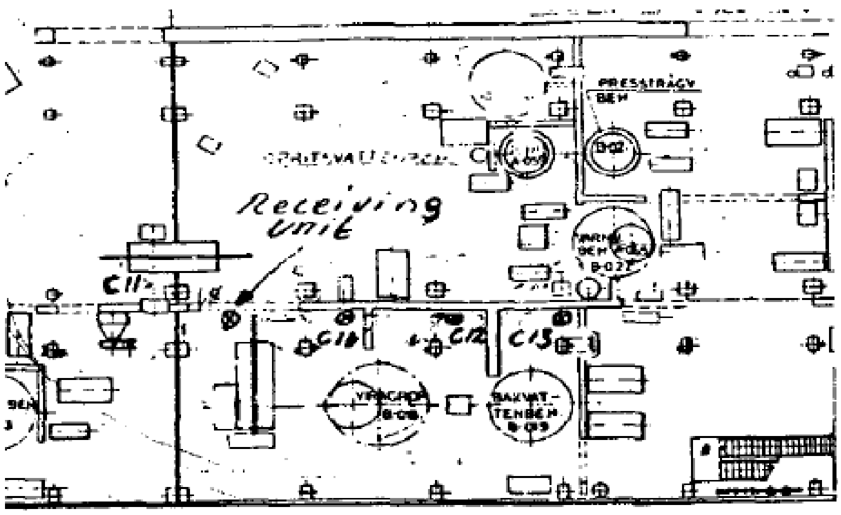


Figure 5.5 Sketch of the test area in the basement of the paper mill.

Figure 1.7: Test area in the paper-mill [26]

A third example is *"Determination of practical extremes of Bluetooth Low Energy: throughput, energy consumption and maximum range"* [28] which is a very interesting paper focusing on the evaluation of the performances of Bluetooth Low Energy version 5 determining range, throughput, and transmission powers through experiments in both indoor and outdoor environments. They started with a BLE connection between two Preview Development Kits of the nRF52840 from Nordic Semiconductor, with encoded PHY (125 kbps), which improves the communication even with low throughput. However, these developments do not confirm the promised 4-way range of the Bluetooth specification. As far as the indoor measurements, the

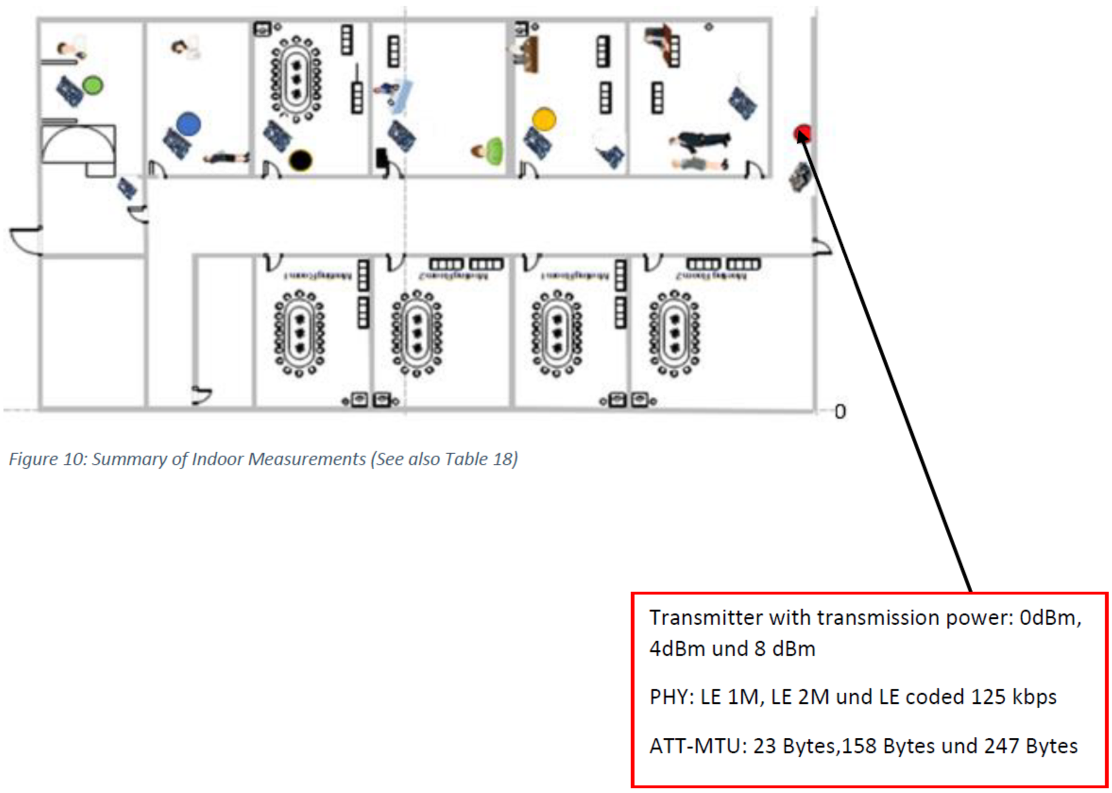


Figure 1.8: Indoor experiment [28]

authors noticed that the floor caused a reflection of the Bluetooth signal, together with the environmental conditions, the walls, and the furniture, depending on the material. The maximum range was 60 meters, and this distance allows many practical applications to be realized. Bluetooth 5 can be also used to control the machine within 60 meters. A concept for Bluetooth 5 in the industry is shown in the picture below, where the temperature of operating machines can be read, stored, and analyzed via BLE in a server. Unfortunately, a long-range mode is not suitable for faster processing because the data is encoded with eight symbols and requires more time to transmit than normal and high-speed modes. They also measured the throughput in the latter modality, with a result of 1283 kbps. This can be used in the automotive industry audio transmission or video transmission of the rear-view camera. Furthermore, the high-speed mode can be used in the household with a digital peephole. Despite

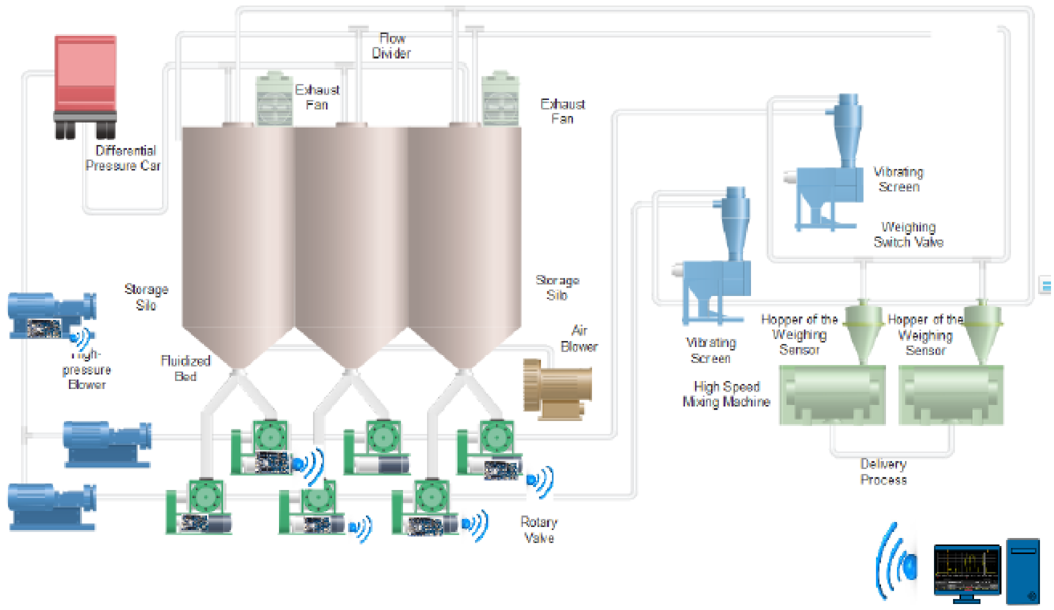


Figure 17: Concept for the use of Bluetooth 5 in the industrial sector

Figure 1.9: Bluetooth 5 in an industrial environment [28]

the existence of these studies and ready-to-use sensors, AROL wanted to create an ad hoc solution for the parameters of its machinery, facing the difficulties that the development of a particular device can have.

This dissertation has been extended also with the participation of Silicon Labs and Arduino, two leading companies in the field of IoT development.

Arduino is an open-source electronics platform based on easy-to-use hardware and software. It was born at the Ivrea Interaction Design Institute as an easy tool for fast prototyping, aimed at students without a background in electronics and programming. As soon as it reached a wider community, the Arduino board started changing to adapt to new needs and challenges, differentiating its offer from simple 8-bit boards to products for IoT applications, wearable, 3D printing, and embedded environments. [29]

Silicon Laboratories, Inc. (Silicon Labs) is a fabless global technology company that designs and manufactures semiconductors, other silicon devices, and software, which it sells to electronics design engineers and manufacturers in the

Internet of Things (IoT) infrastructure worldwide. The company focuses on microcontrollers (MCUs) and wireless systems on chips (SoCs) and modules. The company also produces software stacks including firmware libraries and protocol-based software, and a free software development platform called Simplicity Studio. [30]

Both companies were interested in this project and helped me throughout the issues I had with the usage of the Bluetooth Low Energy (BLE) described in the next section.

1.3 Problem assessment

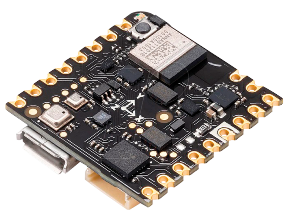


Figure 1.10: Nicla Sense Me [31]

Figure 1.11: EFR32MG12 [32]

The discussion will be focused on the application of Bluetooth Low Energy using two boards provided by different suppliers: the **Nicla Sense ME** by Arduino and the **EFR32MG12** by Silicon Labs.

The said two boards will be communicating as nodes with a central called "concentrator", which will collect all the data. In this case the designed device is the **Portenta Machine Control** (PMC), an industrial board ready-to-use by Arduino. The scope of the project is to create a test bench first, to try different transmissions. After this part, the project will develop trying and applying the same experiment on a real capping machine provided by AROL.

The test bench will be made by a rotating structure, with two stands that can hold the boards similar to a capper head of a real machine. This device will be independent of the experiment and will be possible to switch some characteristics like its rotating speed, angle and verse by using some buttons on it. To measure these parameters a 3D printed gear is used, along with some photosensor, to recreate an encoder.

To decide whether the broadcast is efficient or not, a list of **KPIs** (Key Performance Indicators) has been decided and will be measured during the tests: RSSI, SNR, throughput, latency, transmit power, path loss, and antenna gain.

The first measures the signal strength sent/received, the second is used to see noise interference among the signal sent/received, the third checks how many packages are sent/received and if there are errors in the communication, and the fourth sees the time that a signal takes to be received, the fifth sets a trade-off between range and power consumption and the last two are just used for information purposes, depending on the board and the experiment was executed.

The test bench has been designed to be modular, so the experiment can be reproduced without too much effort also on bigger systems like an in-field application. Also, the firmware with which the different KPIs will be measured is designed to be general for both the boards, to switch them without changing too many functions or lines. In this way, this test bench can be used for testing all kinds of microcontrollers that are suitable for the measurement of useful parameters like temperatures, vibrations, accelerations, and others.

1.4 AROL Closure System

AROL Closure System company, founded in 1973 by Bruno Ariano and Franco Olivieri, was mainly known for its capping machines related to liquors and wines. However, in 1983, with both the guidance of Sergio Cirio and the diffusion of PET bottles, AROL expanded its business to the packaging of all kinds of liquids.

Figure 1.12: Aluminum ROPP capping machine

Still focused on the capping field, it has been then directed at a bigger range of customers which grew exponentially, merging also with other specialized enterprises, evolving into a company world leader in the field of capping systems. In 1995, the corporation acquired CLOSYS, which specialized in small single-headed cappers. These relatively small apparatus are still largely requested by the market. It is, therefore, with this kind of innovation that AROL has installed 1600 machines around the world and continues to produce around 700 of them every year.

In AROL, there are two main types of machines: **autonomous** or **depending**.

The former has its power supply and a separate working area, working independently from other systems. Conveyor belts are used to move the containers to the cap, while the turrets are equipped with mechanical systems able to align them to the capping elements, while the latter must cooperate with other kinds of productive systems: therefore, the organization has to partner with other companies as early as the design stage.

To keep up with the technology around their products, AROL works together with corporations that produce machinery that is connected to the capping systems. For example, AROL usually partners with SIDEL, a firm that develops bottling lines and labelling for different liquid containers. This continuously pushes the firm towards innovation, integrating its systems with everything that is around its active field.

1.5 Thesis outline

Chapter 2 introduces the topic by giving an overview of the entire system, the general design, and showing the different KPIs that must be satisfied to evaluate the transmissions.

Chapter 3 explains the test bench used to try the boards in a laboratory, describing the hardware and the software used. The last section is dedicated to the post-processing of the data, to comment on the results obtained.

Chapter 4 has the same structure as Chapter 3 but it is applied to the capping machine, to try the connection on a real industrial application.

Chapter 5 contains and explains the results obtained, leading to the conclusions.

Chapter 2

Problem statement

2.1 Bluetooth Low Energy transmission

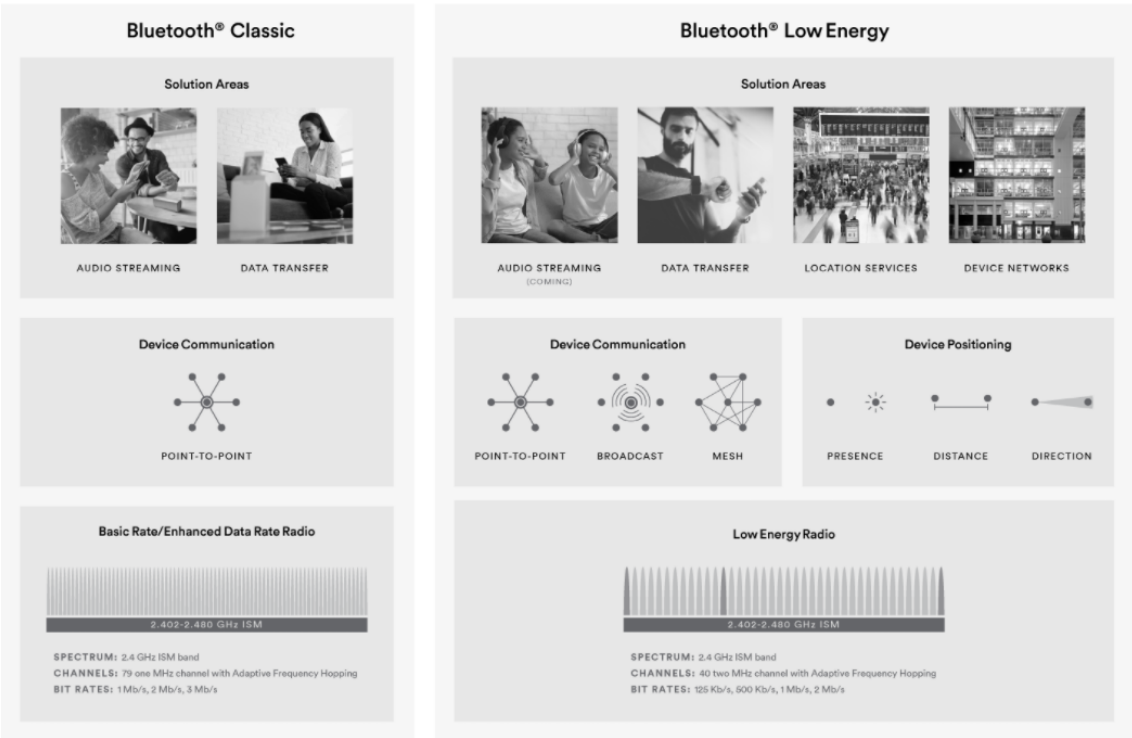


Figure 2.1: Bluetooth Classic vs. Bluetooth Low Energy [19]

The Bluetooth Low Energy uses wireless technology based on radio frequencies, 2.4 GHz, to connect devices not too far away from one to the other. It can be implemented on IoT systems and it is an evolution over the original Bluetooth Classic protocol and is optimized for low-power devices. [33] Usually, for the BLE, the bit rate is 1 Mbit/s and the transmission power is about 10mW (2 Mbit/s and 100 mW Bluetooth 5). [34]

A BLE transmission is mainly defined by three parts:

1. **Profiles**: describes how two or more devices can discover and communicate with each other. Typically implements a definite application. It can be standard or proprietary and each profile have its specifications.
2. **Host**: Upper layer of the BLE protocol stack, composed of the GATT (Generic Attribute Profile), GAP (Generic Access Profile), ATT (Attribute Protocol), SMP (Security Manager Protocol) and L2CAP (Logical link control and adaptation protocol).
3. **Controller**: Formed by the physical layer, which defines how two radios can send bits from one to another, and the link-layer, which defines the link layer states, the device addresses and the packet format that is used.

Definition 2.1.1 (Generic Access Profile)**.** The GAP controls associations and advertising in Bluetooth. It is what makes a device visible to the outside world and determines how two devices can (or cannot) interact with each other. [35]

The GAP can have different roles which correspond to different Link Layer (LL) states: broadcaster, observer, peripheral, central, or both peripheral and central.

The first two are used only for transmitting information (with the first sending and the second scanning the packets received with the LL), while the third and the fourth can establish a connection and talk preferentially. A central/peripheral can have multiple connections with different peripherals/centrals, creating a mesh. This modality has been introduced in Bluetooth 4.1.

Advertising is an operation always done before accepting a connection. This allows having a bi-directional data transfer. A central advertises to send data, RSSI, or I/Q data for directions. A peripheral advertises to transmit data and/or to make itself discoverable for new accesses. There are delays on each channel in this process to avoid interferences with other devices. Bluetooth defines a single packet format for both advertising and data transmissions. This packet consists of four components: preamble, access address, Protocol Data Unit (PDU), and Cyclic Redundancy Check. [36]

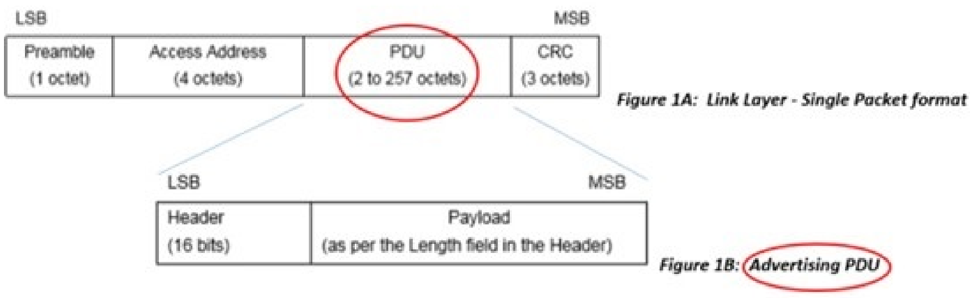


Figure 2.2: Link Layer Single Packet format and breakout of Advertising PDU [37]

The PDU defines whether a packet is an advertising or data one. The advertising PDUs will be focused, where their packet contains a 16 bit header and a variable size payload.

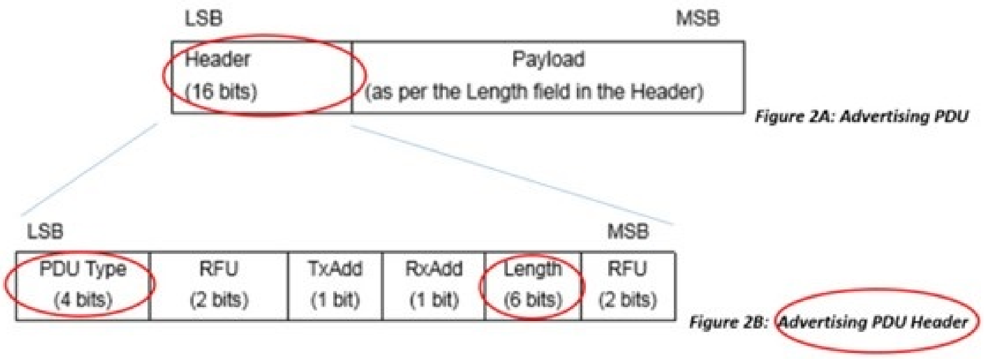


Figure 2.3: Advertising PDU Header, specifically PDU type and length [37]

The advertising header defines 6 segments. It will be focused on the Length and PDU Type fields/segments. The Length field is 6 bits and defines the size of the payload and it is defined by PDU Type.

