A Study on Energy Efficiency of an Internet of Things Sensor Node

Guilherme Ferreira da Luz - 42828

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Engenharia Industrial. Work developed during the double degree exchange program between the Polytechnic Institute of Bragança (IPB) and the Federal Technological University of Paraná (UTFPR).

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Dedication

I dedicate this work to everybody that helped me finish this project in a way or another, in special to my family, professors and friends.

Acknowledgement

Instituto Politécnico de Bragança (IPB) and Universidade Tecnológica Federal do Paraná (UTFPR) for the opportunity of being part of the exchange program between them.

To IPB for providing the necessary equipment and laboratory used to develop this work.

Prof. Dr. Paulo Jorge Pinto Leitão, Prof. Dr. Joaquim de Mira Junior and PhD. student Jonas Queiroz for all the help, support and guidance provided throughout this work.

To the professors of IPB and UTFPR that were part of my development as student and researcher.

My friends that helped me in one way or another during the development of this work.

My family for all the support and patience while I was abroad.

Abstract

The number of Internet of Things (IoT) devices is growing rapidly. It is estimated that by 2025 there will be more than 50 billion connected devices connected to a network. Most of these devices are wireless, therefore, there is a need to use battery in order for the system to work. Since the number of devices is scaling and most use battery, charging and replacing batteries poses a challenge for IoT applications.

This work aims to study the energy efficiency in an IoT sensor node operating in a remote manner and propose an intelligent mechanism to optimize the energy consumption. In order to achieve this goal two steps were performed. The first was related to building a sensor node and study its power consumption considering different parameters. The second part was related to developing an intelligent control, based on Fuzzy Logic, to make the node more intelligent and manage its battery autonomously.

The resulting BMS will give the sensor IoT node the ability of controlling how it will operate based on the battery and environmental data. A higher battery lifetime will make the IoT device more reliable and reduce costs with maintenance.

Keywords: Internet of Things; Energy Efficiency; Battery Management System.

Resumo

O número de dispositivos de Internet das Coisas (IoT) está crescendo rapidamente. É estimado que em 2025 haverá mais de 50 bilhões de dispositivos conectados à rede. A maioria desses dispositos são sem fio, ou seja, é necessário o uso de bateria para que o sistema funcione. Como a quantidade de disposistos está aumentando e a maioria usa bateria, carregar e trocar essas baterias são um desafio para aplicações envolvendo IoT.

O objetivo desse trabalho é estudar a eficiência energética em um nó de sensores IoT operando remotamente e, propor um mecanismo inteligente para otimizar seu consumo de energia. Para que esse objetivo seja alcançado, dois objetivos foram determinados. O primeiro,estava relacionado à construção de um nó de sensores e ao estudo do consumo energia considerando diferentes parâmetros. A segunda parte estava relacionada ao desenvolvimento de um controle inteligente baseado em lógica Fuzzy. Esse controle fará com que o nó fique mais inteligente and gerencie sua bateria autonomamente.

O sistema de gestão de bateria deve fazer com que o nó seja capaz de controlar seu modo de operação baseado em dados da bateria e ambientais. Um maior ciclo de vida da bateria fará com que o dispositivo IoT seja mais confiável e deve reduzir custos custos com manutenção.

Palavras-chave: Internet das Coisas; Eficiência Energética; Sistema de Gestão de Bateria.

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Acronyms

3D Three Dimensions.

API Application Programming Interface.

BLE Bluetooth Low Energy.

BMS Battery Management Systems.

CeDRI Research Centre in Digitalization and Intelligent Robotics.

CoAP Constrained Application Protocol.

HTTP Hypertext Transfer Protocol.

IAQ Index for Air Quality.

IoT Internet of Things.

IPB Instituto Politécnico de Bragança.

IPB Polytechnic Institute of Bragança.

IPES Instituto Português de Energia Solar.

L2I Research and Innovation Laboratory.

LPWAN Low Power Wide Area Network.

MCU Microcontroller Unit.

MF Membership Function.

MQTT Message Queuing Telemetry Transport.

Ni-MH Niquel Metal Hydride.

PCB Printed Circuit Board.

UTFPR Federal Technological University of Paraná.

UTFPR Universidade Tecnológica Federal do Paraná.

Chapter 1

Introduction

1.1 Overview

The fourth industrial revolution, also known as Industry 4.0, is developing fast as industries are moving towards digitalization. Even though Industry 4.0 has a potential to create value estimated in $3.7 trillion for manufacturers and suppliers in 2025, only about 30% companies are taking advantage of this potential today [1].

Businesses are aware of the potential data has to offer, and the Internet of Things (IoT) is capable of generating this key component for companies to grow [2]. Estimations says that by 2025, IoT can generate up to $11.1 trillion of economic value each year. [3]

IoT has also got into people's lives in the form of smart devices, wearable technology and smart buildings for example [4]. It is estimated that in 2020 that people in Western Europe will spend annually more than 12 billion euros on smart devices [5], and by 2025 there will be more than 50 billion devices connected to a network [6].

But for IoT to be widely used by people and industry, it has some challenges such as privacy, security, standard and battery lifetime for example. This work will be focused in the IoT energy efficiency in order to increase battery lifetime. Devices that are located in remote locations will specially benefit from a better energy efficiency, it will reduce cost with maintenance and make the device more reliable. A good environmental impact is also to be expected with batteries lasting longer and required less substitutions over time. How can an IoT sensor node manage it's battery more efficiently?

1.2 Objectives

The main objective of this thesis is to study and understand the power consumption of IoT sensor nodes and then develop a strategy that can make the node intelligent in terms of energy efficiency. An IoT sensor node is a device capable of generating data from a set of sensors, then, transmit it. The meaning behind the word intelligent is that the IoT node will make decisions without human interference regarding its operating strategy to save energy supplied by the battery, particularly in remote areas where IoT nodes can not be connected to the electrical grid.

With the main objective in mind, the problem will be divided in the following specific objectives:

- Build an IoT sensor node that is battery powered and capable to send data using wireless technology.
- Build a dashboard to help in data visualization;
- Develop a testing strategy to understand how the IoT sensor node consumes power.
- Using the power consumption tests and environmental parameters, develop a control strategy that is able to make the IoT sensor node intelligent, managing efficiently the energy consumption.

1.3 Document Layout

This work has six chapters whose content are:

- Chapter 1: Has an overview on Industry 4.0, IoT, describing their importance as well as challenges related to the IoT. It also describes the problem to be solved in this work, objectives to be achieved and benefits of solving it;

- Chapter 2: This is the State of the Art part, it will describe relevant concepts and technologies as well as related work;
- Chapter 3: Description on how the IoT sensor node was built and also the development of a prototype of a real application;
- Chapter 4: Presents a series of test performed in one of the IoT sensor nodes. The results of these tests are presented and explained;
- Chapter 5: The development of a Fuzzy control to make the node intelligent is presented. It also shows simulation results of the control;
- Chapter 6: Conclusions and future work.

Chapter 2

State of the Art

This chapter briefly describes the related work in the field of energy efficiency in IoT nodes.