In BLE there are two reasons to advertise/broadcast [37]:

- ADV_IND: known as Advertising Indications, where a peripheral device requests connection to any central device (i.e., not directed at a particular central device).
- ADV_DIRECT_IND: known as Advertising Direct Indication. Like ADV_IND, yet the connection request is directed at a specific central device.

- ADV_NONCONN_IND: known as Advertising Non-Connectable Indication. Non connectable devices, advertising information to any listening device.

- ADV_SCAN_IND: known as Advertising Scannable Indication. Similar to ADV_NONCONN_IND, with the option of additional information via scan responses.

When a device is connectable, it means that after he broadcasted data of the communication, it has to link with a central. If it switches from transmitter to receiver there is a connection request, which contains the information about the network and the process that is established. The non-connectable advertising instead does not switch to transmitter, so it is a lower power consumption action. It does not have scans or requests, so it is particularly important the trade-off between advertisement and power consumption since devices will stay in that state most of the time.

Definition 2.1.2 (Generic Attribute Profile)**.** The GATT defines the way that two BLE devices transfer data back and forth using concepts called services and characteristics. It makes use of a generic data protocol called ATT. Once a dedicated association is established between two devices, meaning that it has already gone through the advertising process governed by GAP, the GATT activates. Establishing a bond is also the only way to allow two-way communication, where the central device can send meaningful data to the peripheral and vice versa. [35]

Definition 2.1.3 (Attribute Protocol)**.** The ATT implements a simple client-server model. One device is the server, while the other is the client and access the data from the server. The data and its contents are called "attributes". It is used to store services, characteristics and related data in a simple lookup table using 16-bit IDs for each entry in the table. [35]

The services are used to break data up into logical entities and contain specific blocks of data called characteristics. A service can have one or more characteristics, distinguishing itself through a unique numeric ID called a UUID, which can be either 16-bit (for officially adopted BLE Services) or 128-bit (for custom services).

The characteristics are the lowest level concept in GATT transactions, which encapsulates a single data point (though it may contain an array of related data, such as X/Y/Z values from a 3-axis accelerometer for example). Like the services, each characteristic distinguishes itself via a pre-defined

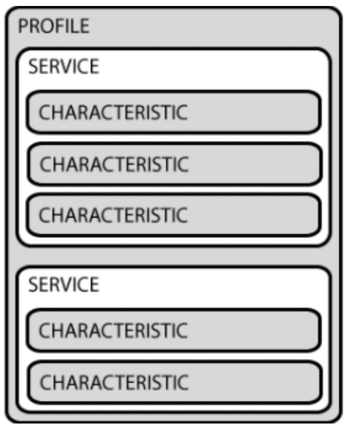


Figure 2.4: A GATT profile

16-bit or 128-bit UUID, the standard characteristics defined by the Bluetooth SIG (which ensures interoperability across and BLE-enabled HW/SW) are free to be used. It is possible also to define custom characteristics that only the peripheral and SW understand. Characteristics are the main interaction from the BLE peripheral, so it is important to define exactly how they behave and what they can do. [38]

2.2 Overview of the system

The general purpose of the system is to build an experiment as similar as possible to the in-field case to evaluate the transmission capability of the two boards, Nicla Sense ME and EFR12MG32, using the BLE protocol.

About the hardware, an experiment has been designed in such a way that it can be applied in different implementations. By being easily scalable, it can be modified to not only test different boards and parameters but also to replicate different systems: from an office test bench to a complex mechanism like a real capping machine. Also the firmware has been studied to act in the same way. Since there are different boards with different features and development environments, the code has been programmed to be capable of running on different boards by changing its lines as little as possible.

To measure when a certain position has been reached or other parameters such as the angular velocity, it has been decided to use some photosensors to check the passage of the boards and simulate an encoder. By obtaining the relative position of the boards having a zero-point as a reference, those values are easily computed.

Since, theoretically, in a capping machine there would be multiple nodes, it is important to verify how they interfere with each other, as well, for example, creating noise and disturbing the transmission.

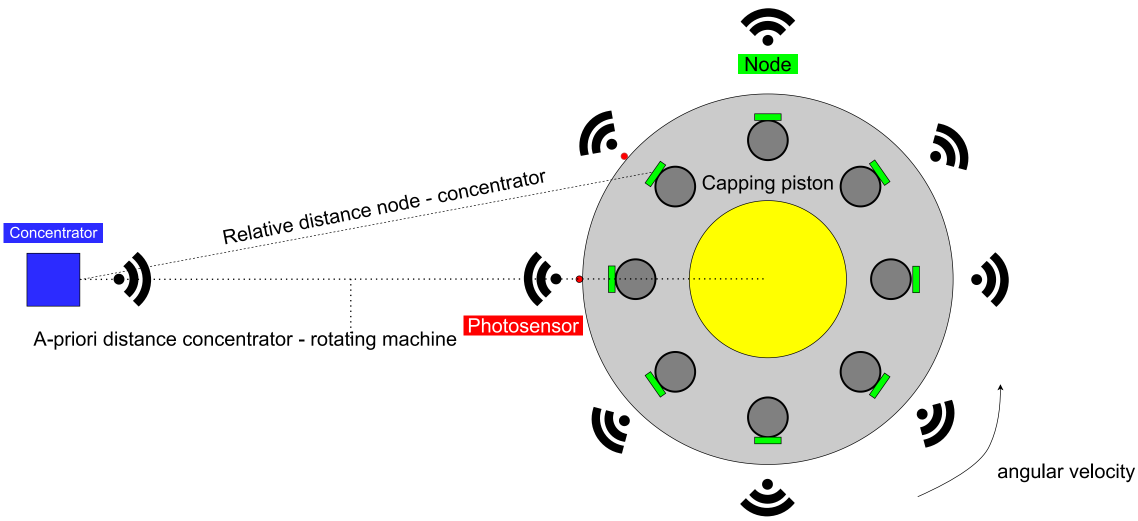


Figure 2.5: Capping machine general case

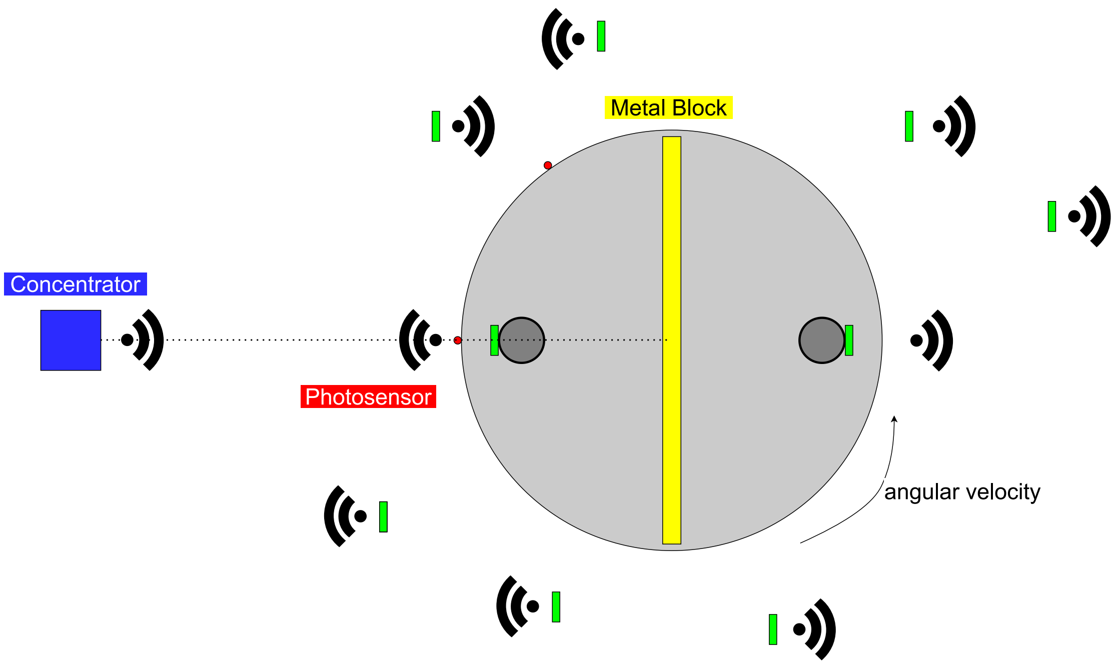


Figure 2.6: Experiment general case

To determine whether the wireless communication is better and which peripheral sends more accurate data, a list of Key Performance Indicators (KPIs) has been decided:

#	Name	Why	How	Notes
1	RSSI	Signal strength	Existing examples	-
2	SNR	Noise interference	Deduced by RSSI	$log(S/N)$
3	Throughput	How many packages transmitted and errors	Existing examples	-
4	Latency	Time that a signal takes to be received	Standard function by the system	A message will be sent to a specific receiver and the result will be divided by two
5	Power	Trade range-power	Using Power Control	-
6	Path Loss	Obstacles influence for the RSSI	By analysing other characteristics	-
7	Antenna	Strength of the signal	-	Information

Table 2.1: KPIs of the system

It is important how they affect the communication and how they have been measured.

1. **RSSI**: the RSSI (Received Strength Signal Indicator) is used to measure the radio signal strength. It is an indication of the power level being received by an antenna and it is a signal strength percentage, mostly defined by each chip manufacturer. The higher the RSSI number, the stronger the signal. There is no standardized relationship of any particular physical parameter to the RSSI reading. [31]

   It is measured by using already existing programs that could be flashed on the boards directly.

2. **SNR**: The receiver has its work complicated by the fact that there is background radiation known as noise in the environment. The closer the level of the background noise to that of the received signal, the harder it becomes to decode the received signal and at some point, errors in the decoding process start to occur. Formally, this term is the ratio of our transmitted signal power to that of the background noise the Signal-to-Noise Ratio (SNR). The strength of the received signal diminishes as the receiver moves further away from the

transmitter and consequently with a more or less constant background noise level, the SNR reduces and with it, the probability of decoding errors increases. [32]

It can be computed by a simple relation:

$$SNR = 20 * log(S/N)$$

Where S is the strength signal received, N instead is the background noise, measured by using the same programs for the RSSI on the central but without the target transmitting.

3. **Throughput**: the frequency with which data are transmitted. It can be defined also as the number of data successfully moved from one point to another in a certain period. Its velocity is measured in bit per second (bps). [39]

   The throughput can be measured in two different modes: with acknowledged or unacknowledged data. [40] In the first case the reception of all data packets is acknowledged by the receiver: in fact, the peripheral sends a response for every read/write request in the next connection interval. Usually this leads to a low throughput values. With the latter instead the packets can be sent sequentially without waiting for acknowledgment from the other side. This ensures much higher throughput, but a less reliable connection.

   For how the peripherals were programmed, the case used is the first, with acknowledged data transmission. The measurements relies principally on three parameters: the connection interval, the MTU size and the ATT (Attribute Protocol) operations.

   The connection interval specifies the frequency of sending data, which varies between 7.5 ms up to 4000 ms. After the sender sends data (or request), the sender has to wait for the receiver to send an acknowledgment. Therefore, one (GATT) operation takes two connection intervals. The lower the connection interval, the higher the potential data rate.

   Maximum Transfer Unit (MTU) specifies the number of bytes that can be sent within one GATT operation. It is the number of bytes that can be sent within two connection intervals. MTU size can be set for each connection. However, it has an upper limit, which varies with Bluetooth stack versions.

   MTU size includes the GATT header, which has a variable length and means that the useful payload is a bit smaller than the MTU. The size of the GATT header depends on the operation type, hence the maximum useful payload is different for different operations.

Bluetooth Stack Version	Maximum MTU Size
For legacy devices (BLExxx)	
<= 1.5.0	23
For Blue Gecko devices	
1.0.x	23
2.0.x	58
2.1.x	126
2.3.x or later	250

Figure 2.7: MTU size depending on the stack version

Once every parameter has been defined, the computation of the throughput can be done as follows:

$$Throughput = \frac{1000ms}{2{*}(connection\,interval)} * (MTU\ size - 1)bytes$$

ATT Operation	Max Useful Data / ATT Operation
Read	MTU - 1 bytes
Write	MTU - 3 bytes
Indication	MTU - 3 bytes
Prepare write	MTU - 3 bytes
Signed write	MTU - 15 bytes

Figure 2.8: ATT opration bytes

For both the Nicla Sense ME and the EFR32MG12 a specific code has been created to measure these values, following the specifications of the boards.

4. **Latency**: delay before data begins to move after it has been sent an instruction to do so. In regards to Bluetooth, latency describes the length of time that it takes for a signal transmitted from a central to the peripheral that receives it.

   For both the peripherals standard programs to compute the time passed since a function has been activated have been used. They measured how much passed between the transmission and the reception of a signal. This measure is affected by an error since this time includes not only the broadcast but also the time the peripheral takes to read data and reply to the message. However, an approximation is made and the result is just divided by two.

5. **Transmit Power**: the actual amount of power (in watts) of radiofrequency (RF) energy that a transmitter produces at its output. It is measured to set

a trade-off between range and power consumption (for a battery for example) since they are inversely proportional. [41]

It is measured by using a feature included in Bluetooth 4.2 called LE Power Control, which can be used to adjust a connected peer device's transmit power level based on the receiver's signal level. [42]

6. **Path Loss**: reduction in power density (attenuation) of an electromagnetic wave as it propagates through space.

   This term is commonly used in wireless communications and signal propagation. This is not an actual measured parameter; it is possible to see simply how the other values modify depending on where we put the system. The experiment should be replicated under different conditions to see the modifications of the data obtained.

7. **Antenna Gain**: the ability of the antenna to radiate more or less in any direction compared to a theoretical antenna. If an antenna could be made as a perfect sphere, it would radiate equally in all directions. Such an antenna is theoretically called an isotropic antenna and does not exist. However, its mathematical model is used as a standard of comparison for the gain of a real antenna.

   Also this term is purely for information purposes since it depends on the manufacturer and the board chosen.

2.3 Use cases

Once the design has been exposed and showed what the system should do, some mandatory use cases have to be taken into consideration, listed in the table below. The so-called central in the application will be substituted by the concentrator:

#	Title	User story	Request	Notes
UC.1	Position and angle detection	The rotating platform must have some photosensors around it to know when a certain node passed from a position. There should be a "zero" point for restarting the experiment and more accurate measurements. In this way we can compute the angular velocity, to have all the values we need for the transmission quality	Mandatory	-
UC.2	Sensor response	The sensor must send data whenever the central asks them.	Mandatory	-
UC.3	Communication of the central	The central has to communicate with the nodes and with the photosensors to determine the transmission quality. We measure the KPI between the two boards: the values depend on three rotation characteristics: speed, position of the antennas and distance between sensor and central (a-priori information computed by hand).	Mandatory	-

Table 2.2: UCs of the system

Chapter 3

The bench experiment

3.1 Hardware

3.1.1 The test bench

A study of the board has been executed to understand what they could do and how to utilize existing programs to measure the KPIs defined on page 25, chapter 2.

In fact, by trying a throughput example for the EFR32MG12 to simulate a system like the capping machine, the board was rudimentarily attached to a kitchen roll using some adhesive tape and made rotating with a hand while it was measuring throughput and RSSI at a certain distance from an identical board acting as central.

The results were of course very general and approximative, but it was a start for the next step: recreate the same structure with a more precise, reproducible, and modular test bench. The scope is to represent a capping machine in a simplified way, adding sources of disturbance to see how the communication changes with those interferences.

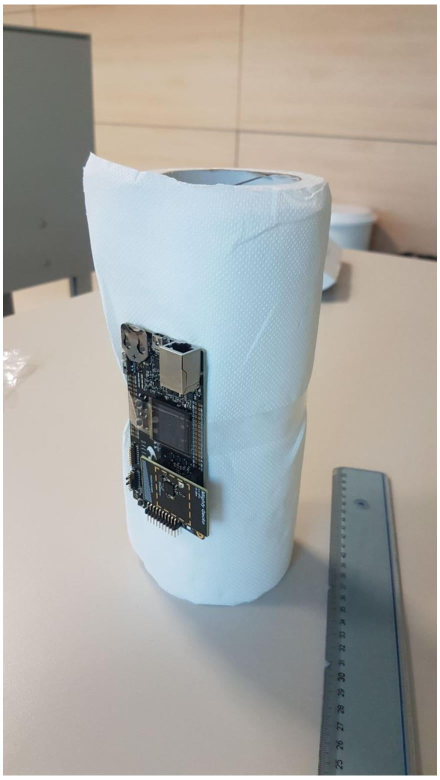


Figure 3.1: Test with kitchen roll

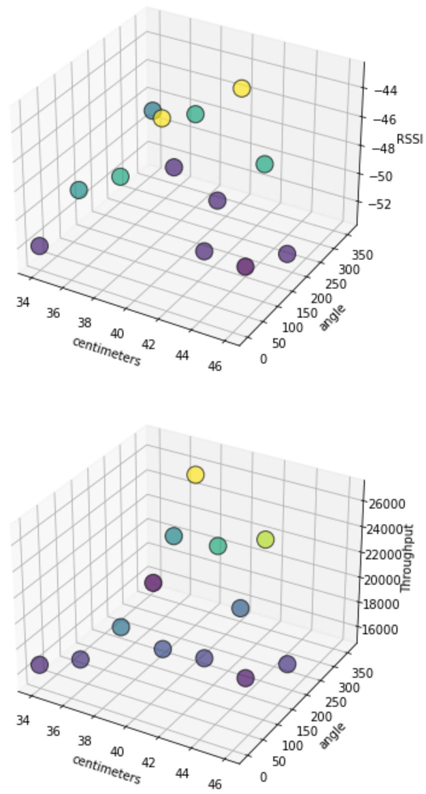


Figure 3.1: Test with kitchen roll **Figure 3.2:** Results of test

At first, a rotating platform is chosen, bought on Amazon, which could represent the motor and the basis for the entire system. The idea was not to buy something expensive and with a lot of features, since it is not part of the experiment of the communication. In fact, the base is considered independent, turning without any kind of customised software uploaded on it. For this reason, a simple exposition platform was chosen, which can move clockwise and counter-clockwise and can change its rotational speed and circulation.

Obviously, on the market, there are much more expensive platforms with more features, even remote controls. This will maybe lead to a more precise work or a better aesthetic, but, in this case, what was chosen is sufficient for executing the planned measurements.

The next problem to be solved was that it should be possible to detect the heading of the rotating plate during the circumvolution to see where the board was during the rotation. For this reason, an encoder has been built with some photosensors to detect the position.

Figure 3.3: Rotating platform features

An incremental encoder is a linear or rotary electromechanical device which has two signals, A and B, which produces a pulse whenever the device is put in motion. These two signals indicate the occurrence and the direction of the displacement. Usually, a zero is highlighted to have a reference position. Unlike other types of decoders, like absolute ones, an incremental just reports a position change or the direction of the movement. [43]

At first, a prototype made of cardboard has been built, to understand how the different parts would be made together. The angles at which the sensors are positioned are wrong, but this model was used to understand how to arrange the boards and how to program the PMC to read when the black strip passes through the cavities.