2.1 Internet of Things

IoT is a technology inserted in the context of Industry 4.0. The IoT is when objects or devices have the ability to generate and communicate data [7]. These objects could be a watch, a cellphone, a car, a light bulb and so on. Figure 2.1 shows some things people use everyday that are examples of IoT devices.

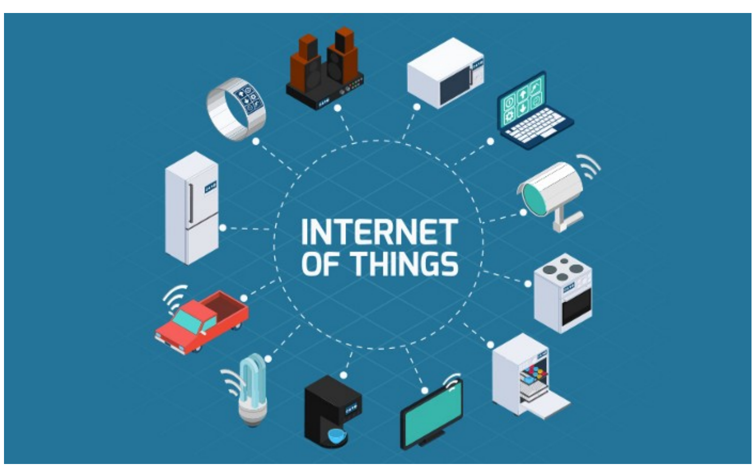

Figure 2.1: Internet of Things. [8]

Figure 2.2 shows fields where IoT can be used. In agriculture, a IoT sensor node could be built to measure temperature, humidity and soil moisture for example. In a building, a device can detect if there are people in the room and turn on the lights and air conditioning system.

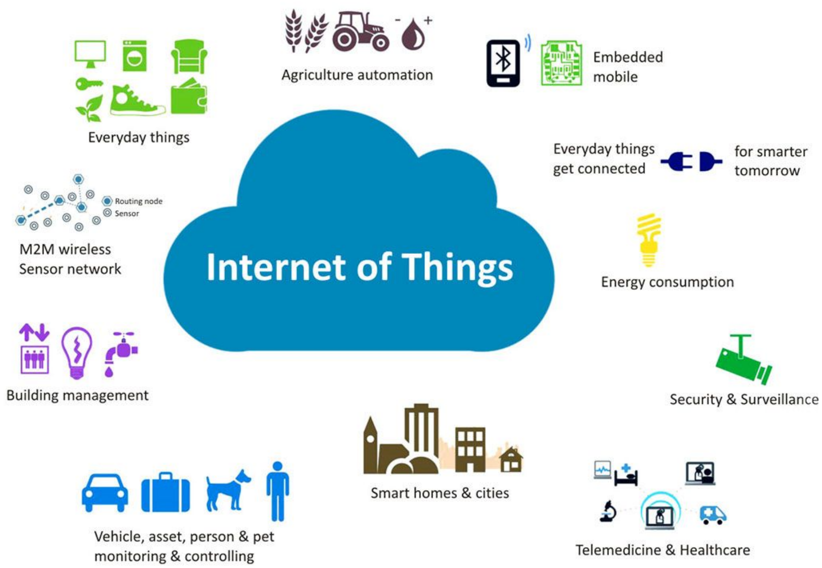

Figure 2.2: Internet of Things Applications. [9]

IoT has a great potential of value creation and a wide variety of applications. But there are challenges that hold back the growth of the IoT:

- Security: IoT devices are connected to a network. If a vulnerability exists in this device, someone could exploit it and get access to the network, exposing devices connected to it;
- Privacy: Other major concern is the leak of important information. For example, considering a person has smart home applications, these devices could leak personal information from that individual;
- Inter Operability: There are many technologies and manufacturers of IoT devices. If a application requires multiple devices from from different companies, it can be challenging to make everything work together.

- Battery: Most IoT application use batteries, therefore, battery lifetime is a key factor in the success of IoT devices. High battery capacity is a key factor consumer take into account when buying electronics. This also reduces battery waste and costs with maintenance.

Some of the data transmission technologies used in IoT will be introduced in subsection 2.1.1, and, in 2.1.2 two important communication protocols will be detailed.

2.1.1 Data Transmission Technologies

IoT devices communicate information to or from a destination. For this information to reach a network or another "thing", it is necessary to use a data transmission technology in order for that to happen. There are a wide variety of wireless transmission methods and the system requirements will help choose the most suitable one.

Wi-Fi

Wi-Fi is a wireless technology that makes an interface with the Internet, allowing devices to access it. The device compatible with Wi-Fi connects with a wireless router and then with the Internet. The IEEE 802.11 standard defines protocols to enable connection between Wi-Fi enabled devices [10]. The advantage of Wi-Fi is that it is widely available, has a high data rate, provides a direct communication with the Internet and easy to connect and disconnect devices from it. When it comes to IoT applications, Wi-Fi is not regularly used due to it's high power consumption.

Bluetooth

Bluetooth is used to connect devices to each other wirelesslly in order to transfer data. Common uses of Bluetooth are headphones, computer peripherals and cellphone. Compared with Wi-Fi, Bluetooth has a lower data rate but uses less power, has lower cost and devices detect each other automatically. [11]

For IoT applications,Bluetooth Low Energy (BLE) also known as Bluetooth Smart is more used. BLE is designed for low latency, short-range and low bandwidth IoT applications. Compare to classic Bluetooth, BLE has a low setup time, low energy consumption and can support an unlimited number of nodes. [12]

ZigBee

Zigbee was created by ZigBee Alliance [13] based on IEEE 802.15.4 standard for low-power wireless networks. The main applications of ZigBee are home and industrial automation. It was designed focusing low power, low cost, standardization, security and co-existence with other signals. ZigBee creates low power digital radio in a personal low size area network. It is suited for applications requiring long battery life, low data rate and secure network. [14] [12]

LoRa

LoRa is a Low Power Wide Area Network (LPWAN) managed by LoRa Alliance [15] that has become the go to technology for IoT applications. LoRa is designed to be used in IoT devices because it is a long range, secure, bi-directional, interference immune technology that can have a long battery lifetime and high capacity of nodes in the network. [16]

Table 2.1 shows a comparison between Wi-Fi, ZigBee, LoRa and Bluetooth.

Parameters / Technologies	**Bluetooth**	**ZigBee**	**Wi-Fi**	**LoRa**
Standart	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.11	IEEE 802.15.4g
Frequency	2.4 GHz (unlicensed)	868/915 MHz and 2.4 GHz (unlicensed)	2.4 GHz, 5 GHz and 6GHz (unlicensed)	869/915 MHz (unlicensed)
Modulation	GMSK	BPSK/OQPSK	BPSK/OQPSK	GFSK
Data Rate	1 Mbps	20, 40 and 250 kbps	11-54 and 150 Mbps	50 kbps
Power Consumption (Tx)	10 mW	36.9 mW	835 mW	100 mW
Range	Indoor: 20m Outdoor: 100m	100m	100m	Urban: 2-5 km Suburban: 15 km

Table 2.1: Transmission Technologies Comparison. [17] [18]

2.1.2 Data Transmission Protocols

The use of communication protocols such as the Hypertext Transfer Protocol (HTTP) is important to ensure devices understand each other, that is, make sure they speak the same language. For IoT applications the Constrained Application Protocol (CoAP) and Message Queuing Telemetry Transport (MQTT) are the main protocols.