To construct the encoder a gear with 12 teeth has been designed, so each tooth is at 30° with respect to the other, where one photosensor is at zero reference position. The second sensor, since the waveform must start in the middle of the first one, has been positioned with an angle of 45° with respect to the other and a bit far away, to read only the longer tooth. In this way, the two waveforms have the correct phase but shifted. Surely due to imperfections, there would be two kinds of errors: symmetry and phase, as shown above. They are correlated and happen when the second waveform is not exactly half of the first one, having different results.

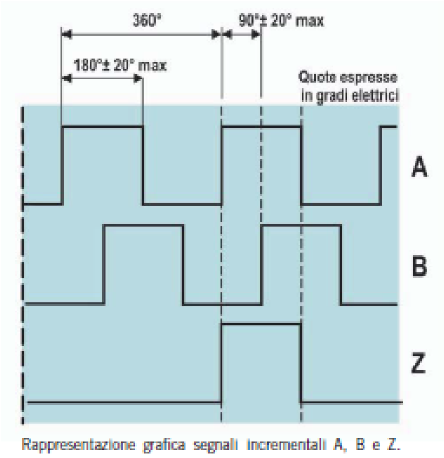


Figure 3.4: Encoder waves [43]

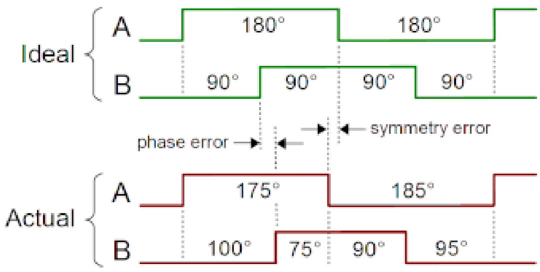


Figure 3.5: Encoder errors [43]

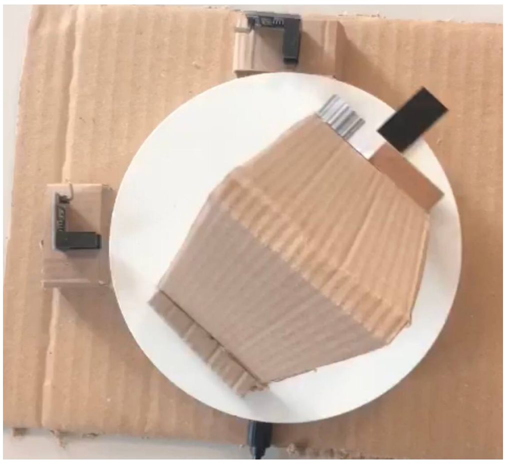


Figure 3.6: Upward view

Figure 3.7: Perspective view

The model of the encoder was initially printed on paper, but it was not the best way, since the aim was to have it more precise and to make the experiment more repeatable, also for the future in case someone wanted to have the exact results that were found. For this reason, a 3d CAD (Computer Aided Design) has been generated and printed in PLA. By using modern technologies as explained in chapter 1 with the addictive manufacturing, it should be possible to print these parts in other materials like metal or wood. Surely these changes would modify the results since the transmission is affected by these parameters. However, to keep it simple, it was decided to keep it in plastic, also for the lack of equipment, since AROL does not have a 3D printer for different elements.

Photosensors are sensors of light made by a transmitter and a receiver, which can detect when an object passed through a ray of light emitted. Both the transmitter and the receiver in this case are in a unique device. When the sensor is free it has an output of $0V$, instead, when an object blocks the transmission, it reaches the $5V$.

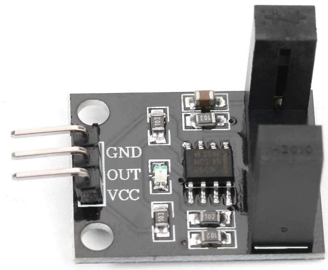


Figure 3.8: Photosensor

For this reason, it is simple to detect an object by just using a digital input. Since it must be supplied with $5V$ and not $24V$, a USB cable has been modified to take the right voltage directly from the PMC, transferring the power to a breadboard and then switching on the two sensors.

The CAD created, also with some help from AROL colleagues, is the following:

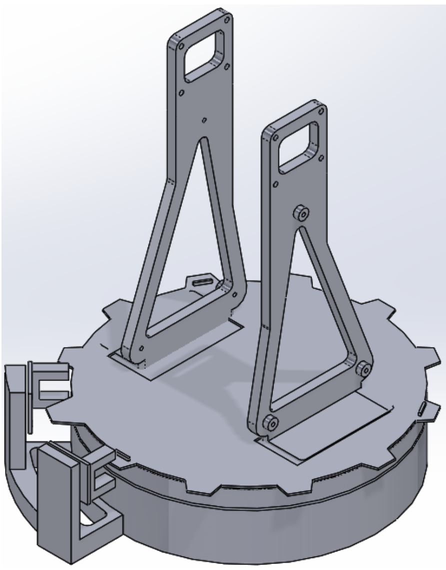


Figure 3.9: Frontal view

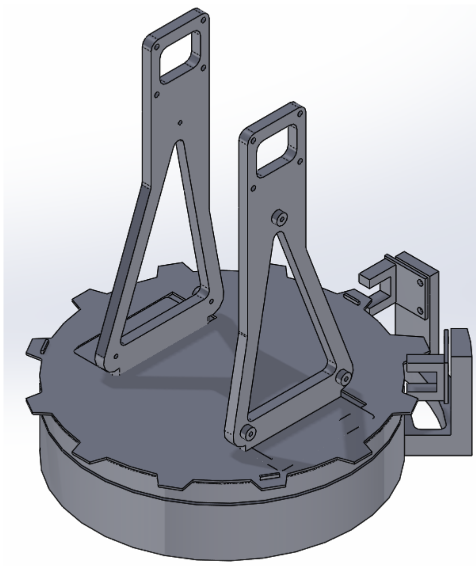


Figure 3.10: Back view

The model is composed principally of three parts: the gear (already explained before), the stands for the photosensors and the stands for the boards.

The stands for photosensors are a unique piece, made of two vertical rectangles, where the sensors are attached horizontally, to let the teeth enter between the holes. The base has a cavity to save costs and material. The positioning of the sensors has been already explained, probably there would some errors, but they should be negligible since the printed object should be precise enough.

The stands for the boards are divided in two: a triangular-shaped part and a square-shaped one. The first is used for the EFR32MG12, where the holes on it are used to screw the carrier board. As before, the structure is almost empty to reduce the cost and save material from the printing. Instead, the second part is for the Nicla Sense ME case, which has a hole for the battery and the antenna.

To respect the best location possible for the antennas, it has been decided to put them vertically, facing the exterior, to not have during the transfer of data any kind of obstacle. It has been decided to put the boards one over the top of the other to use them at the same time, trying both the transmissions and, if possible, establishing a mesh between them.

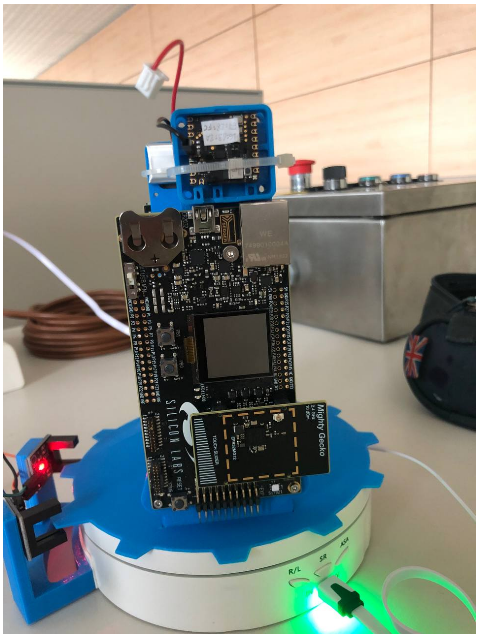


Figure 3.11: Frontal view

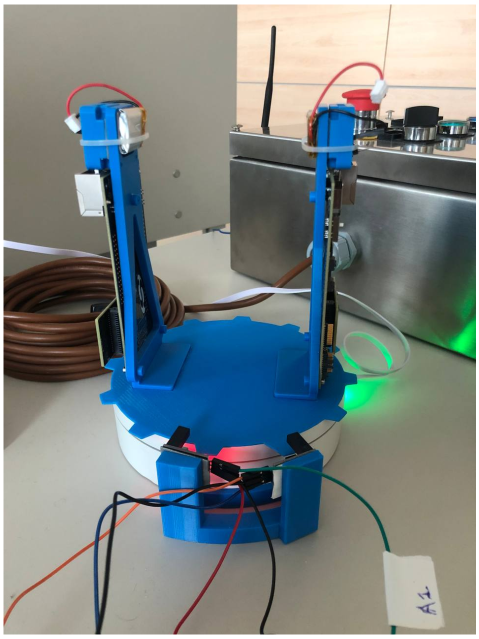


Figure 3.12: Side view

Now that every part is assembled, the problem was to understand how to connect everything to use the boards, the test bench and the Portenta Machine Control (PMC) together.

In fact, the objective of the experiment is to verify the transmission of data, through the measurement of the different KPIs, between the two said boards as peripheral and the PMC as central.

The photosensors have three pins: the output, the ground and the $5V$ supply. As said before, a USB cable type A has been modified for the last two pins, while the output is connected directly to the PMC on the analogue input. In this way, the central will read the values of the sensors and recognise the position of the peripherals.

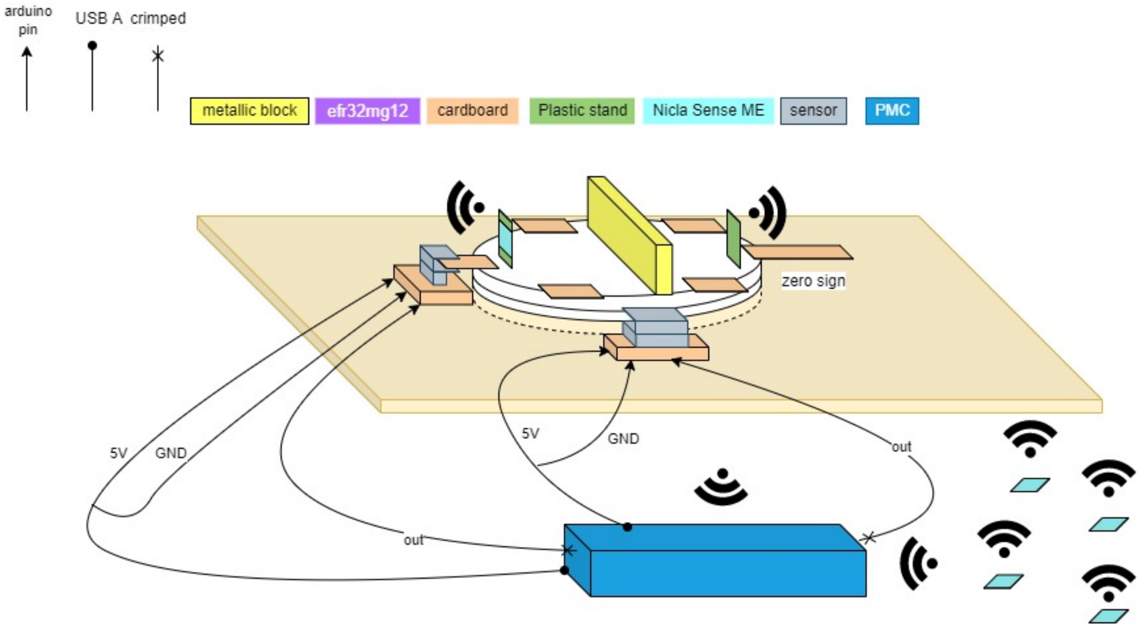


Figure 3.13: Test bench definition

3.1.2 EFR32MG12

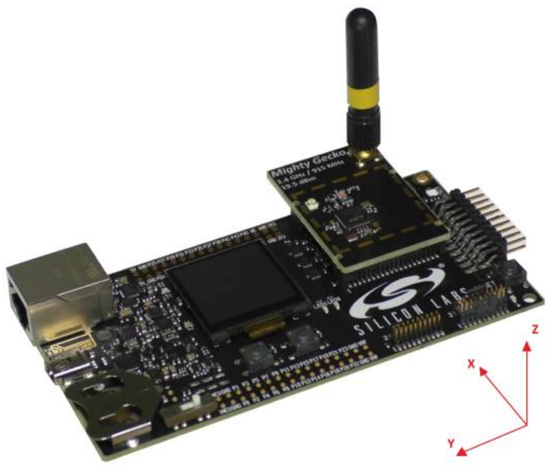


Figure 3.14: EFR32MG12 and its carrier board

The BRD4162A Mighty Gecko Radio Board (EFR32MG12) enables developers to develop Zigbee, Thread, Bluetooth low energy and proprietary wireless applications.

The board contains a Mighty Gecko Wireless System on Chip 2.4 GHz and optimized for operation with 10 dBm output power. With the on-board printed antenna and RF connector radiated and conducted testing is supported.

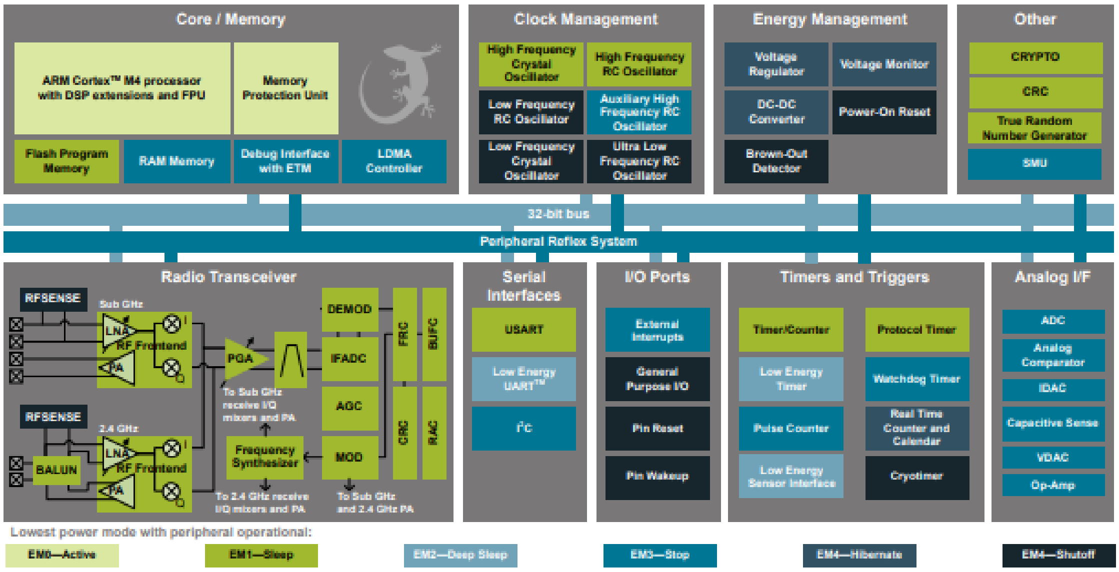


Figure 3.15: EFR32xG12 Wireless Gecko System-On-Chip Block Diagram [32]

The BRD4162A Mighty Gecko Radio Board plugs into the Wireless Starter Kit Mainboard provided with the Mighty Gecko Starter Kit to get access to display, buttons and additional features from Expansion Boards. With the supporting Simplicity Studio suite of tools, developers can take advantage of graphical wireless application development; mesh networking debug and packet trace; and visual energy profiling and optimization. The board also serves as an RF reference design for applications targeting 2.4 GHz wireless operation with 10 dBm output power.

The EFR32MG12 is a board mounted on a carrier board PCB4001 Rev A3, which can be supplied by a 3V coin battery, the standard debug USB cable, or a USB regulator on the radio board called AEM (for devices with USB support only). In the case of utilisation with the coin battery, the carrier board is not powered. The choice is made by using a switch on the latter, which can permit to power of the VMCU, a 3.3 V power rail, monitored by the AEM (Advance Energy Monitor). [32]

3.1.3 Portenta Machine Control and Portenta Breakout

The Portenta Machine Control is an indsutrial board that adds IoT capabilities to standalone industrial machinery. It enables the collection of real-time data from the factory floor and supports the remote control of equipment, even from the cloud, when desired.

Thanks to its computing power, the Portenta Machine Control enables a wide range of predictive maintenance and AI use cases. It can be programmed using the

Figure 3.16: Portenta Machine Control

Arduino framework or other embedded development platforms. It can create an infrastructure of interconnected machines, which can be controlled onsite or via the cloud when needed; moreover, human-machine interaction can be further enahnced via mobile apps thanks to BLE connectivity.

The modular design is very useful for upgrades and adaptations. Since each I/O pin can be configured, the Portenta Machine Control can be highly customizable while allowing companies to avoid vendor lock-in. Its hardware is robust and secure by design. [44]

However, despite the power of the Arduino devices, there has been some problems during the development of the software for the experiments. In fact the coexistence of the two libraries ArduinoBLE and ArduinoMachineControl was not possible, since they initialize wrongly some GPIOs of the board, leading to a malfunction in the system. In fact, it was not possible to use the Bluetooth functions if also the other library was present. To solve this issue another board has been used: the Portenta H7 with the carrier board Portenta Breakout (with which it will be refer to from now on), which has exposed GPIOs and so avoided the issue. It is very similar to the Portenta Machine Control, the only difference is that the system is not enclosed in an industrial package but it has a simpler design with exposed GPIOs. A MOLEX 2.4 GHz flexible antenna 206994 has been used, with the following specifications:

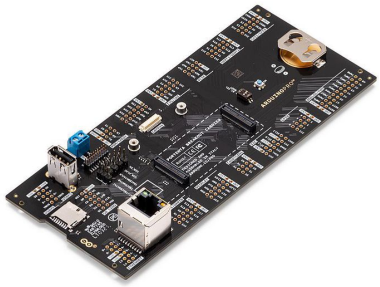


Figure 3.17: Portenta Breakout

ANTENNA PERFORMANCE FOR CABLE LENGTH 100mm			
P/N	2069940100		
Frequency Range	2.4GHz-2.5GHz	5.15GHz-5.85GHz	5.925GHz-7.125GHz
Peak Gain (Max)	3.6dBi	3.6dBi	2.7dBi
Total efficiency	>55%	>70%	>40%
Return Loss	<-10dB	<-5dB	<-3dB

Figure 3.18: MOLEX 2.4 GHz specifications

3.1.4 Nicla Sense ME

The Nicla Sense ME is a tiny, low-power tool that sets a new standard for intelligent sensing solutions. With the simplicity of integration and scalability of the Arduino ecosystem, the board combines four state-of-the-art sensors from Bosch Sensortec. [45]

This enables powerful data fusion capabilities on the edge. Analyse '**M**otion' and '**E**nvironment' with industrial grade Bosch sensors that can accurately measure rotation, acceleration, pressure, humidity, temperature, air quality and CO2 levels. This board is their smallest form factor yet, with a range of industrial grade sensors packed into a tiny footprint. Measure process parameters such as temperature, humidity and movement. It features a 9 axis inertial measurement unit and the possibility for Bluetooth Low Energy connectivity (version 4.2).

This product possess the onboard BHI260AP, BMP390, BMM150 and BME688 Bosch sensors. The first is used for machine learning and AI projects, since it is a self-learning AI sensor, the second is a pressure sensor, the third magnetometer and the last is a miniaturized gas sensor.

The Nicla Sense ME does not have a carrier board: a 3D printed case has been built to contain and power it, also using a lithium battery attached on the back.

About the antenna, it mounts a module called ANNA-B112, which is a Bluetooth

5 low-energy module packed into a System-in-Package design. The frequency at which it operates is 2.4 GHz band and depending on the polarization the gain changes. This means that theoretically the position at which the device will be is going to modify some parameters, like the RSSI and the throughput.

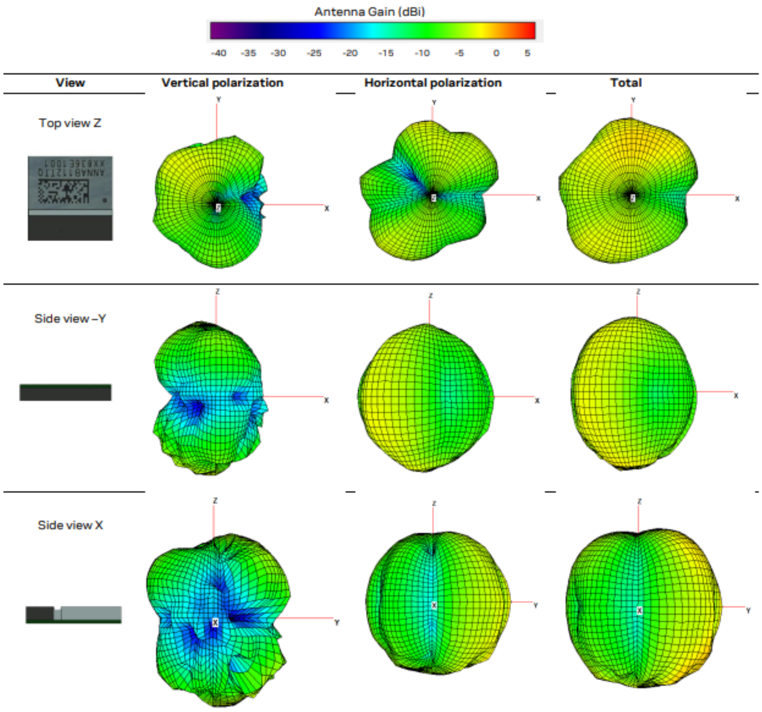


Figure 3.19: Gain-polarisation Nicla Sense ME 1

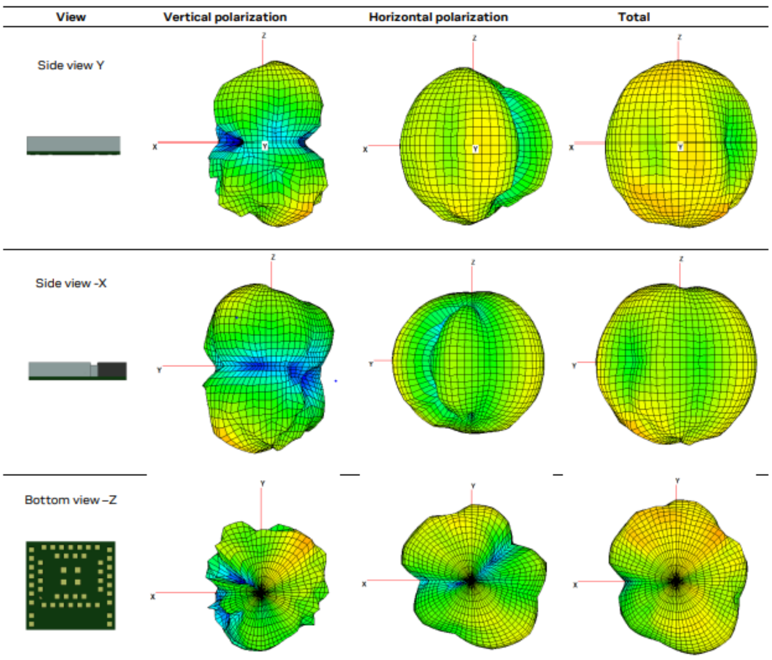


Figure 3.20: Gain-polarisation Nicla Sense ME 2

3.2 Software

The software of the test bench must measure the different KPIs explained in the 2nd chapter, page 21.

For every value searched, an in-depth explanation is presented to better understand the codes. Since the boards tested are from different suppliers, as said before, it is very important to have a code as general as possible, to make it interchangeable, without modifying it during the tests.

Two IDEs (Integrated Development Environment) have been used to program them: Arduino IDE 2.0.0-rc8 and Simplicity Studio 5. They are very different and are intended also for distinct targets.

Arduino IDE (by Arduino) is very simple, almost oversimplified. The boards are recognised autonomously, and the libraries are added-on, depending on what are the needs of the users and the functions that they use. Online, especially in the open-source community, there can be found a lot of different libraries for infinite applications. Very often someone had an idea that can be useful, and through forums and GitHub, issues are solved in real-time, discussing also if someone had made a mistake by accident, or if it is a new implementation.

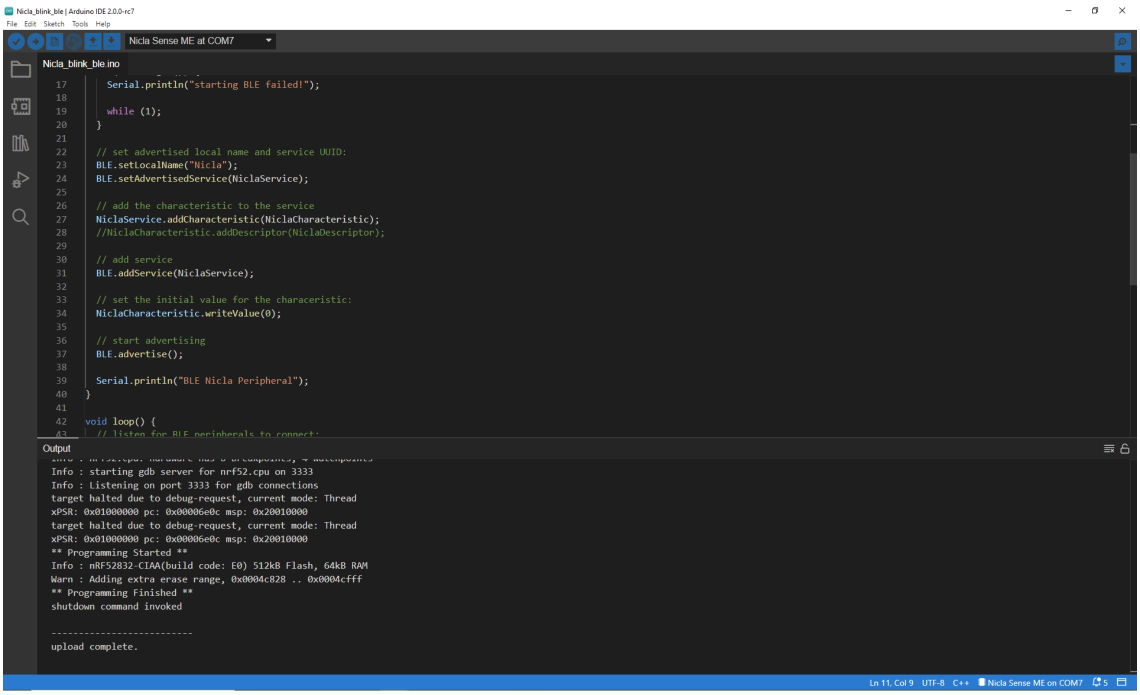


Figure 3.21: Arduino IDE

Simplicity Studio 5 (by Silicon Labs), on the contrary, is targeted at people who have a middle-high skill level in computing. It is more complex and difficult to follow since the different files are stored in a maze-like menu. However, it is much more customizable and completed than the other one shown before. When a new application is created, everything can be modified, like the GATT and its resources, or some features like the sniffer, the network analyser, and others. It offers a lot of ready examples to explain how to use it, so it is not difficult to get used to it. However, it is not as immediate as other IDEs.

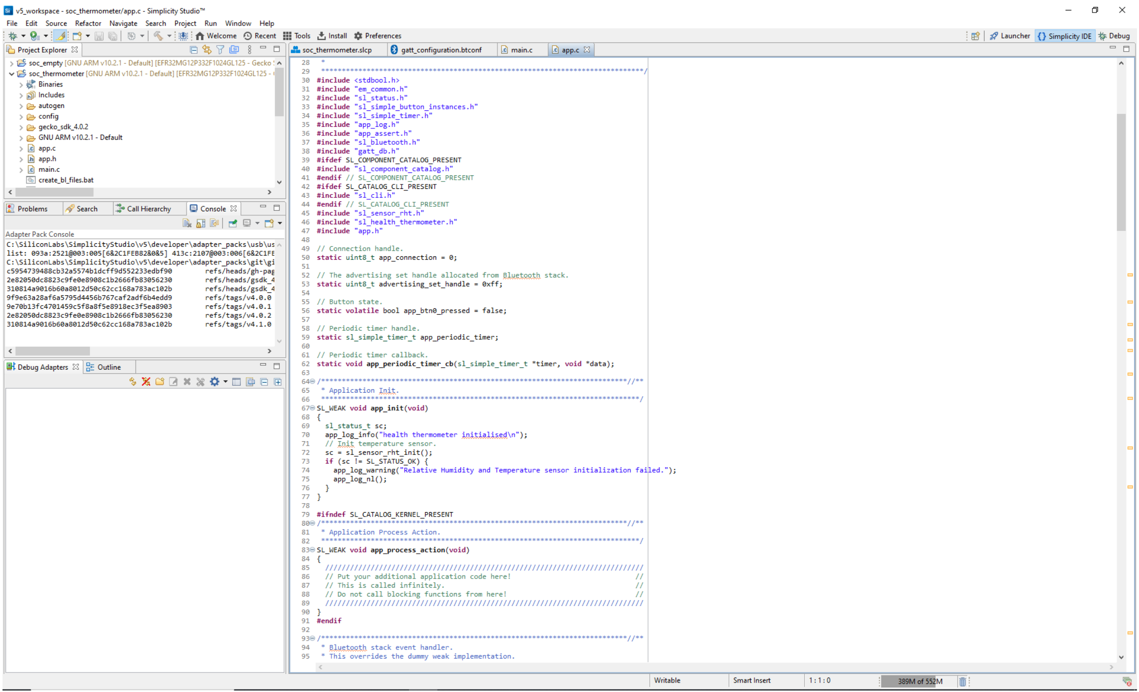


Figure 3.22: Simplicity Studio IDE

3.2.1 Portenta Breakout and Nicla Sense ME code

For the simplicity in the representation, here below the diagram of the code focuses only the Nicla Sense ME, but the same operations are done also with the EFR32MG12:

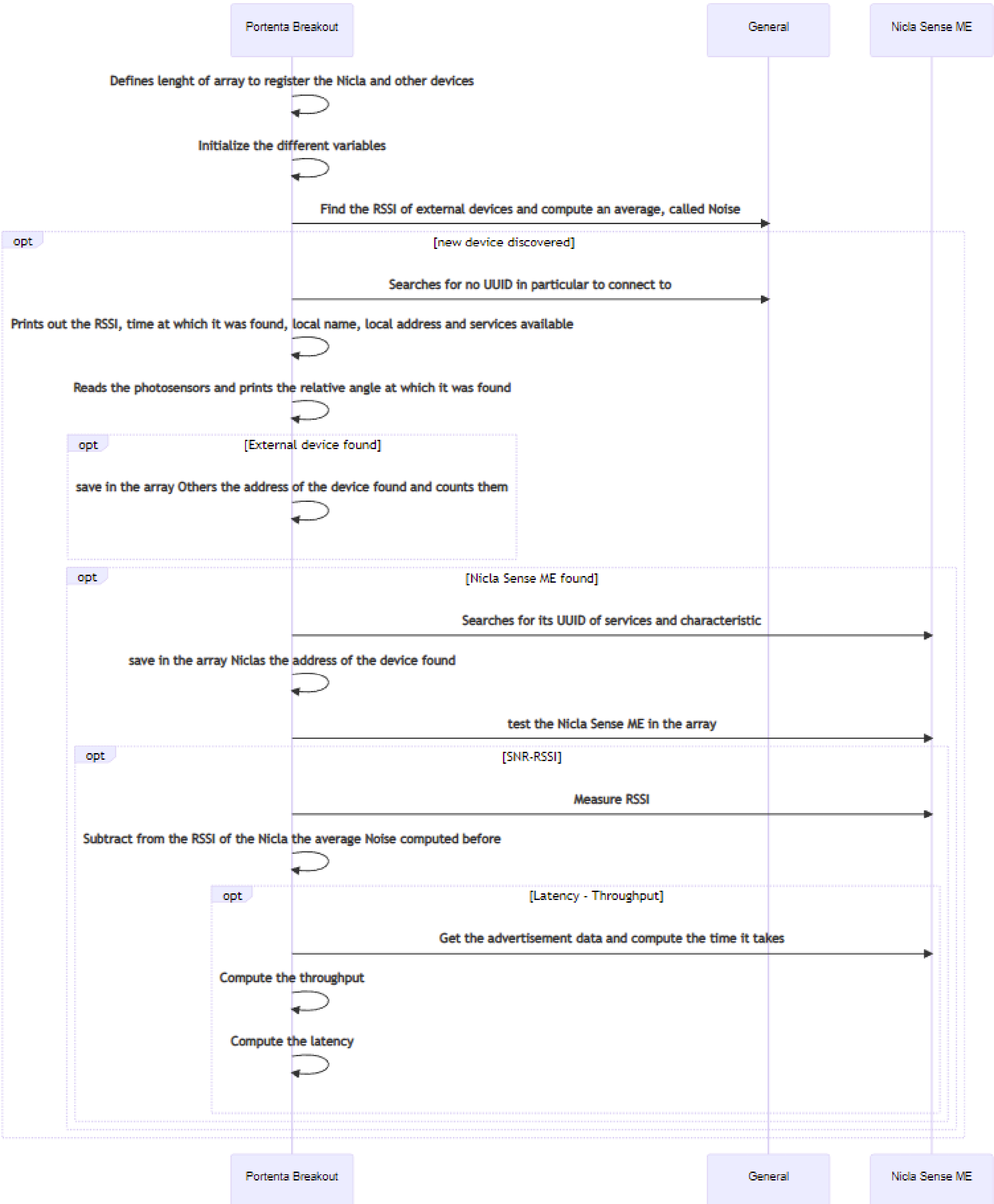


Figure 3.23: Software of the Portenta Breakout

The code for the Portenta Machine Control is based on connections, discovering services and characteristics of the peripheral, where the central can write and read values, and evaluating the features of the device. The problem with this approach regards the BLE stack since its limits were reached after a few connections.

For this reason, it has been suggested to use manufacturer data and broadcast them, making the PMC only reading them, without any connection established. However, the problem is that by using this approach the throughput and the latency were not measurable because no data would be exchanged between the two devices. Another problem was understanding which peripheral is saying what and distinguishing what sensors are involved in a test. To solve the latter issue , an SD card can be used, where a text file can be made to contain a list of addresses where the different Nicla Sense ME can be found. The program reads the text file whenever finds a peripheral, sees if it is a peripheral involved in the test or not, sees if its address has been already registered and, in case, adds it to the file.

Since the SD card trials were not successful, an array called “Niclas” has been set substituting the SD card file, to contain the different addresses that will be tested.

If an address does not correspond to a Nicla Sense ME, the output results in an RSSI corresponding to an external device, printing it as “Noise”, and a counter increments to see how many peripherals are present in a certain location. If the right address is found instead, the test for the peripheral starts, measuring the different KPIs.

The system works in the same way for the EFR32MG12, where an array called “Silicon” is initialized and contains the addresses of those boards.

- **RSSI**: this parameter is simply calculated by using the function BLEDevice.peripheral.rssi(), which as result returns this data.
- **SNR**: Unfortunately, without a spectrum analyser this parameter cannot be computed precisely. To give an idea of this value, it is computed by subtracting the average of the Noise from external devices from the RSSI of a peripheral. The data obtained will not be used to evaluate the results, just to have a piece of information about the behaviour of the external devices.
- **Throughput**: unfortunately, due to the API (Application Programming Interface) available, it was not possible to determine exactly the bit rate of a transmission. What has been measured is the number of bit per second sent during the connection intervals through the time needed for the transmission and the number of bytes in the payload of the packets. By looking at the Bluetooth 4.2 standard and the ArduinoBLE source codes, the MTU is 23 bytes, the reading process is MTU-1 byte, the connection interval set is between 7.5 ms and 4000 ms and since it is an acknowledged transmission, the GATT takes two connection intervals to transmit data.

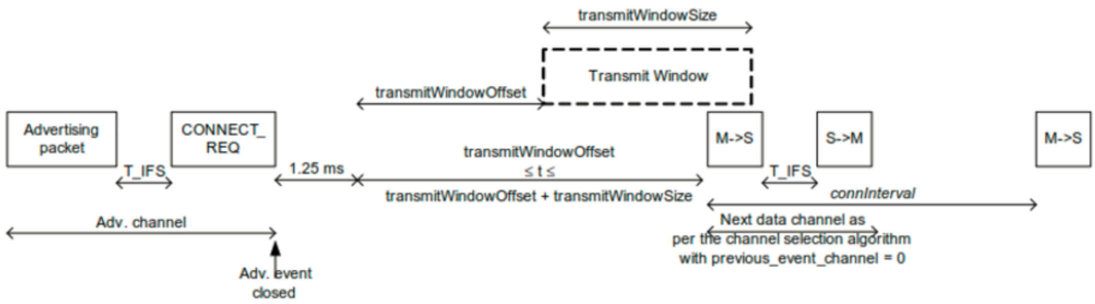


Figure 3.24: Connection model

This mean that, by looking at the theory presented in chapter 2, depending on the connection interval of the board, the throughput can vary between 1466.7 bytes/s (11733.6 bps) and 2.74 byte/s (22 bps).

$$Throughput\,7.5ms = \frac{1000ms}{2*(7.5ms)} * (23-1)bytes * 8\frac{bit}{byte} = 11733.6bps$$

$$Throughput\,4s = \frac{1000ms}{2*(4000ms)} * (23-1)bytes * 8\frac{bit}{byte} = 22bps$$

By trying different arrays sizes in the characteristic, the maximum number of bytes that the Portenta Breakout could read from the Nicla Sense ME characteristic by using the function BLE.readvalue was 241 bytes, even though (by looking at the reference page of the ArduinoBLE library) the characteristic could be up to 512 bytes. This is true also for the EFR32MG12, even though the board could send up to 255 bytes in a characteristic.

For this reason it was decided to compute the throughput by using 1 byte array and then an array made of 240 bytes. In this way it was possible to delete the "useless" CPU time since a single byte is almost immediatly read by the Portenta Breakout and compute an actual throughput.

- **Latency**: this parameter is computed by taking the time the peripheral took to respond to the request of the Portenta to write and read the characteristic and then dividing it by two.
- **Transmit Power**: unfortunately, this parameter could not be measured, since even though Bluetooth 4.2 has the Power Control feature, it is not implemented in the Nicla Sense ME and EFR32MG12 boards.

About the code for the Nicla Sense ME, it is based on connections too. It builds a service with a writable characteristic, which the central could access to. It creates a characteristic made of 241 or 1 bytes and initializes it at zero. The central will change its value and light a white LED. The advertising process has an interval of 100 ms.