MQTT

The MQTT is a protocol based on publish/subscribe architecture. It was created by IBM and Eurotech and today follow a standard by the OASIS group. MQTT is suited for applications in restricted environments, high latency and reduced bandwidth networks, low power and limited bandwidth devices. [19] [20]

MQTT communication has a central server known as MQTT Broker that manages data exchange between all devices in the network. The action of a device sending data to the broker is called publish and receiving information is subscribe. All this data traffic is separated in topics. A temperature sensing device can publish it's data in the topic temp, then, the broker will transmit this data to all devices subscribed to the topic temp. [21]

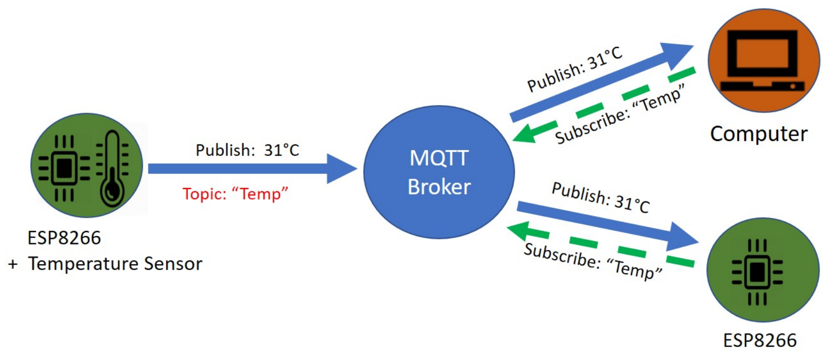

Figure 2.3: MQTT Application Example. [22]

CoAP

CoAP is used in constrained networks and node in IoT. This protocol can be seen as a lighter version of HTTP for IoT applications. As the name says, the CoAP is used in limited resources environments such as low bandwidth, limited power devices and networks with a lot of traffic and loses. This protocol uses four types of messages: Confirmable (CON), Non-Confirmable (NON), Recognition (ACK) and Reset (RST). When it comes to requests and responses, CoAP has four methods: GET, POST, PUT, and DELETE. [19] [23]

2.2 Battery Management

As new technologies are developed as well as worries regarding the environment intensifies, new and cleaner energy sources are being explored. The energy that is generated via solar or wind for example, has often to be stored in batteries, therefore, Battery Management Systems (BMS) are essential. The BMS are also used in operating battery powered systems in order to optimize battery usage and extend it's lifetime. [24]

There are a lot of BMS research in the field of electric vehicles and smart grid systems often involving local electricity generation using solar or wind energy.

Even if good hardware and technologies are selected to build an IoT device, the use of a BMS can boost even further the energy efficiency of these nodes.

There is a lot of research related to BMS in the electric vehicles field. [25] is a work that proposes a new BMS strategy, it says that BMS is used to guarantee a high battery performance, but, most works were focused on driving conditions. Their solution was a low power BMS strategy that can switch from one operating mode to another depending on the condition of the vehicle. There were three modes in [25], Normal Mode, Standby Mode and Stop Mode. This paper [25] is relevant to this work given it's similarity in the idea of switching operating modes in order to optimize battery consumption.

Energy efficiency also plays a main role in battery lifetime, [24] is a work that proposes a Fuzzy logic control for a lightning system supported by IoT. The main objective of [24] is to control the illumination of a room based on the battery state, movement in the room, environment light level and date. This work uses Fuzzy logic to control the lamp and not the battery mode, but, for it to control the illumination, battery level data is required as well as date information. This data information is important to determine light requirement in different time of the year, it can change if it is summer or winter for example.

A paper that has a similar work to this is [26], it's title is Power Management in IoT Weather Station. It describes a power management model for a weather station based on IoT and operated by batteries. This weather station had a Microcontroller Unit (MCU), solar panel, battery pack, power management circuit and sensors. The authors chose Wi-Fi over other technologies because it has a direct access to the internet even tough it consumes more power. They tested their IoT system and with the results, optimized the electronic circuits and algorithms. The MCU has three operating modes that are controlled by the power management algorithm. The same algorithm also changes the frequency at which the Wi-Fi transmission happens.

2.3 Fuzzy Logic

Standard logic is used to determine if something if true or false. Fuzzy logic has degrees of truth, something can be totally true or half true for example. The degree of truth is determined by what is called Fuzzy sets. A Fuzzy set represents the degree of membership or the degree of truth. Fuzzy set value go from 0 (completely false) to 1 (completely true).

Given a input, the Fuzzy value is defined by the Membership Function (MF) graph. The MF maps all input values and shows an 0 to 1 equivalency. The process of converting the input value to a Fuzzy set value is called Fuzzification.

After a Fuzzy set value is defined, the control follows a set of rules in order to give an output. This set of rules are If-Then conditioned.

Considering a system that has a person height as input, and the desired result is to know if the individual is tall or not. If the input is a tall person's height, the result could be that the person is tall with a 0.9 degree of truth. If the person's height is average, it means that the person is tall with a 0.5 degree of truth.

The Fuzzy logic is suited for applications with imprecise inputs, it also work well in complex problems, because, it resembles human reasoning.

As an example of a Fuzzy logic application, consider a simple cooling system with a temperature reading and a fan. The temperature reading (input) goes from 0 (cold) to 1 (hot) and the fan speed (output) goes from 0 (stop) to 1 (fast). In this case, if temperature is very hot (0.9), then, fan speed is very fast (0.9). Or, if temperature is cold (0), then, fan is turned off.

This was a simple example of a single input and output system with a direct relation between them. But, Fuzzy control systems, will get more complex the more inputs or outputs are considered. A more complex Fuzzy control will be described in chapter 5.

Chapter 3

IoT Sensor Node

This chapter describes the development of a IoT sensor node, namely its hardware and software development.

3.1 Development of the Testing Sensor Node

An IoT sensor node has a general structure that can be seen in the block diagram from figure 3.1.

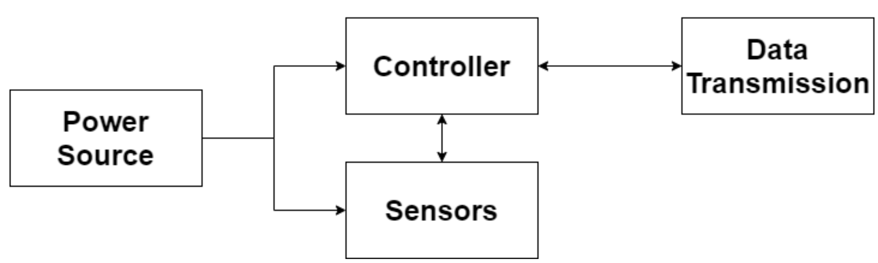

Figure 3.1: Generic Sensor Node Block Diagram.