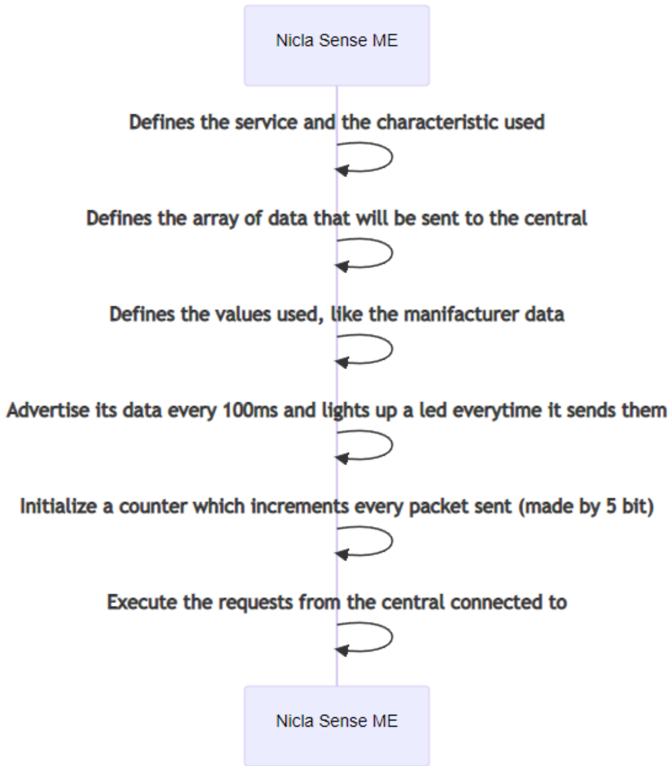


Figure 3.25: Software of the Nicla Sense ME

3.2.2 EFR32MG12 code

About the EFR32MG12 code, it has been used a SoC (System on Chip) empty example, with a customized GATT that let the central to connect to a certain service and characteristic. The only parameter changed are the number of bytes in the payload (241 or 1) and the fact that the advertising interval had to be the same of the Nicla Sense ME: 100 ms. It was not possible unfortunately to create a counter for the manufacturer packets.

3.3 Experiment execution

The experiment has been conducted in a laboratory, in a controlled environment. The tests have been divided into four categories:

1. The test bench was still and the Portenta studied all the devices in the area.
2. The test bench was still and the Portenta focused only on the Nicla Sense ME and EFR32MG12.

3. The test bench was moving clockwise and the Portenta studied all the devices in the area.
4. The test bench was moving clockwise and the Portenta focused only on the Nicla Sense ME and EFR32MG12.

Four peripherals were used in total: two Nicla Sense ME and two EFR32MG12. On one side there was the Nicla1 (with address 09:e5:1e:9a:2a:1b) with below the Silicon1 (address d0:cf:5e:87:4d:fc) while on the other there was Nicla2 (with address 16:43:2a:e7:28:fc) and Silicon2 (with address d0:cf:5e:87:4d:f2).

The aim of the first and third cases of the experiment was just to have an idea of the number of devices in the room, in order to understand how many interferences could be present during the accomplishment of the experiment.

For every test, the mean values of latency, throughput and RSSI are considered, as well as their standard deviations. The last is computed by the following formula:

$$SD = (\sqrt{\frac{\sum |x - mean|^2}{n}})$$

Where the x is the single sample taken, mean is the mean of the overall samples and n is the total number of samples measured.

3.3.1 First Test

In the first test, the test bench was still, with a 0-degree heading, with the Portenta Breakout analysing all the devices present in the area. The program counted 70 devices and the test lasted 172,653 seconds (2,8 minutes) before the Portenta blocked itself.

3.3.2 Second Test

In the second test, the test bench was rotating, with the Portenta Breakout examining all the devices present in the area. The program counted 64 devices before the Portenta blocked itself and the test lasted 316,498 seconds (5,27 minutes).

3.3.3 Third Test

In the third test, the test bench was still, rotated of 0 grades, with the Portenta Breakout inspecting only the Nicla Sense ME and the EFR32MG12 mounted on the structure. The test lasted 273,036 seconds (4,55 minutes).

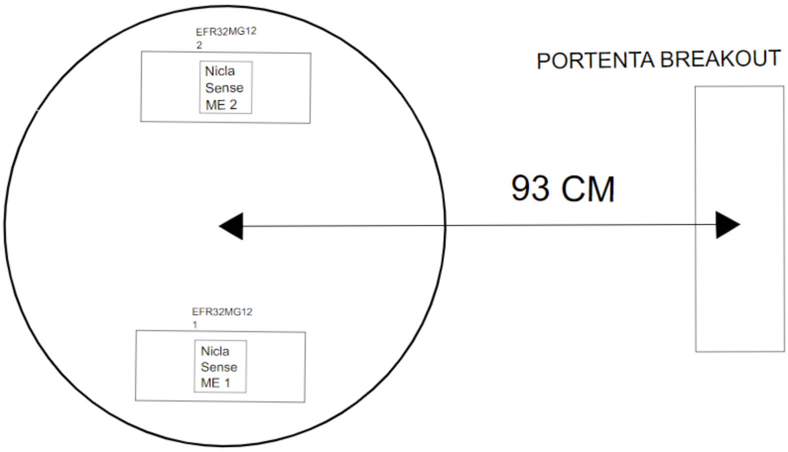


Figure 3.26: Test bench position

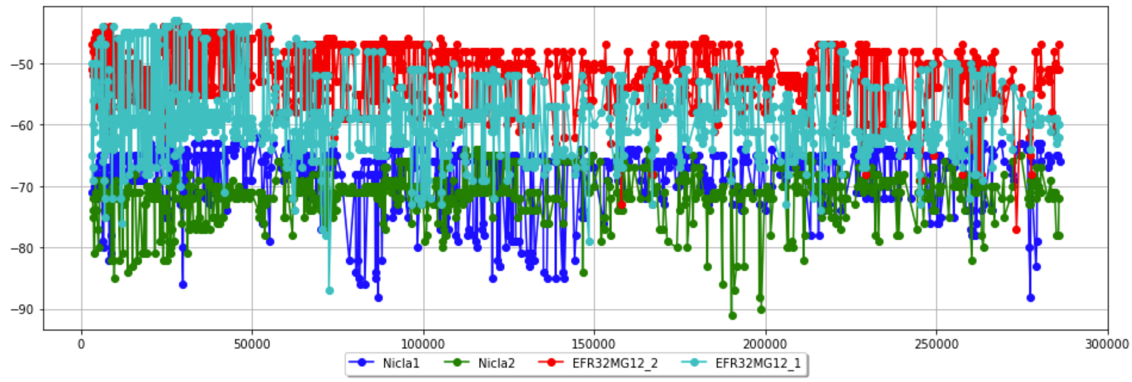


Figure 3.27: RSSI third experiment

Theoretically, by looking at the position of the boards, the RSSI should be contained on a certain range (it is possible to have some disturbances that would cause a bouncing performance), where the Nicla Sense ME and the EFR32MG12 should have almost the same values since they are quite at the same distance from the central antenna.

This is approximately what happened since the RSSI are for sure in a certain range and they are well mixed with one to the other. It is recognizable a better behaviour from the two Silicon Labs devices than the Nicla Sense ME, since their values are higher, despite their position. About the advertising latency, the EFR32MG12 shows a better behaviour than the Nicla sense ME, but with a higher standard deviation than the other peripheral.

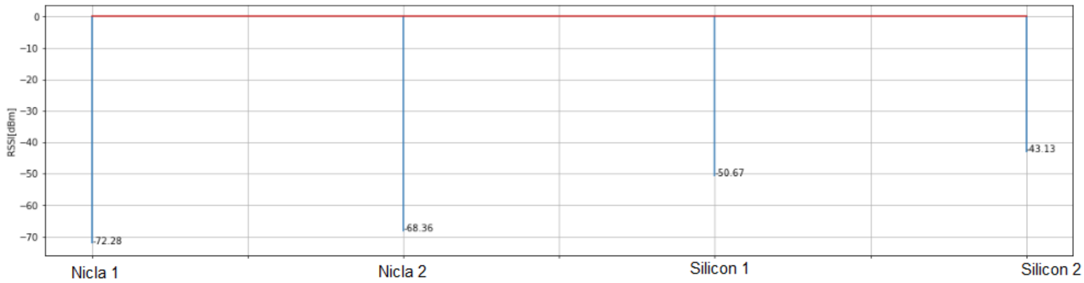


Figure 3.28: RSSI third experiment (median values)

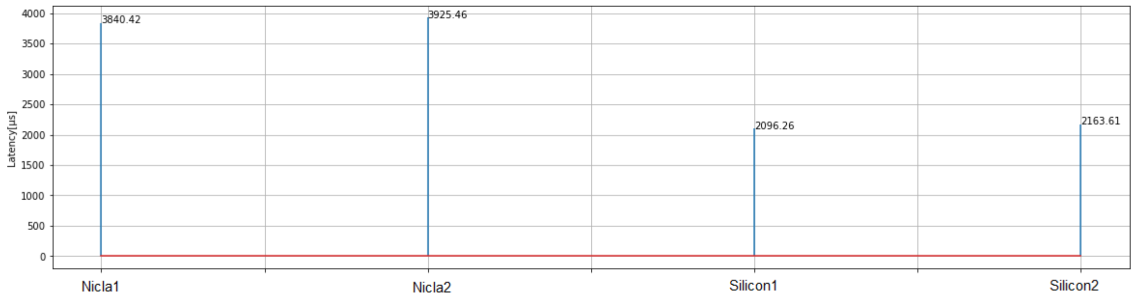


Figure 3.29: Latency advertising third experiment (median values)

Board	RSSI [dBm]	Latency (Advertising) [µs]
Nicla1	-72.28 (5.41)	3840.42 (24,35)
Nicla2	-68.36 (2.54)	3925.46 (23,16)
Silicon1	-50.67 (4.15)	2096.26 (34,47)
Silicon2	-43.13 (2.84)	2163.61 (33,46)

Table 3.1: Mean values RSSI, latency and their standard deviation, third experiment

Regarding the latency for the connections, only one peripheral per supplier has been studied: the Nicla Sense ME with address 16:43:2a:e7:28:fc and the EFR32MG12 with address d0:cf:5e:87:4d:fc. Below the results are presented.

The EFR32MG12 slightly works better again, by looking at the median values registered. Nonetheless, it must be acknowledged the standard deviation since it is preferable a predictable behaviour. In fact, by looking at those measurements (in the brackets inside the table above) it can be said that the Silicon Labs products do have a higher oscillations of values (even if it is very little since the parameters are very low).

Experiment	Nicla Sense ME latency [ms]	EFR32MG12 latency [ms]
241 bytes	248.38 (3.76)	246.45 (18.15)
1 byte	28.69 (0.42)	26.97 (0.82)

Table 3.2: Values latency third experiment

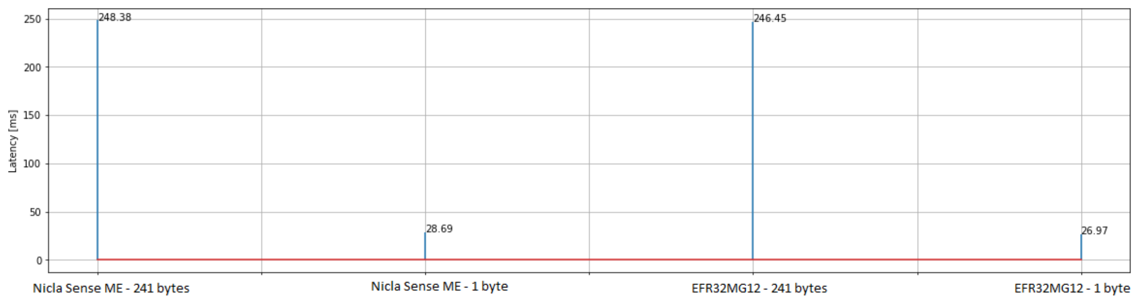


Figure 3.30: Latency connection third experiment (median values)

3.3.4 Fourth test

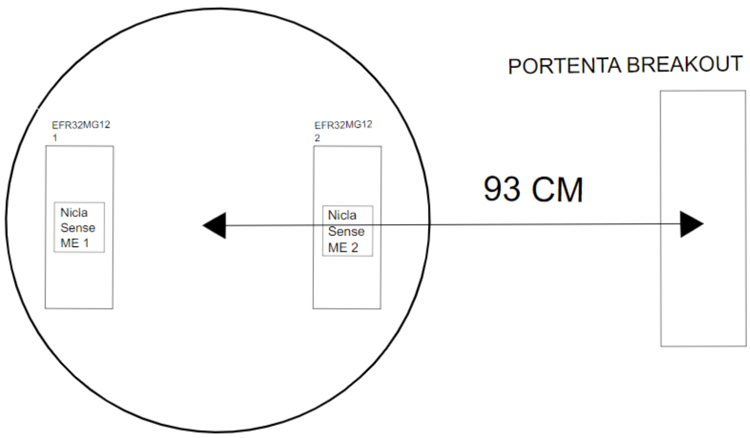


Figure 3.31: Test bench position

In the fourth test, the test bench was still, rotated of 90 grades, with the Portenta Breakout scanning only the Nicla Sense ME and the EFR32MG12 of the experiment. The test lasted 285,957 seconds (4,76 minutes).

The RSSI is analogous to the previous experiment, yet, is noticeable a division between the different boards, with higher values for the Nicla2 and Silicon2, the devices directly facing the antenna. It is theoretically what was expected, even though the difference between the two radio systems led the EFR32MG12 to have better information than the Nicla Sense ME. Also in this case the values of the

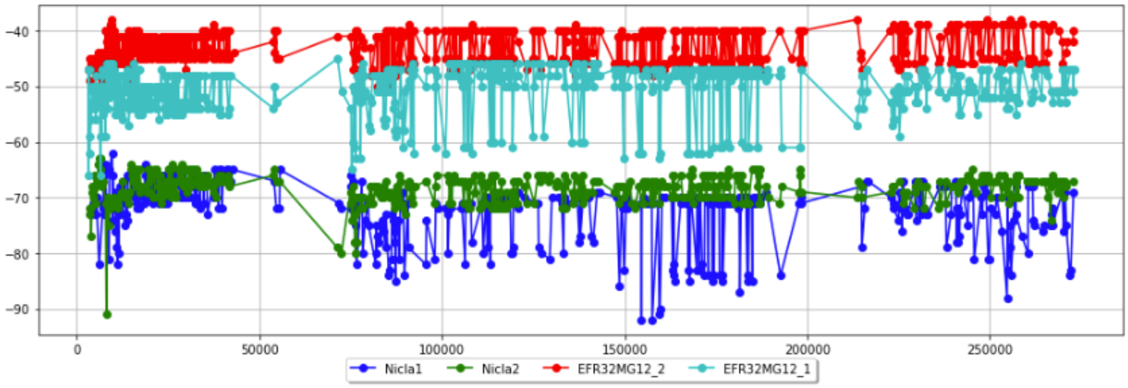


Figure 3.32: RSSI fourth experiment

advertising latency are better for the Nicla Sense ME with lower standard deviation.

Figure 3.33: RSSI fourth experiment (median values)

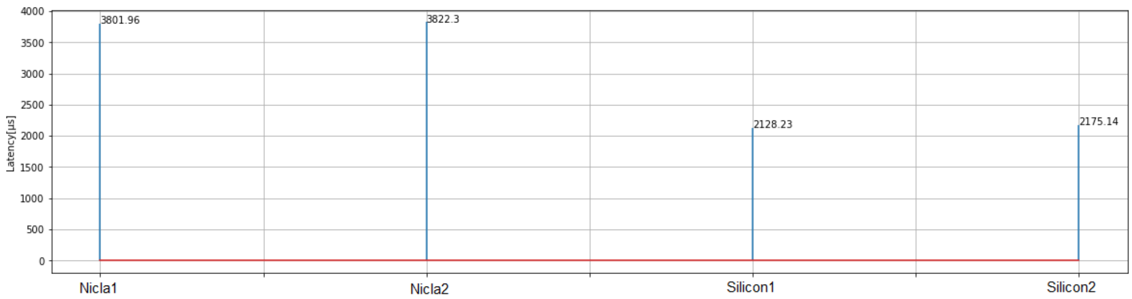


Figure 3.34: Latency advertising fourth experiment (median values)

Regarding the latency, for the advertising the same results are obtained as before, as well as for the connections, since the values are comparable to the earlier test. The time needed to transmit the bytes are always almost the same, only the standard deviation is a little different but nothing that can be preferable to an other since the

Board	RSSI [dBm]	Latency (Advertising) [µs]
Nicla1	-68.49 (4.47)	3801.96 (24.3)
Nicla2	-71.55 (4.00)	3822.30 (23.67)
Silicon1	-58,96 (6.13)	2128.23 (32.71)
Silicon2	-51.71 (4.99)	2175.14 (32.32)

Table 3.3: Mean values RSSI, latency and their standard deviation, fourth experiment

values are very small. This time the standard deviation for the EFR32MG12 for the 241 bytes is smaller than before.

Experiment	Nicla Sense ME latency [ms]	EFR32MG12 latency [ms]
241 bytes	248.13 (3.6)	247.89 (4.3)
1 byte	28.58 (0.33)	26.79 (0.69)

Table 3.4: Values latency fourth experiment

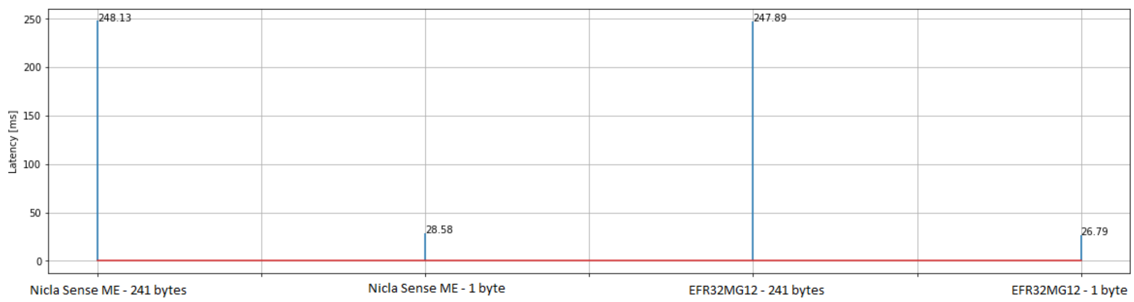


Figure 3.35: Latency fourth experiment (median values)

3.3.5 Fifth test

In the fifth experiment, I made the test bench rotate (with a rotation of 0,785 rad/s) with the software focusing only on the peripherals. The test lasted 306,357 seconds (5,11 minutes).

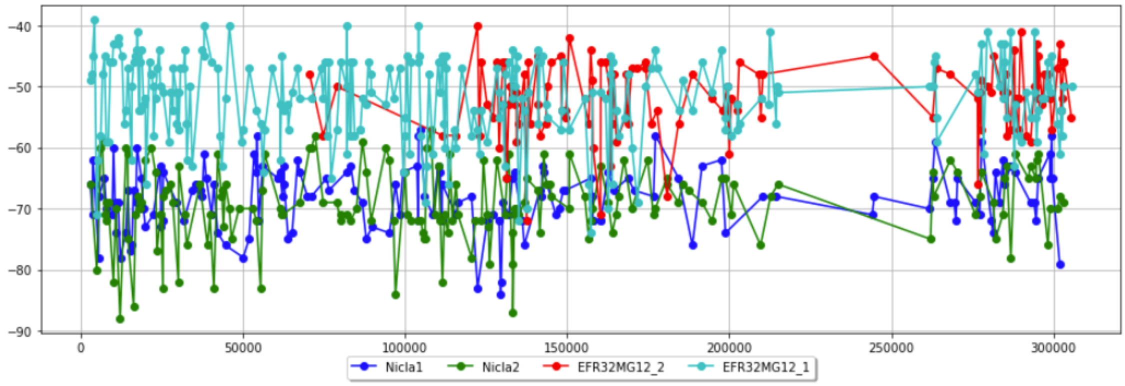


Figure 3.36: RSSI fifth experiment

By looking at the RSSI we can notice that they can still be reconducted to a certain range, however, they change during the rotation as it goes up and down. The radio from EFR32MG12 still is better than the Nicla Sense ME ones, as the RSSI has higher values.

It is worth mentioning the fact that in general the boards have be seen fewer times than before. This is not because of the functioning of the devices but of the post-processing decision to analyse only the data with complete information, including the angles. In fact, the software prints a log everytime the Portenta Breakout receive the transmission, not depending if the angle has been recorded or not. For this reason, some lines are not completed and so discarded. If the angle and the transmission are detected at the same time, a complete log is formed.