The power source is going to provide energy to everything, it can be done by cable or battery. Sensors are the IoT device's way of interacting with the environment and transform physical characteristics into an electric signal. The controller is the node's brain, it is responsible for managing how the node operates. The last component is data transmission, it is responsible for transmitting all necessary data to a desired destination.

In order to build an IoT sensor node, which will be used in this work as testing platform to study the energy consumption, the device should:

- be able to transmit data wirelessly;
- have a battery as power source;
- count with a set of sensors.

The chosen controller for the IoT sensor node was an ESP32, because, it was available in the laboratory, can connect to Wi-Fi and has a wide amount of material available. The power source was a 12V-800mAh Niquel Metal Hydride (Ni-MH) battery that was available in the laboratory. Since the goal was to understand how the test node consumes energy, there was no need to look for a specific battery. The used sensors were:

- ADXL345: It is a three axis accelerometer [27];
- BH1750: Light intensity sensor [28];
- BMP280: Temperature, pressure and altitude sensor [29].

In order to measure the test node's power consumption a power meter device was assembled. The power meter was built using an ESP8266 as controller and the INA219 [30] voltage and current sensor. The INA219 was not built in the sensor node, because, it was important to measure constantly the voltage and current. This was not possible in the sensor node due to the use of the Wi-Fi Sleep mode, where it stops transmitting data.

Figure 3.2 shows a block diagram of the whole system and, Figure 3.3 shows the schematic for the developed IoT sensor node and the power meter. The final developed setup for the test of the sensor node can be seen in Figure 3.4.

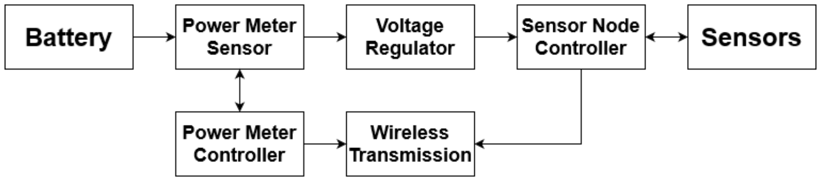

Figure 3.2: Sensor Node Block Diagram.

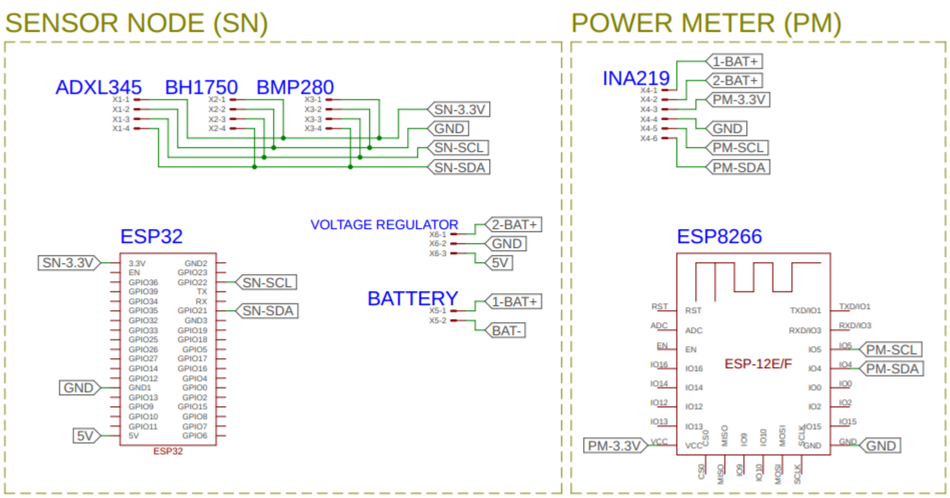

Figure 3.3: Test bed schematic.

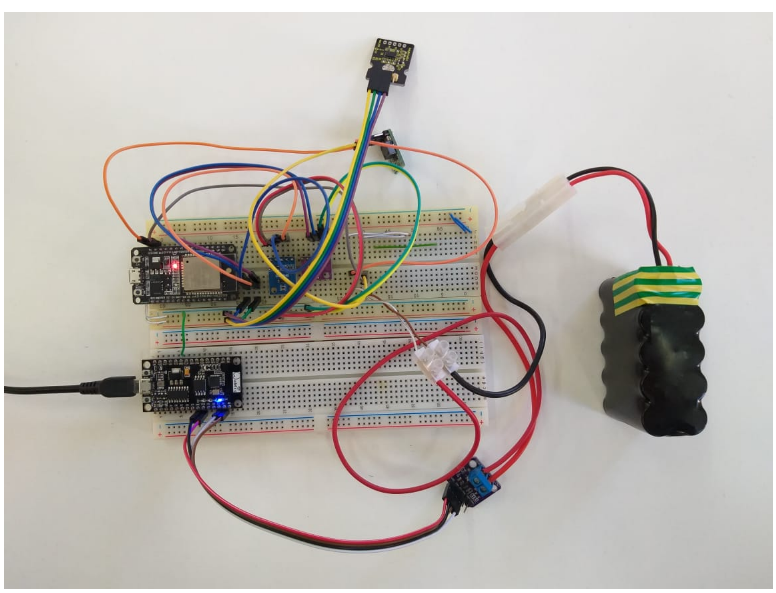

Figure 3.4: Test bed built on breadboard.

3.2 Data Storage and Visualization

The IoT sensor node and the power meter, were programmed to send data via Wi-Fi using the MQTT protocol. The internet network used was a regular home Wi-Fi. In order to setup the MQTT communication, the open source MQTT broker Mosquitto by Eclipse was used [31].

To visualize and storage data from the sensor node and the power meter, it was used Node-RED by OpenJS Foundation [32]. Node-RED is a browser-baser tool used to connect hardware with online services and Application Programming Interface (API). It is possible to crate flows using a wide variety of nodes available in Node-RED, and, create functions using JavaScript.

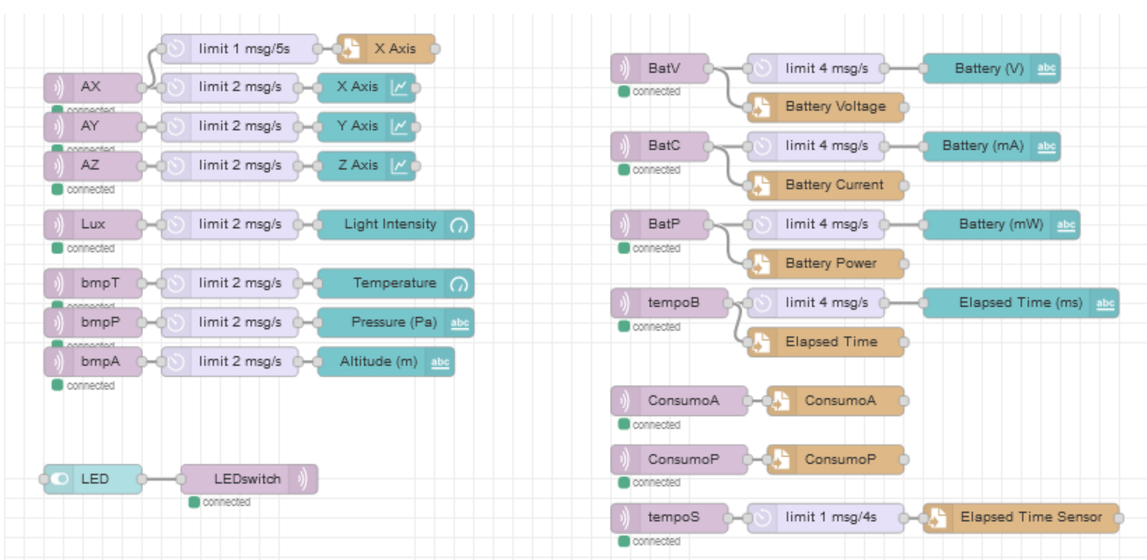

Figure 3.5: Node-RED Program Flow.

Figure 3.5 shows the flow created in Node-RED. This program is responsible for accessing the MQTT broker, displaying information in a dashboard and saving data in .txt files. Node-RED already have MQTT related program blocks, therefore, it is simple to setup the communication using this tool.

Figure 3.6: Node-RED Dashboard.

Figure 3.6 shows the dashboard built in Node-RED for data visualization. All sensor data is shown as well as battery information. The dashboard is primarily used in the tests to check if everything is working as they are supposed to.

The development of this system in Node-RED was made in a flow illustrated in Figure 3.5 using existing blocks. In order to make the MQTT connection, a library containing the specific block was included. All MQTT blocks were configured with the local Mosquitto broker address and a specific topic.

3.3 Building a Prototype Sensor Node

In addition to the testing sensor IoT node, it was developed and prototype another IoT node comprising more sensors for indoor environment monitoring. This prototype was installed at the Research and Innovation Laboratory (L2I) in the Research Centre in Digitalization and Intelligent Robotics (CeDRI) from the Instituto Politécnico de Bragança (IPB).

The building process is similar to what was described in Section 3.1. The controller for this prototype was an ESP8266 that works similarly to the ESP32. The sensor used were the BH1750 mentioned before and the BME680. The BME680 is a temperature, pressure, humidity and gas sensor [33]. This device was built to be indoor, therefore, the chosen power source was an regular outlet.

The main difference from the test node described in Section 3.1 is the data storage and visualization. For this prototype, sensor data was storage in InfluxDB [34] database. The dashboard was built in Grafana by Grafana Labs [35].

InfluxDB is an open source database focused on monitoring systems, analytics and IoT development. It is built to handle huge volumes from time-stamped sources of data produced by sensors, infrastructure and applications.

Grafana is an open source platform focused on building dashboards for data visualization. It counts with a large variety of visualization options and it supports a wide amount of databases such as InfluxDB. The dashboards created in Grafana can be shared with other people, and, be programmed to send alerts based on data thresholds.

The node transmitted data via Wi-Fi using MQTT protocol. Node-RED was used to subscribe to the MQTT broker, get sensor data and send it to the InfluxDB database. Then Grafana connects to the database and shows environment information in the dashboard.

For the physical construction, a Printed Circuit Board (PCB) was developed using EAGLE [36] and the housing was drawn using SOLIDWORKS [37], then, it was printed in a 3D printer. Figure 3.7 shows the PCB model made in EAGLE, and, the 3D model of the box can be seen in figure 3.8.

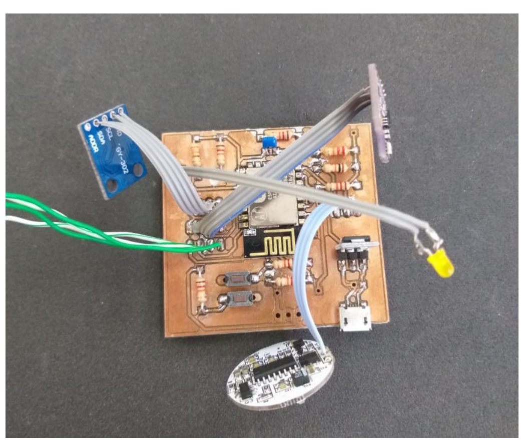

Figure 3.7: Printed Circuit Board Model.

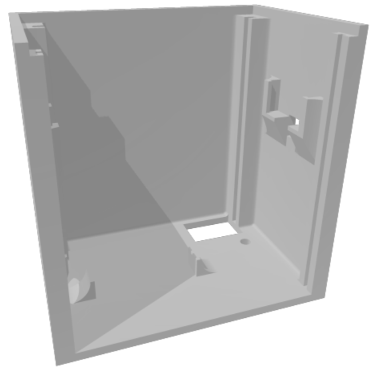

Figure 3.8: Box 3D Model.

The resulting prototype in Figure 3.9 was tested during a week. A week-long worth of data can be seen in Figure 3.10. This dashboard shows humidity, temperature, light intensity and air quality from L2I in CeDRI. The air quality was measured using the Index for Air Quality (IAQ). The IAQ classifies air quality in a scale from 0 (best) to 500 (worse). IAQ readings were made using code from Bosch Sersortec Library for the Arduino IDE available in GitHub [38].

Figure 3.9: Prototype.

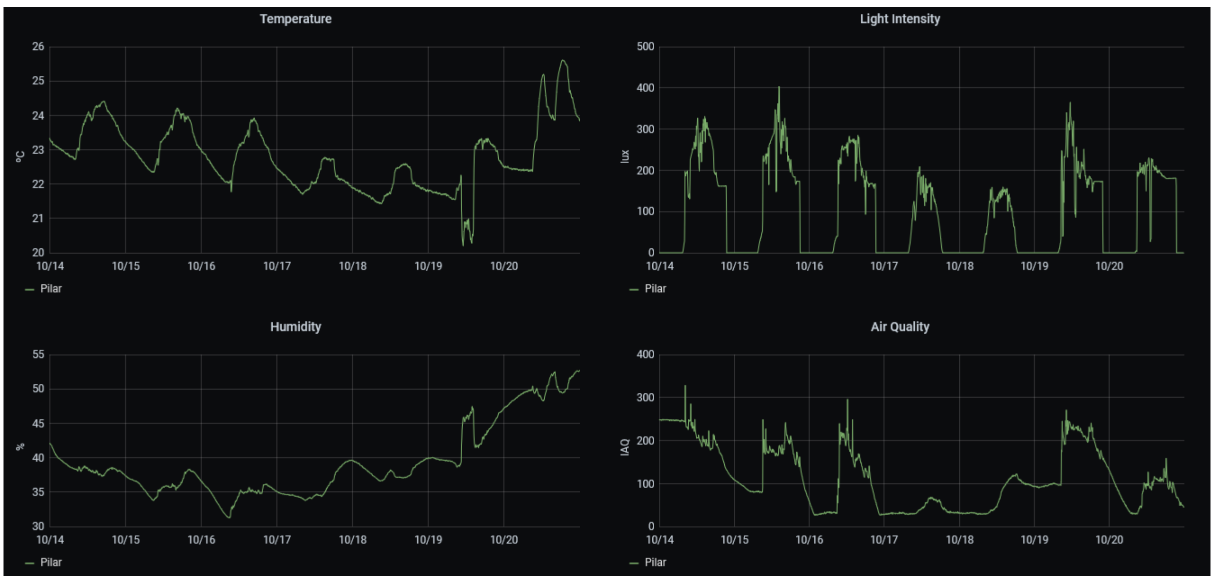

Figure 3.10: Grafana Dashboard.