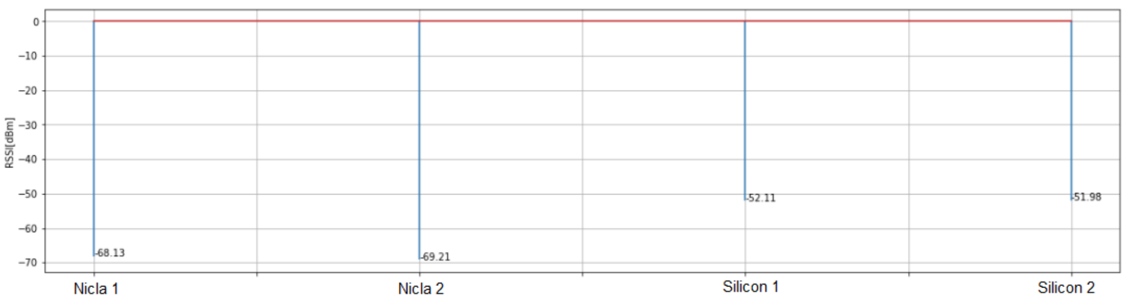


Figure 3.37: RSSI fifth experiment (median values)

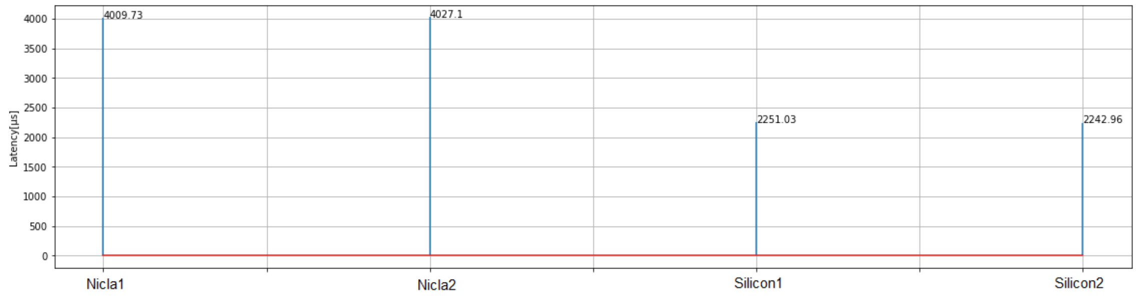


Figure 3.38: Latency advertising fifth experiment (median values)

Board	RSSI [dBm]	Latency (Advertising) [µs]
Nicla1	-68.13 (5.10)	4009.73 (25.70)
Nicla2	-69.21 (4.94)	4027.10 (25.61)
Silicon1	-52.11 (6.77)	2251.03 (34.45)
Silicon2	-51.98 (5.98)	2242.96 (34.54)

Table 3.5: Mean values RSSI, latency and their standard deviation, fifth experiment

By looking at the data obtained the consideration are similar to the ones done in the past experiments. In this case the latency is slightly worse than before, probably the rotation of the test bench caused a difficulty in the transmission. Also the standard deviation is a bit higher than before. This is valid for both connections and advertising.

Experiment	Nicla Sense ME latency [ms]	EFR32MG12 latency [ms]
241 bytes	249.34 (3.45)	247.49 (3.81)
1 byte	29.0 (1.01)	26.86 (0.66)

Table 3.6: Values latency fifth experiment

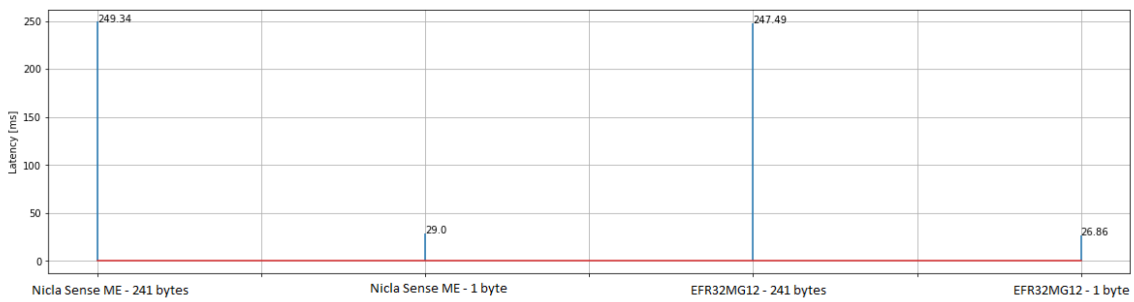


Figure 3.39: Latency fifth experiment (median values)

3.3.6 Sixth Test

In the sixth experiment, I made the test bench rotate (with a rotation of 0,209 rad/s) with the software focusing only on the peripherals. The test lasted 185,056 seconds (3,08 minutes).

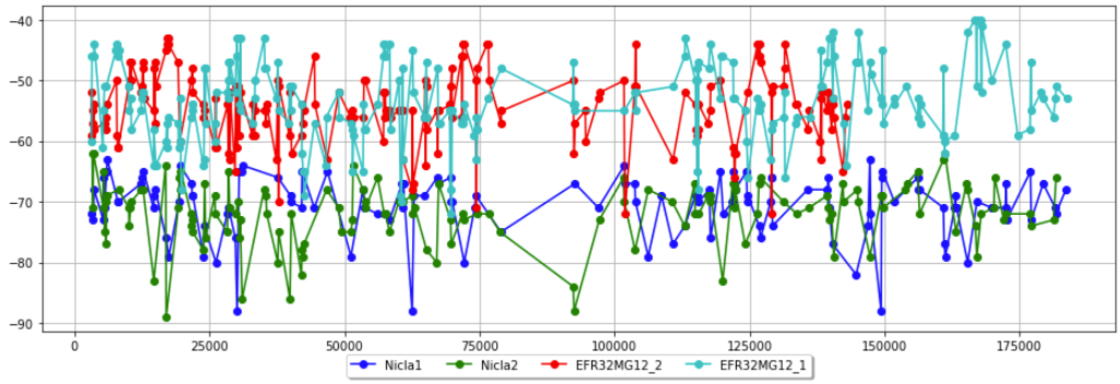


Figure 3.40: RSSI sixth experiment

As before the rotation is visible. Even though the slow rotation the Portenta Breakout blocked itself quite early this time, considering the other durations. Maybe it has been some interference or an event that triggered the software of the central. As usual, the EFR32MG12 has better RSSI than before.

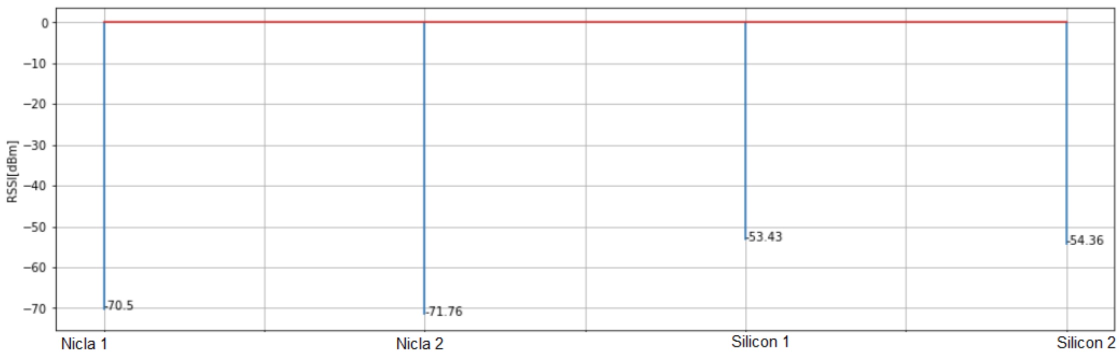


Figure 3.41: RSSI sixth experiment (median values)

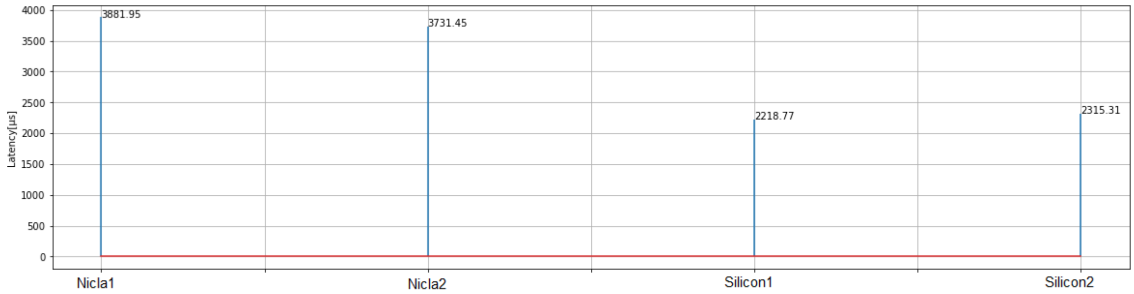


Figure 3.42: Mean values RSSI, latency and their standard deviation, sixth experiment

Board	RSSI [dBm]]	Latency (Advertising) [µs]
Nicla1	-70.5 (3.80)	3881.95 (25.88)
Nicla2	-71.76 (3.94)	3731.45 (24.72)
Silicon1	-53.43 (6.56)	2218.77 (31.56)
Silicon2	-54.36 (5.81)	2315.31 (33.17)

Table 3.7: Mean values RSSI and its standard deviation sixth experiment

Due to the shortened duration of the test, the results are remarkably akin to the precedent ones. Anyhow, it is remarkable the fact that the values are a bit lower than the fifth test.

Experiment	Nicla Sense ME latency [ms]	EFR32MG12 latency [ms]
241 bytes	248.95 (3.95)	247.05 (3.16)
1 byte	29.0 (1.01)	26.86 (0.66)

Table 3.8: Values latency sixth experiment

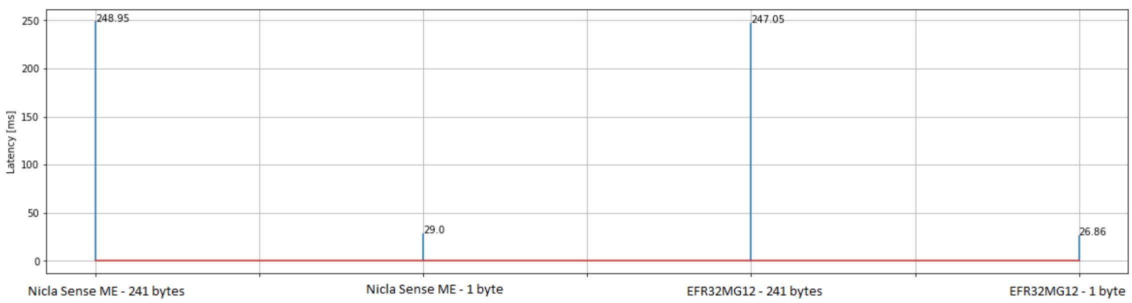


Figure 3.43: Latency sixth experiment (median values)

The latencies for the connections are identical as before, especially the 1 bytes cases, which reproduced the same values with the same standard deviation. This means that the behaviour is highly reproducible even in a in-field context.

3.4 Throughput study and Comments to the results of the bench experiments

The throughput, as explained in the section Software of this chapter (page 42), has been computed similarly to the latency, with the Nicla Sense ME address 16:43:2a:e7:28:f and the EFR32MG12 address d0:cf:5e:87:4d:f2. The different values has been measured for the experiments number 3, 4, 5 and 6, where the times needed to read the peripheral characteristic has been registered. The time to read the 1 byte arrays has been subtracted from the time to read the 241 byte array and the result has been used to compute the throughput of 240 bytes/seconds.

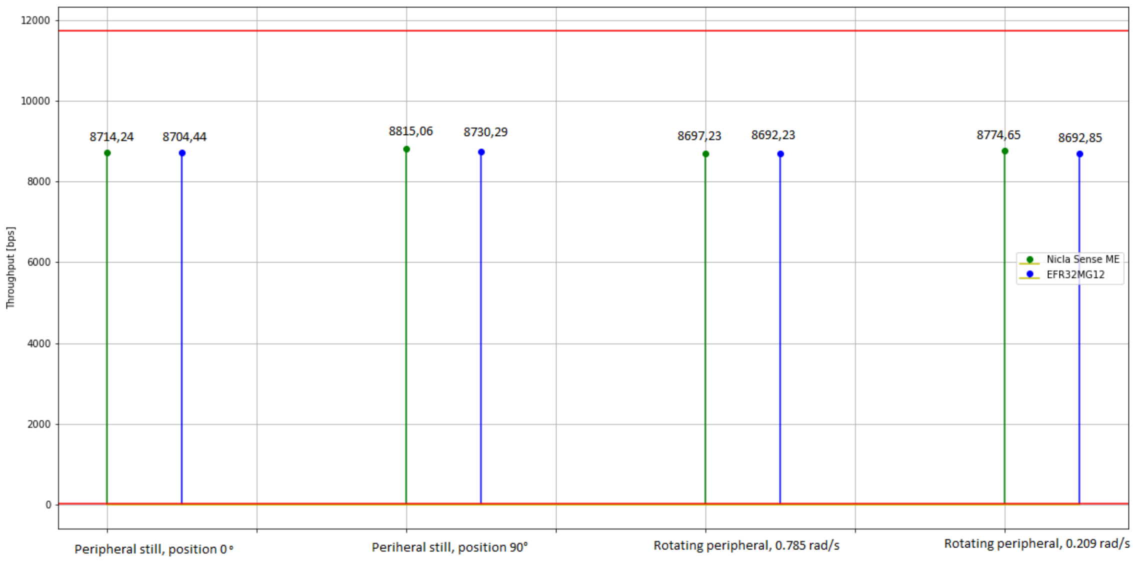


Figure 3.44: Throughput of the experiments (median values)

As said in the second chapter, the expected theoretical throughput should be in the range between $22bps$ and $11733{,}3bps$. The results are acceptable from this point of view and it can bee seen that they are quite high, almost reaching the optimal values.

In fact, the ratio of the data obtained with the parameter obtained with a connection interval of $7.5ms$ (the better one) is:

Experiment	Nicla throughput [bps]	EFR32MG12 throughput [bps]
Peripherals still 0°	8714.24	8704.44
Peripheral still 90°	8815.06	8730.29
Rotating peripherals 0.785 rad/s	8697.23	8692.23
Rotating peripherals 0.209 rad/s	8774.65	8692.85

Table 3.9: Throughput of the experiments

Board	Experiment	Ratio
Nicla Sense ME	Periheral still, 0°	74,21%
Nicla Sense ME	Peripheral still, 90°	75,13%
Nicla Sense ME	Rotation 0.785 rad/s	74,11%
Nicla Sense ME	Rotation 0.209 rad/s	74,83%
EFR32MG12	Periheral still, 0°	74,22%
EFR32MG12	Peripheral still, 90°	74,44%
EFR32MG12	Rotation 0.785 rad/s	74,02%
EFR32MG12	Rotation 0.209 rad/s	74,08%

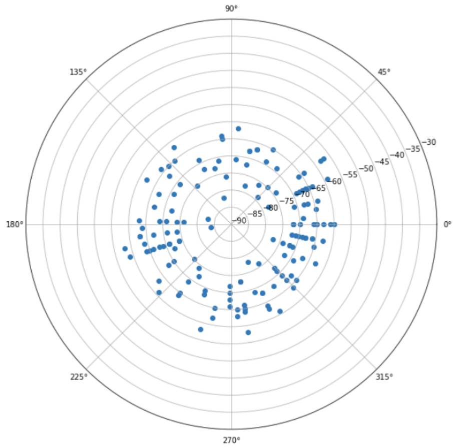
Table 3.10: Throughput ratio with theoretical one

It can be noticed that it is quite constant and both the peripherals have the same value. Actually, the throughput measured are higher since the receiver of the transmission (the central) just measured it by looking at the payload. However, as said in chapter 2, a packet is composed by more bytes which are the preamble(1 octet), the access address(4 octets), the CRC (3 octets), the header(16 octets), adding 24 bytes to the total number that is transmitted. However, due to the API used, it was not possible to know if these extra bytes are added for each byte communicated or only for the total amount sent.

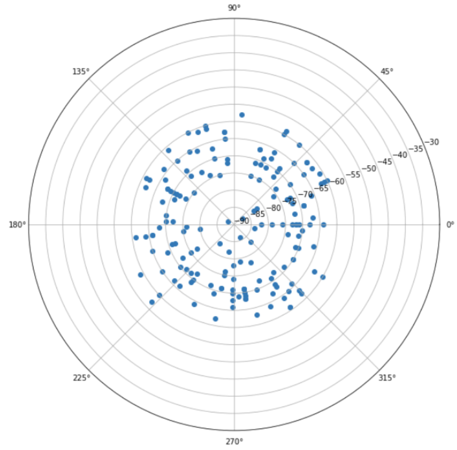
If the first supposition is correct, then for sure the resulting throughput would for sure recover the 36% missing, otherwise other factors have to be considered: troubles in the communications, interferences or other issues that made the process longer, making the final values worse.

Another topic, as said before, is that even though both the Nicla Sense ME and the EFR32MG12 could build larger characteristic than 241 bytes, the Portenta Breakout could read only those 241 at a time. This means that for sure these values are determined by this limitation of the central, which can be studied and expanded in the future.

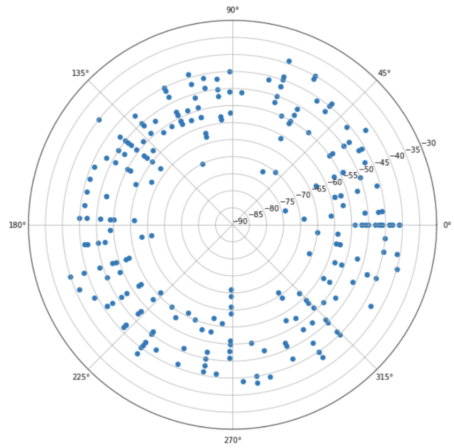
In order to see if there is a correlation between the angle of transmission and the results, here below the representation of both the RSSI and the throughput respect to the angle:



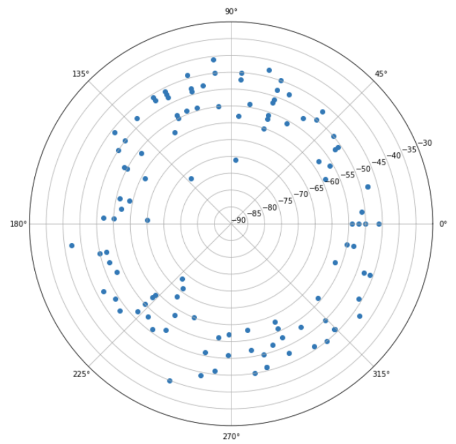
(a) RSSI Nicla1 fifth experiment



(b) RSSI Nicla2 fifth experiment



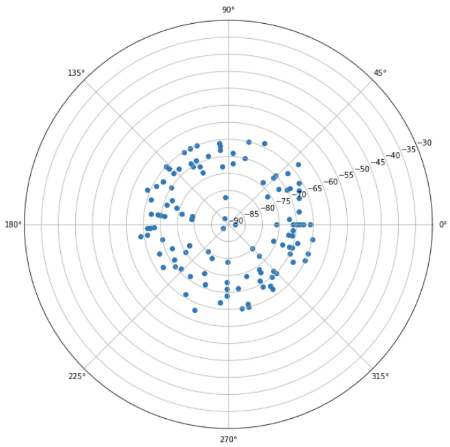
(c) RSSI Silicon1 fifth experiment



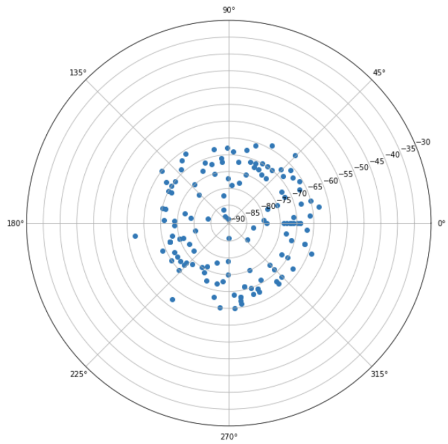
(d) RSSI Silicon2 fifth experiment

Figure 3.45: RSSI over angle, fifth experiment

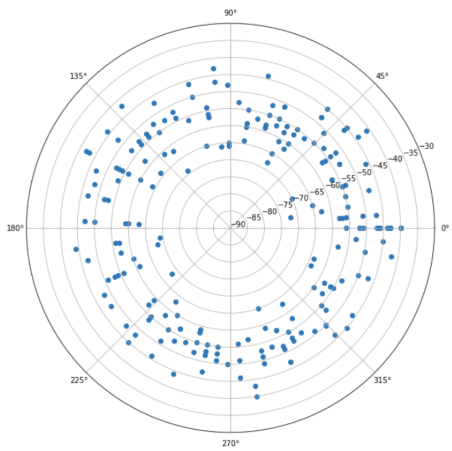
This measurement has not be done with the connections but only using the advertising mode. This lead to more data in less time, to see the correlation with the angle, even with the exclusion of malformed data. It can be noticed not only that the EFR32MG12 has a better RSSI than the Nicla Sense ME as said before, but also that even though the board was at the same angle, the RSSI measured is vastly different. There is a lower dispersion for the Nicla Sense ME, even though the values are worse than the other peripherals.



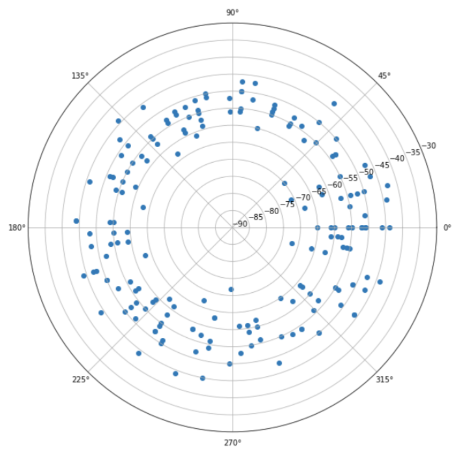
(a) RSSI Nicla1 sixth test



(b) RSSI Nicla2 sixth test



(c) RSSI Silicon1 sixth test

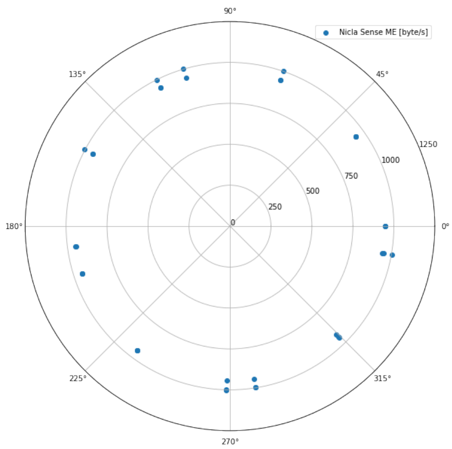


(d) RSSI Silicon2 sixth test

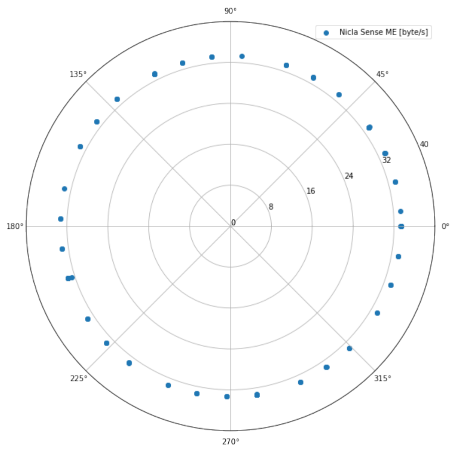
Figure 3.46: RSSI over angle, sixth experiment

Looking at the different results of the experiments, it can be said that the angle does not seem to be particularly relevant for the transmission. The collection are fewer since not only the connections have been used, but also exclusively the completed measurements are taken in consideration: those who have registered both the information of the throughput and the angle at which they were present.

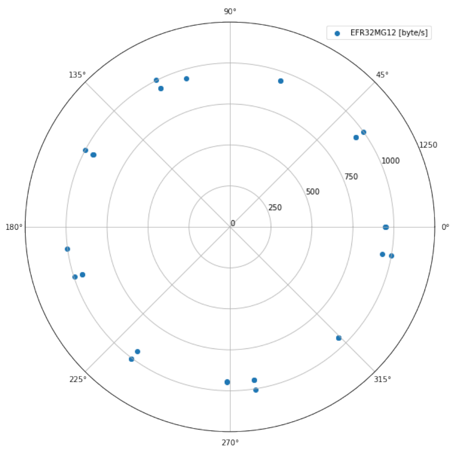
Interesting is noticing that while the data for the 1 byte transmission are almost constant, the EFR32MG12 in the sixth experiment did not manage to transmit the value as in the fifth, leading to fewer detections. Probably the peripheral have done more measurements while the angle was not recorded, so most of the values have been deleted.



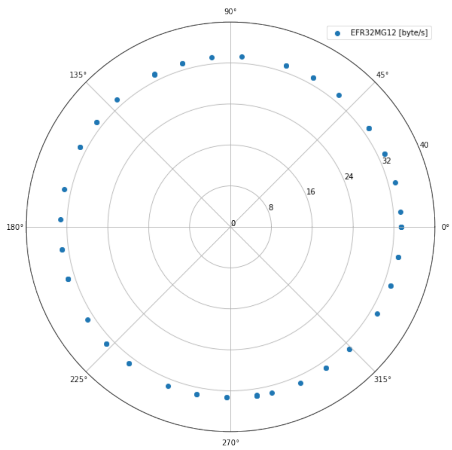
(a) Throughput Nicla 241 bytes TX



(b) Throughput Nicla 1 byte TX

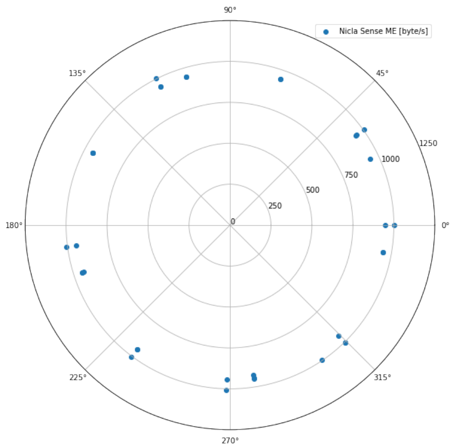


(c) Throughput EFR32MG12 241 byte

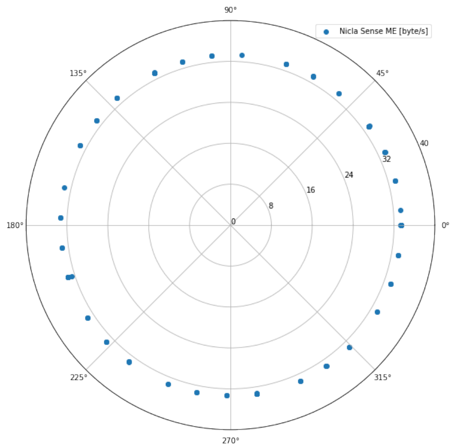


(d) Throughput EFR32MG12 1 byte TX

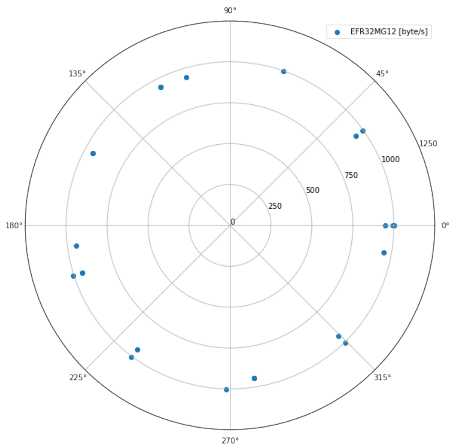
Figure 3.47: Throughput over angle, fifth experiment



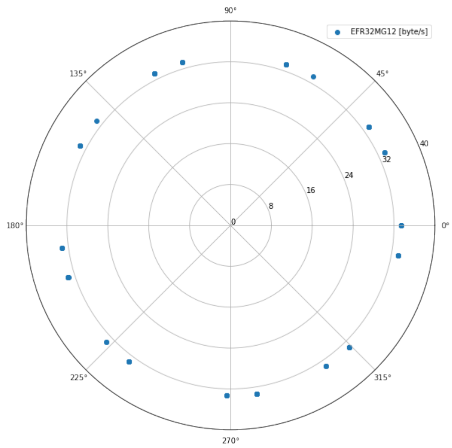
(a) Throughput Nicla 241 bytes TX



(b) Throughput Nicla 1 byte TX



(c) Throughput EFR32MG12 241 byte



(d) Throughput EFR32MG12 1 byte TX

Figure 3.48: Throughput over angle, sixth experiment

In general, the EFR32MG12 has better results than the Nicla Sense ME for the RSSI and the advertising latency. The connections latency and the throughput are almost equivalent, even though the Arduino Nicla Sense ME board showed a slight better transmission rate.

Theoretically, the angle at which the device is positioned should influence the results of the experiment; however, it is not immediately seen. In fact, the results are not clearly distributed and nothing can determine a specific connotation. The only thing that stands out is the dispersion of the values from the Silicon Labs boards for the RSSI.

To study the behaviour in the in-field experiment, the Nicla Sense ME has been chosen: since with the parameters measure it cannot be said which peripheral is better, the hardware has been considered. In fact, the Arduino board is smaller, easier to mount on a capping machine and, looking at the RSSI, it showed less unpredictability since it has less dispersion, even with a worse behaviour than the EFR32MG12.

Chapter 4

In-field experiment

The in-field experiment has been conducted in the main office in Canelli, where the real capping machines are built and tested. The experiment was conducted on the machine J0628, which had already installed an old version of the sensor node, where the Zigbee protocol was used. The Nicla Sense ME, as for the test bench, was powered by a battery mounted on the back of the case printed. The aim of the test was to see if the Nicla Sense ME could work in a industrial environment and see if there would be problems in recognising the boards.

4.1 Hardware and Software

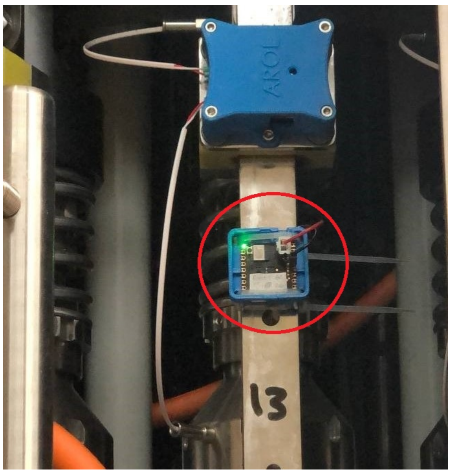


Figure 4.1: Nicla Sense ME mounted on a machine

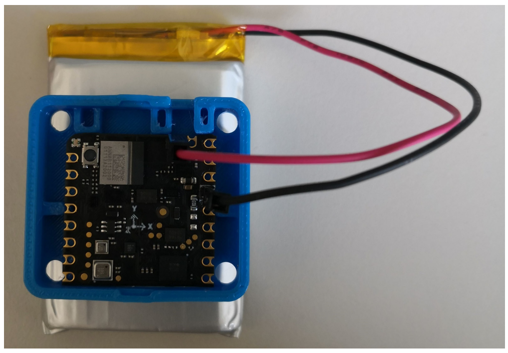


Figure 4.2: Nicla Sense ME and battery

The hardware used is similar to the test bench. Fifteen Nicla Sense ME have been mounted on each capping piston, with a battery on the back. The machine was put in rotation manually, through a switch.

Other than my experiments, also Ing. Gianpaolo Macario, my supervisor, had to verify some aspects of the transmission. For this reason, the software was a bit modified for this application: it was based in fact on the advertising process, where the manufacturer and advertising data are set to be 5 bytes and the event has been set to happen every 1 s, lighting the green LED every time, with an advertising interval of 5 s.

The tests have been divided into the same four cases of the test bench and they aim to compute the parameters useful to determine the communication between a central (the Portenta Breakout) and the peripherals (15 Nicla Sense ME). The KPIs defined in the design are latency and RSSI, since the throughput could not be measured in the advertisement modality.

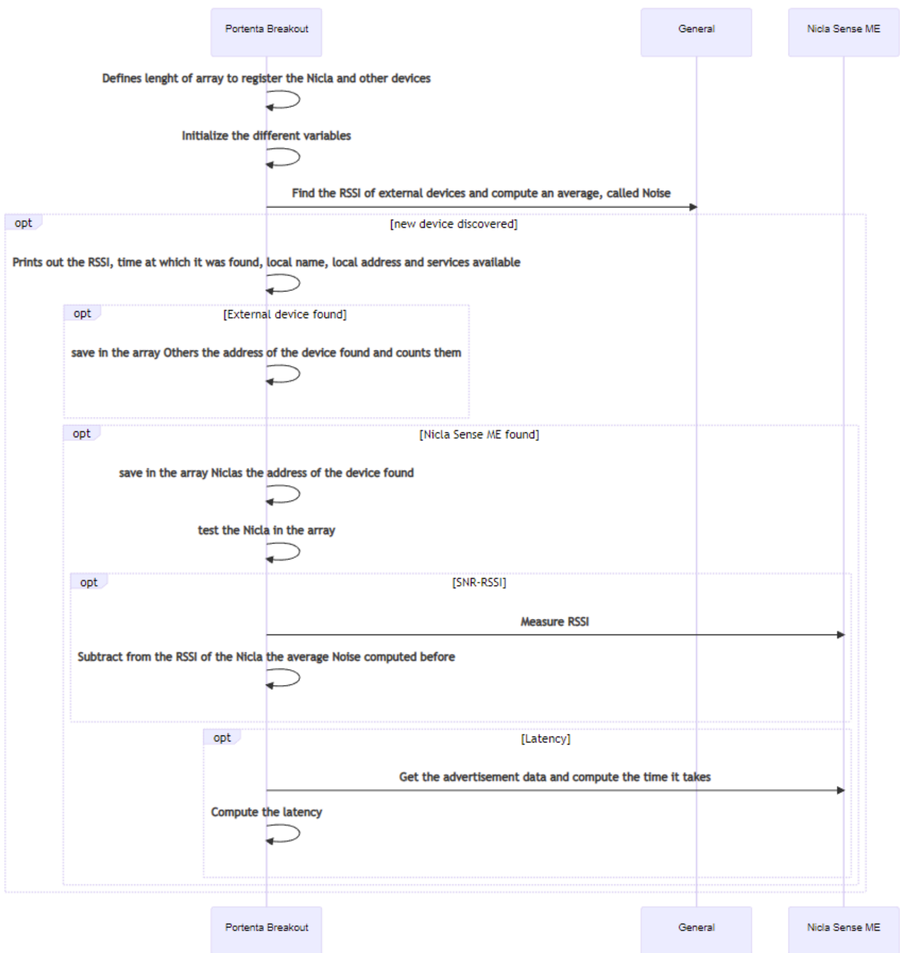


Figure 4.3: Software for the Portenta Breakout, in-field experiment

4.2 Experiment execution

4.2.1 First test

In the first test, the antenna of the Portenta Breakout (and the board itself) was 583 cm (5,83 m) far away from the Nicla sense ME. The machine was stationary, and the firmware considered all the devices in the area. The software found 97 devices, confirmed also by using an external app to identify the number of Bluetooth devices in an area.

Due to a malfunction in the Arduino's software protocol on the library BLE, as well as what happened during the test bench, the Portenta Breakout blocked after a while, leading to a short test (15,858 s) and the reset of the board. This also blocked the capability to discover all the Nicla sense ME mounted on the machine, finding only 7/15 during the advertising process.

4.2.2 Second test

In the second test, only the Nicla Sense ME were considered, leaving the positions unchanged. The Portenta Breakout did not show any kind of interruption, however, after a while (474,919 s or 7,9 min) it did not find any new advertising service. It is noticeable that the Nicla sense ME were rarely found, only a few nodes in facts are registered. All 15 are taken into consideration after 219,393 s (3,65 min).

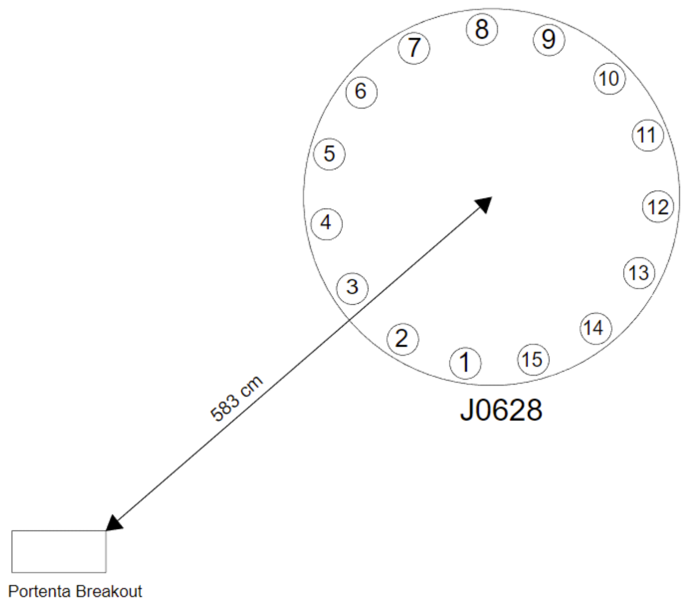


Figure 4.4: Position of the Portenta respect to the machine, second test

For how the nodes were distributed, the Nicla Sense ME directly facing the antenna should have been the number 3, however, it is not the one with the best RSSI, which is number 12. These numbers can be explained by the metallic carter of the machine, which could probably make the signal bounce or block an optimal connection between the nearest Arduino peripheral and the Portenta Breakout.