Chapter 4

Understanding the IoT Node Energy Consumption

This chapter describes the set of tests that were performed to understand the IoT node's power consumption, particularly, the parameter dependencies for the evolution of the energy supplied by the battery along the time.

4.1 Test Strategy

In order to develop an intelligent BMS, it was important to understand the IoT sensor node energy consumption. For that, the test node and the power meter were assembled together and submitted for testing. There were three tests: full battery cycle, transmission frequency and data amount variations.

For all tests, the power meter was configured to sample a hundred data points of battery voltage, current and power. These readings were then averaged and sent via Wi-Fi and MQTT to Node-RED in order for them to be stored in .txt files. The approximate data acquisition frequency for the power meter is 2Hz (500ms between each reading). This frequency is approximate because of the time is takes to sample 100 values and average them. The battery power consumption in mW/h was also calculated locally in the power meter and then transmitted. The basis for this calculation was made based on the equation:

$$E = P * t$$

where E is the electric energy, P is power and t is time. This formula was used each time a new sample was acquired. Figure 4.1 shows the part of the code that makes this calculation.

```
deltaT = currentTime - currentTimeAnt; //Calculates time between each data aquisition
deltaT = deltaT/(1000*60*60);          //Converts ms to h

auxConsumoA = current_mA * deltaT;     //Multiplies the current reading with deltaT
auxConsumoP = power_mW * deltaT;

consumoAcumuladoA = consumoAcumuladoA + auxConsumoA; //Adds the new vlaue to the total
consumoAcumuladoP = consumoAcumuladoP + auxConsumoP;

currentTimeAnt = currentTime;
```

Figure 4.1: Energy consumption calculation.

In each of the three tests, the sensor node was configured with certain parameters. Battery cycle test had the goal of recording battery data during a full cycle, that is, from full until the node stops working. For that, a frequency of 1Hz (1/s) was set for data transmission.

The idea behind the next two tests was to observe how a parameter variation impacts the IoT test node power consumption. For each parameter variation, a fifteen minute test was conducted six times. From these six values, the highest and lowest were discarded and the remaining four were averaged. Two ESP32 modes were used: standard and Wi-Fi sleep. The standard mode is the default configuration when using the ESP32 Wi-Fi connection library (WiFi.h) in the Arduino IDE. The Wi-Fi sleep is when the Wi-Fi part of the controller was tuned off at the end of each transmission, then, turned back on when a new data was sent.

The first test aimed to understand the impact of data transmission frequency variation in both operating modes. The intervals between each transmission were 1s, 2.5s, 5s, 7.5s, 10s, ..., 30s.

In order to test the impact of data amount variation, the IoT sensor node transmission frequency was set at 0.1Hz, that is, data was sent every 10s. For the data amount variation, a while loop 4.2 was used to send the same data several times. The amounts tested were 1x, 2x, 4x, 8x, 16x, ..., 512x. The total size of all data transmitted was 81 bytes per transmission.

```
while(aux1 < dataAmount){
  client.publish("AX", ax);
  client.publish("AY", ay);
  client.publish("AZ", az);
  aux1 = aux1 + 1;
}
```

Figure 4.2: Data transmission loop.

The second test was done again, but with only the Wi-Fi sleep mode using two frequencies 0.1Hz and 0.2Hz, that is, 10s and 5s between each transmission. The data amount multipliers used were 1x, 2x, 4x, 8x, 16x, ..., 128x.

4.2 Battery Test Results

After running each set tests, the generated .txt files containing battery consumption data were processed in MATLAB. The first results are from the full battery cycle test.

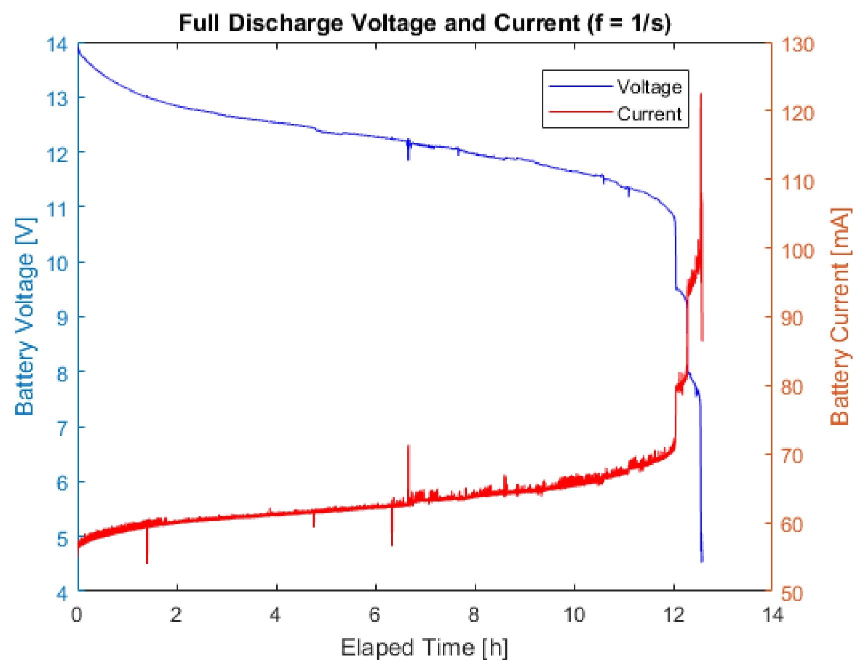

Figure 4.3: Voltage and current during a full discharge.

The graph in Figure 4.3 represents the voltage and current behavior during a full battery cycle. A key point to pay attention to is when the battery voltage reaches 11V. At this point the battery has a drastic drop in voltage, but, this is to be expected given how the Ni-MH battery works [39]. The approximate time length of this test was 13h, for an IoT device it is very low. This happens because the battery has a 800mAh capacity and the sensor node draws almost 70mA throughout the test.

Figure 4.4 shows that the power remained constant during the test. It was expected to be constant since the node is operating in the same way from start to finish. In figure 4.3 it is possible to see voltage and current balancing in order for the power to be the same. The are two bigger peaks in figure 4.4. The first one is likely caused by noise, and the second one happens when the battery can not supply enough power for the IoT sensor node to keep working.

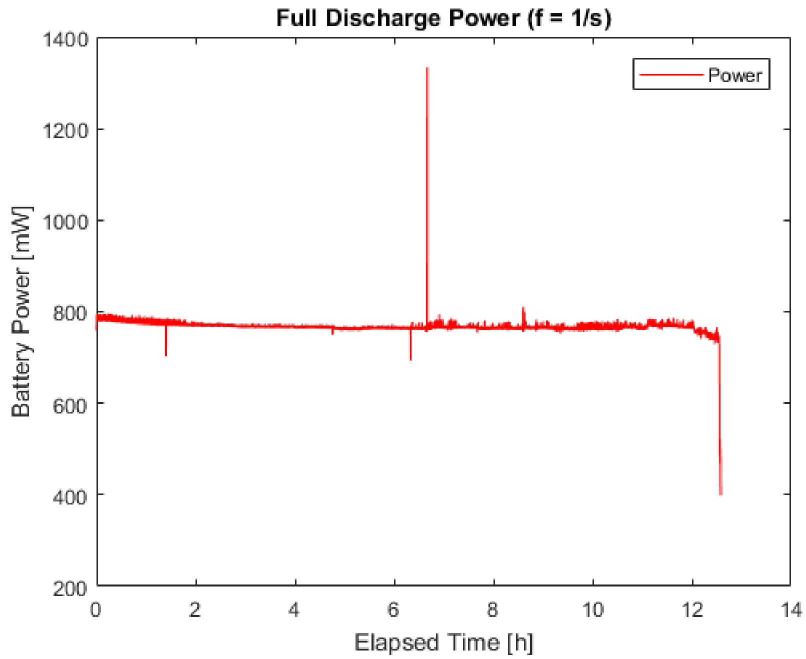

Figure 4.4: Power during a full discharge.

Figure 4.5 shows the impact that data transmission variation has in two different operating modes. Around the interval of 10s between each data transmission (0.1Hz) both lines cross each other. It shows that if the interval is lower that 10s ($f > 0.1$Hz), it is better to use the standard mode and not the Wi-Fi sleep. And if the interval is higher than 10s ($f < 0.1$Hz), Wi-Fi sleep becomes the best choice. This happens because wake-up ernergy has a big impact in battery lifetime [40]. When $f > 0.1$Hz the benefit of using the Wi-Fi sleep in neutralized by the impact of the wake-up energy consumption.

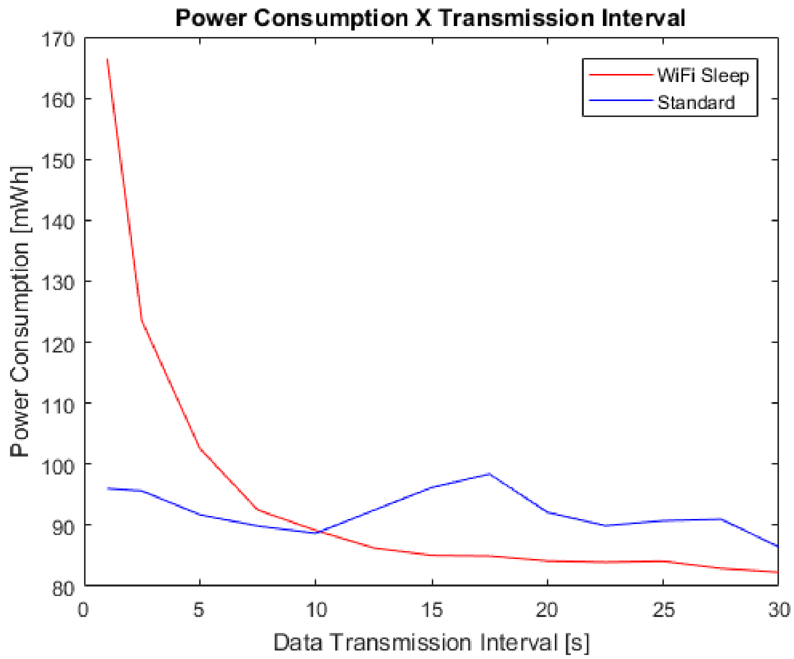

Figure 4.5: Power consumption x Transmission interval.

Figures 4.6 and 4.7 shows the results of the data amount variation test. The first figure shows all the tested points, while the second, shows data until the 32x multiplier. It is clear that, for this node, at approximately 2500 bytes (32x), there is a significant difference in power consumption. After this point, standard mode is more efficient than Wi-Fi sleep.

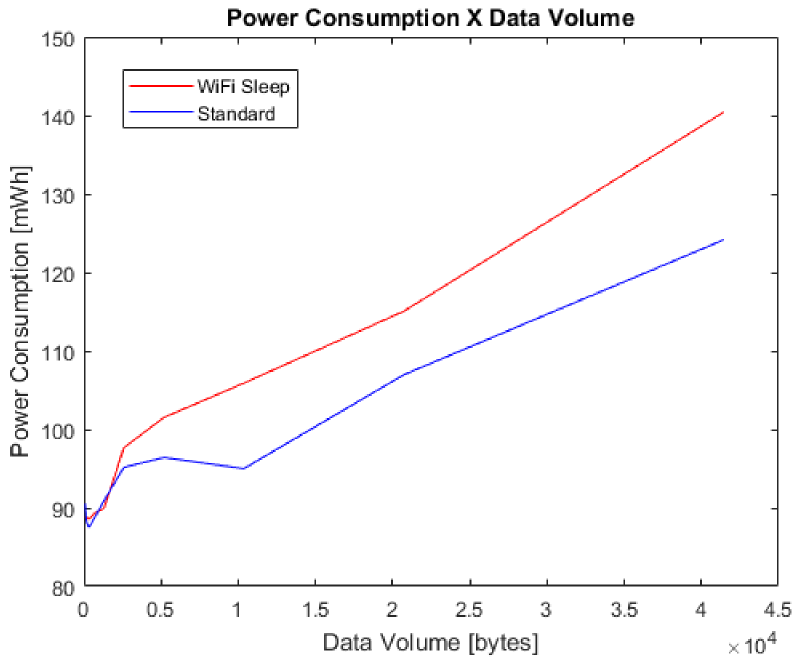

Figure 4.6: Power consumption x Data Amount.

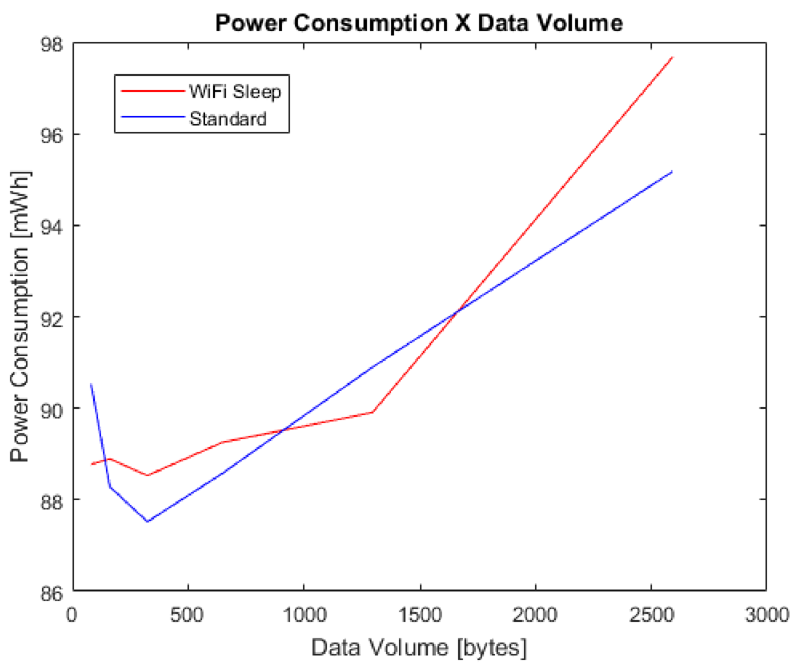

Figure 4.7: Power consumption x Data Amount (First points).