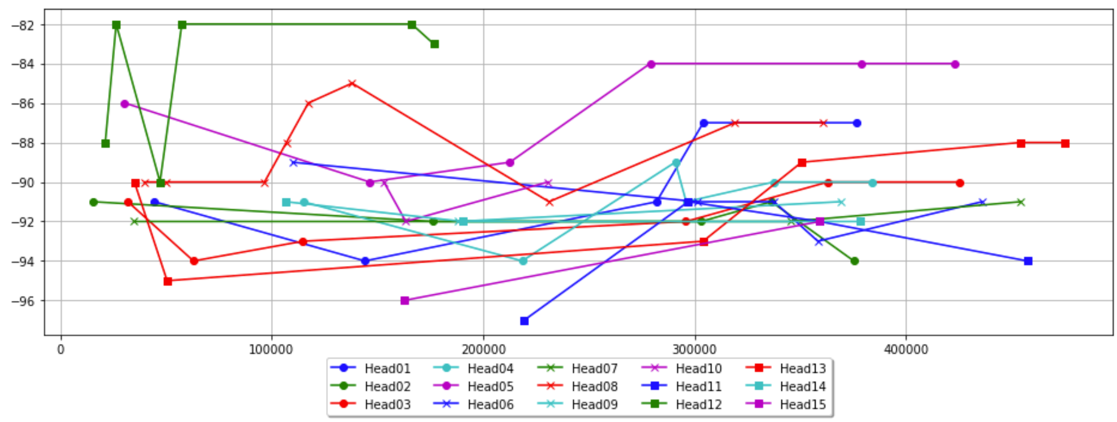


Figure 4.5: RSSI second test

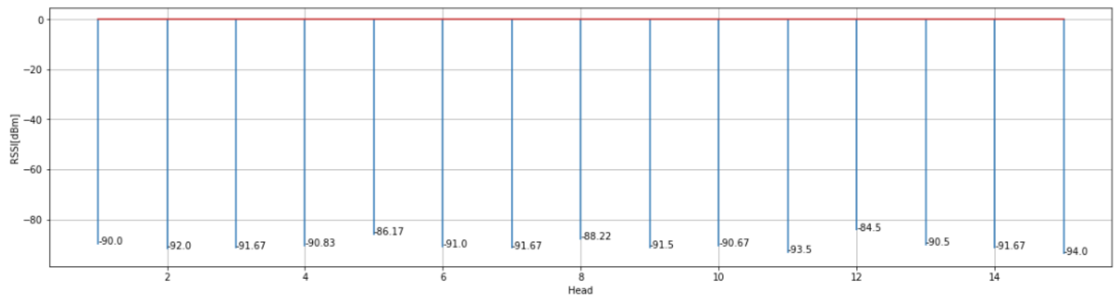


Figure 4.6: RSSI second experiment (median values)

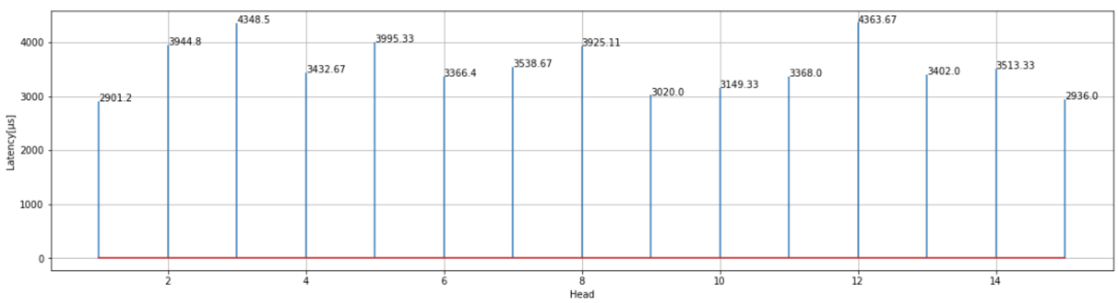


Figure 4.7: Latency second experiment (median values)

From the graphs below, it can be noticed that the capping head with the better behaviour is number 6. It has a RSSI which is not optimal but still in a range considered good, with low latency. The worst peripheral is number 12, despite its RSSI, because of its high latency. It is also the head which was lesser seen.

Board	RSSI [dBm]	Latency [µs]
Head01	-90.0 (2.68)	2901.2 (164.00)
Head02	-92.0 (1.095)	3944.8 (933.83)
Head03	-91.67 (1.49)	4348.5 (500.14)
Head04	-90.83 (1.57)	3432.67 (321.49)
Head05	-86.17 (2.48)	3995.33 (1175.89)
Head06	-91.0 (1.27)	3366.4 (883.95)
Head07	-91.67 (0.47)	3538.67 (1119.24)
Head08	-88.22 (1.99)	3925.11 (964.43)
Head09	-91.5 (0.5)	3020.0 (220.00)
Head10	-90.67 (0.94)	3149.33 (232.07)
Head11	-93.5 (2.29)	3368.0 (885.11)
Head12	-84.5 (3.25)	4363.67 (1176.7)
Head13	-90.5 (2.68)	3402.0 (164.00)
Head14	-91.67 (0.47)	3513.33 (1006.04)
Head15	-94 (2.0)	2936.0 (100.50)

Table 4.1: Values second experiment

The two heads are at 184° of distance, which means that they are at the opposite position and can be seen as a reasonable result.

By looking at the standard deviation graphs, it can be seen that the head 12 is still the worst one but the number 10 is the best not only for the results obtained but also for the low dispersion in the values measured. In general, it can be said that the dispersion values are not bad, apart from heads 5,6 and 12, which have higher values in almost all the measurements. For sure the software bug which stopped the experiment did not help in obtaining reliable data, but it is strange how a Nicla Sense ME is seen for only an interval of time and then no more.

4.2.3 Third test

In the third test, I put the Portenta Breakout with its antenna at 1 m from the centre to the machine, with head 01 facing it. I considered all the devices in the area and, as before, not all the Nicla are found and the Portenta interrupts the firmware after 49,988 s. It found 100 external devices.

4.2.4 Fourth test

In the fourth test, only the Nicla Sense ME were considered, keeping the same position as before. By looking at the results, it can be seen immediately not only how often the peripherals are found with respect to the previous tests, but also that the RSSI is improved. All 15 are taken into consideration only after 74,387 s (1,24 min). The overall test lasted 802,065 s (13,37 min).

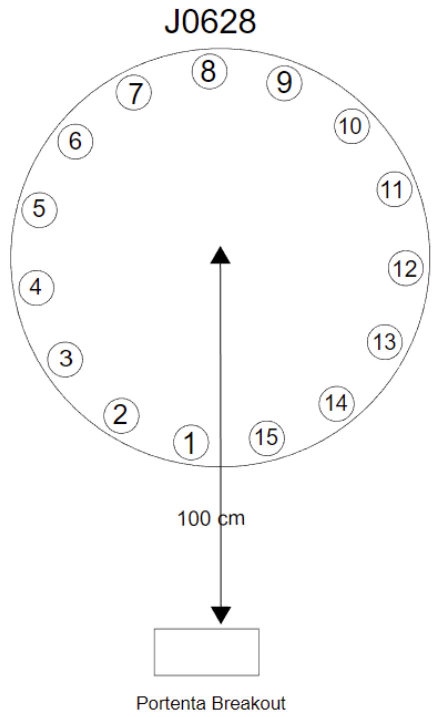


Figure 4.8: Position of the Portenta respect to the machine, fourth test

The best head is number 10, even though it is still on the opposite side of the machine. Also, heads number 4,6 and 15 are not bad, more coherent with the position of the antenna.

By looking at the results of the experiment, the better Nicla Sense ME should be number 6 for its latency and RSSI. The worst case for this experiment is head 8 for the highest latency.

The results are quite low, not reaching the high values of the EFR32MG12 during the testbench tests, however, this can be explained by the presence of not only more external devices but also the metallic material of the machine. Also for the fact that the Portenta was nearer the machine, with the interferences of Nicla Sense ME mounted on it and the Portenta Machine Control used by Gianpaolo Macario for his evaluations.

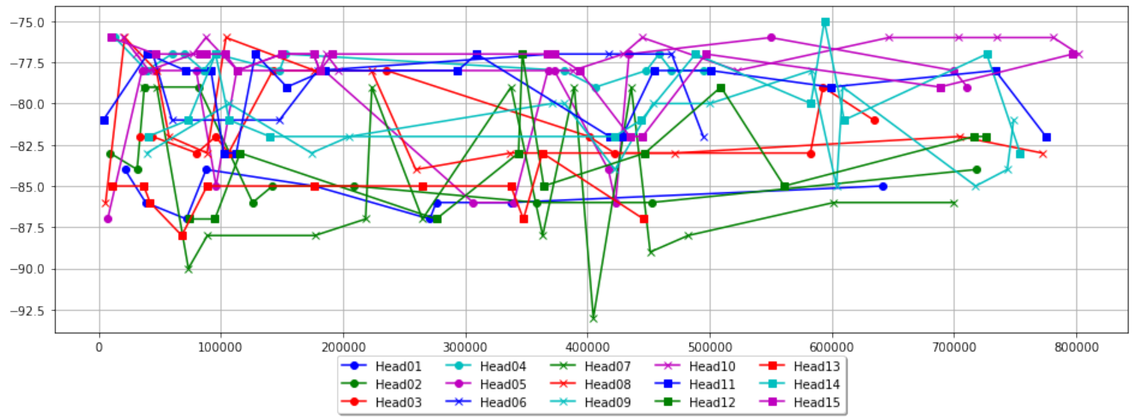


Figure 4.9: RSSI fourth test

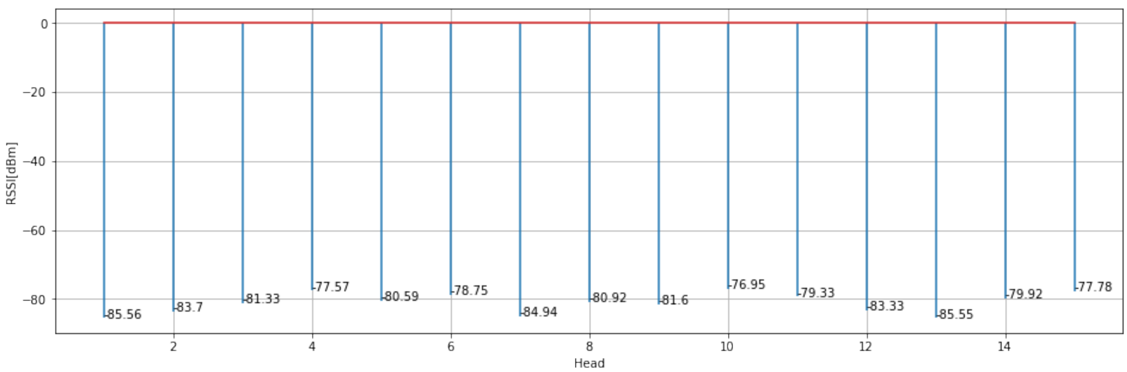


Figure 4.10: RSSI fourth experiment (median values)

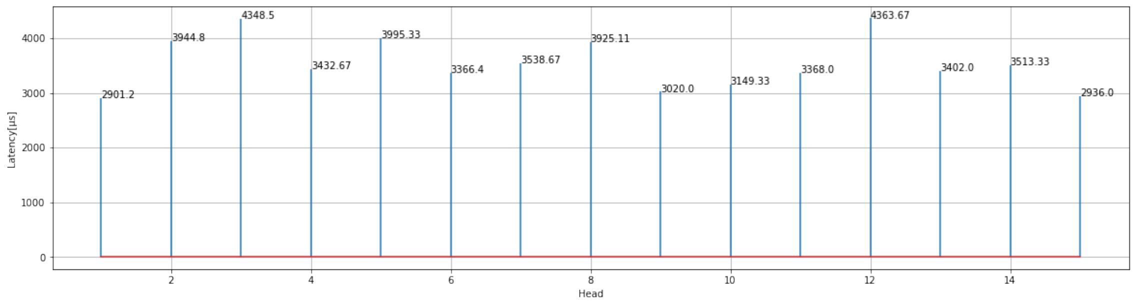


Figure 4.11: Latency fourth experiment (median values)

By looking at the graphs, the standard deviation is quite constant for every head, apart from head 7 which had a high dispersion in its data. This means that the measurements are highly predictable since all the Nicla Sense ME behaved almost in the same way.

Board	RSSI [dBm]	Latency [µs]
Head01	-85.56 (1.03)	3701.56 (25.15)
Head02	-83.7 (2.53)	3877.35 (27.53)
Head03	-81.33 (1.84)	3420.42 (28.13)
Head04	-77.57 (0.73)	3955.0 (32.66)
Head05	-80.59 (3.83)	4073.38 (30.58)
Head06	-78.75 (2.05)	3396.5 (27.02)
Head07	-84.94 (4.64)	3276.82 (27.86)
Head08	-80.92 (3.15)	4452.69 (29.20)
Head09	-81.6 (2.18)	3291.33 (25.57)
Head10	-76.95 (0.81)	3623.2 (29.37)
Head11	-79.33 (2.11)	4268.33 (32.44)
Head12	-83.33 (3.01)	3702.33 (32.89)
Head13	-85.55 (1.06)	4153.73 (25.16)
Head14	-79.92 (2.433)	3690.46 (31.60)
Head15	-77.78 (1.62)	4122.11 (32.45)

Table 4.2: Values fourth experiment

4.2.5 Fifth test

In the fifth test, I considered all the devices in the area while the machine was rotating. It found only 7 peripherals but recognised the 100 external devices advertising their information. The test lasted 34,061 s.

4.2.6 Sixth test

In the sixth test, I considered the rotating machine case, considering only the boards in the space of the experiment. The test lasted 204,476 s (3,41 min) and all Nicla Sense ME were recognised after 64,622 s.

The RSSI is very hard to read by the graph, but it is possible to notice that the heads rotated from the up-down movement of the curves.

All the measurements are quite stable and constant. All the heads have almost the same results, apart from little differences from one to another. This means that during the rotation all of them passed in the best and worst points, resulting in a similar outcome.

Unfortunately, since there has not been used any kind of sensor to detect the position, it is not possible to understand where these best/worst points are. The standard deviation, they are not as constant as the results. Nevertheless, it is quite usual that they are more varied since due to the rotation the values measured are different. It is noticeable in fact how different the graphs are from when the machine was still, with much more stable data.

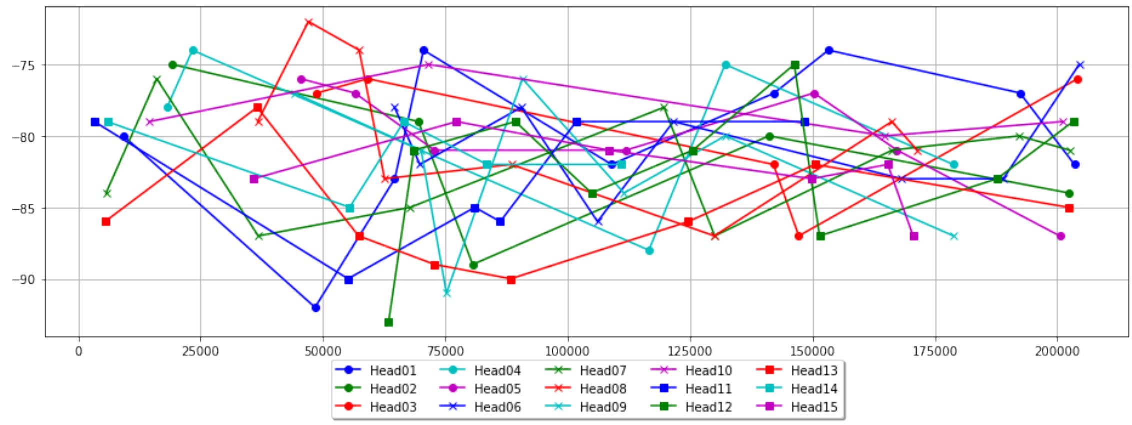


Figure 4.12: RSSI sixth test

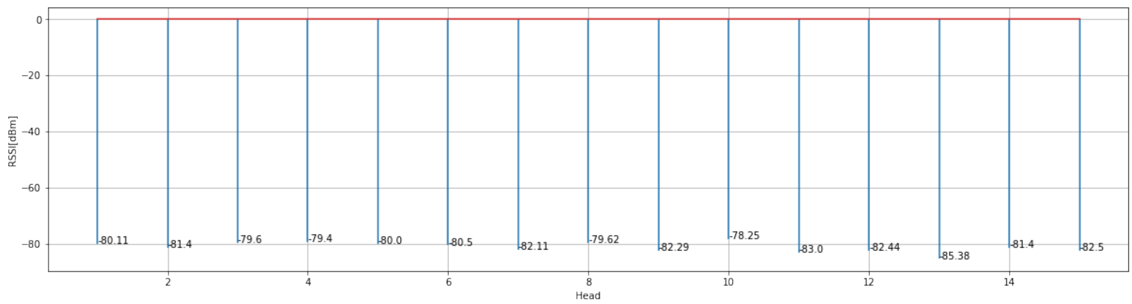


Figure 4.13: RSSI sixth experiment (median values)

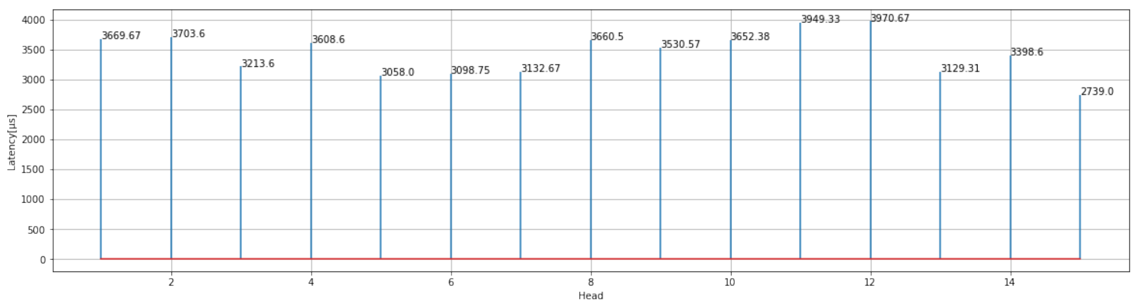


Figure 4.14: Latency sixth experiment (median values)

Board	RSSI [dBm]	Latency [µs]
Head01	-80.11 (5.28)	3669.67 (1048.99)
Head02	-81.4 (4.75)	3703.6 (854.95)
Head03	-79.6 (4.32)	3213.6 (493.71)
Head04	-79.4 (5.12)	3608.6 (1220.48)
Head05	-80.0 (3.50)	3058.0 (180.72)
Head06	-80.5 (3.35)	3098.75 (433.86)
Head07	-82.11 (3.66)	3132.67 (396.69)
Head08	-79.62 (4.52)	3660.5 (956.59)
Head09	-82.29 (5.00)	3530.57 (718.79)
Head10	-78.25 (1.92)	3652.38 (774.03)
Head11	-78.25 (4.28)	3949.33 (890.98)
Head12	-82.44 (4.92)	3970.67 (842.69)
Head13	-85.38 (5.28)	3129.31 (1048.99)
Head14	-81.4 (2.23)	3398.6 (426.01)
Head15	-82.5 (2.43)	2739.0 (39.66)

Table 4.3: Values sixth experiment

Chapter 5

Conclusions and future work

The objective of this thesis was to measure and determine the **transmission** of two different boards by using a **system** which had to be easily reproducible and scalable.

The **test bench** built has demonstrated to be an example of how this physical structure could be, proving to measure the different parameters and simulate efficiently the capping machine, letting the user add interferences at his/her will.

For the future, the construction is easily extensible, where different rotating platforms can be chosen to modify the tests that can be performed with different characteristics and abilities. As said in chapter 3, nowadays manufacturing can not only build platforms of different materials but also add features that can make the experiments more precise, like the usage of a remote controller or different types of rotations. The study can be improved by adding a sort of shield between the stands to make the transmission more difficult and see if there are changes in the values. An idea was to try to use an aluminium tray and see the changes in the parameters registered.

About the **two peripherals**, they manifest a very similar behaviour for all the parameters measured (RSSI, latency and throughput), not leading to a choice for better performance. It has carried out experiments with the Nicla Sense ME for its hardware specifications and meagre dispersion than the EFR32MG12. About the other KPIs (SNR and Antenna gain), it can be said that the angle at which the peripherals find themselves does not seem to affect the capability of connecting with the central and that the SNR (for how it was computed) is not relevant on the study done. Also different boards with different protocols can be studied, see how the results are with different kinds of connections.

The **in-field measurements** prove how efficient is the Nicla Sense ME in a context with multiple interferences, not only caused by the presence of external devices, but also by the different metallic layers that surely affect the transmission. The advertising latency is comparable since the recorded values are basically very similar both in the in-field experiment and the test bench. The connection latency in the test bench took 0.25 seconds to read and write the characteristic of the peripherals, while the advertising process took from 0.0043 to 0.0029 seconds to receive, read, and print the manufacturer data of the Nicla Sense ME. This, together with the RSSI measured, can demonstrate how these different behaviours characterize the peripherals' performances.

For future work, an in-depth study of the central will be done, to understand how the throughput is affected due to the limitation of the methods chosen since only 241 bytes could have been transmitted between the sensors. With the utilisation of a spectrum analyser, also the real SNR value can be computed, to evaluate better the peripherals and their abilities in ignoring the noise during communication.

Due to logistic issues, an in-field experiment for the throughput could not have been executed, so for sure that kind of experiment is a must to describe the in-field transmission.

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