The last test was to compare the Wi-Fi sleep mode with two set frequencies when the data amount changes. Figure 4.8 shows the graph comparing the Sleep Mode using transmission interval of 10s and 5s when data amount changes using 1x, 2x, 4x, 8x, ..., 128x multiplier.

Figure 4.8 results from using the Wi-Fi sleep mode with two different frequencies (0.1Hz and 0.2Hz) while data amount changes. It shows that the lower the frequency, the more efficient Wi-Fi sleep becomes.

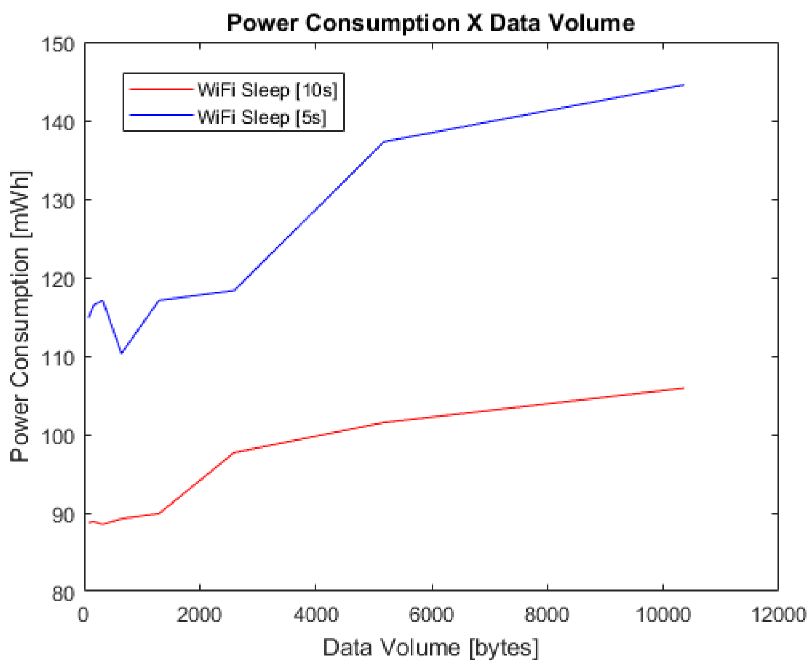

Figure 4.8: Power consumption x Data Amount (Sleep mode only).

4.3 Summary

All of these tests have helped understand how battery consumption in an IoT node works. They also showed how changes in parameters can impact power consumption. Even though some differences in consumption are no higher than some mWh, in the long run, they can have a big impact in battery lifetime.

Chapter 5

Fuzzy Control for Energy Efficiency

In this chapter will be explained the development of the Fuzzy control for the IoT node became intelligent and manage how it operates in order to save the battery energy overtime given some conditions.

5.1 Control Description

After building an IoT node and testing it to understand the battery consumption, it was time to think about a control that could make the IoT sensor node manage it's own battery.

The Fuzzy logic was chosen because of it's characteristics. It is a rule based system, mimics human logic, works well with imprecise inputs and is lighter than a Machine Learning system.

In order to develop this control, it was considered a scenario where the IoT device has a solar charger and a battery as power sources. The possible inputs for this Fuzzy control were battery voltage, rain probability, local solar irradiation and time of the day. These parameters take into account hardware and environmental conditions. Environmental information is useful for applications that have a solar charge in its systems, it is specially important for remote applications since they often have battery and solar charging.

The control's output are the possible operating modes for the IoT node, in this case there were three: Regular Mode, Saving Mode, Critical Mode. The definition of how each mode behave will depend on the application. The idea is the Regular Mode to be used when everything is working as expected, that is, battery level is good and solar charging can handle the power consumption. Saving Mode would come into action when conditions starts to get worse, for example, battery level is starting to get lower, or the solar charger is not being efficient due to bad weather. The Critical Mode will be activated when battery level reaches a low level or the solar charger is barely generating electricity.

The results from the Section 4.2 were not used because they are specific of the test node used in this work. Considering only the battery and environmental information, this control can be used in a wider amount of applications. But this do not mean these information can not be useful for a BMS.

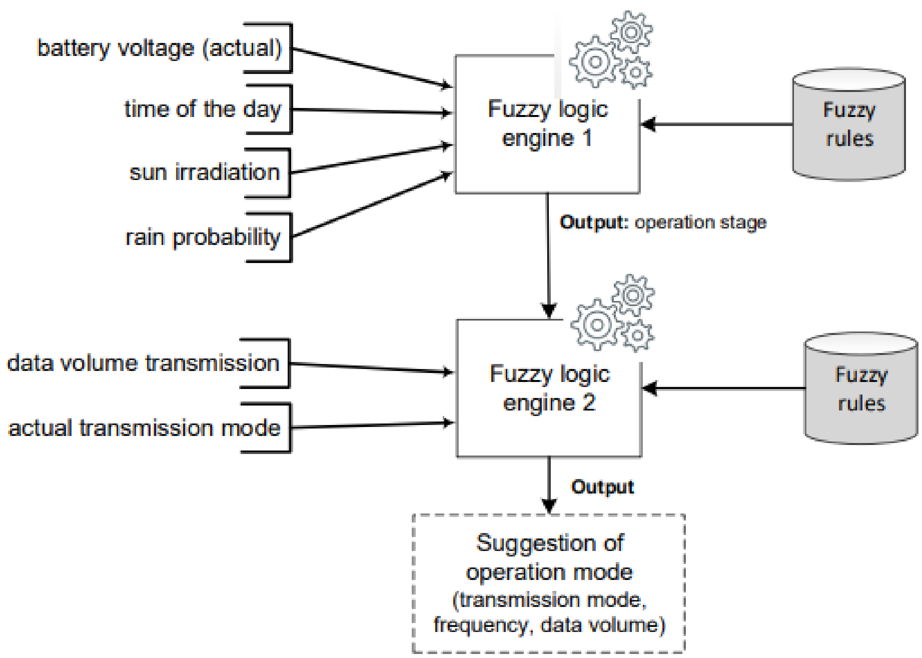

Figure 5.1: Fuzzy Control Block Diagram.

Figure 5.1 shows a block diagram for a two stage Fuzzy control. The first stage developed in this work, uses as inputs the battery voltage, time of the day, sun irradiation and rain probability in order to choose an operating mode (Regular, Save or Critical).

The second stage of this control is for future work. The output of the first stage, data volume and the transmission mode (Standard or Wi-Fi Sleep) are inputs for the second stage. The outputs of the second stage are operating mode, transmission mode, frequency and data volume.

5.2 Control Model

To develop the Fuzzy control, all the necessary MF were created. These MF will be shown and explained in this section.

Figure 5.2 shows the MF that represents the battery voltage, these MF were based on the battery voltage behavior during a full discharge cycle 4.3. The main thing taken into account was the 11V point, where the battery voltage drops drastically, that is, the battery level is very low and will not last very long.

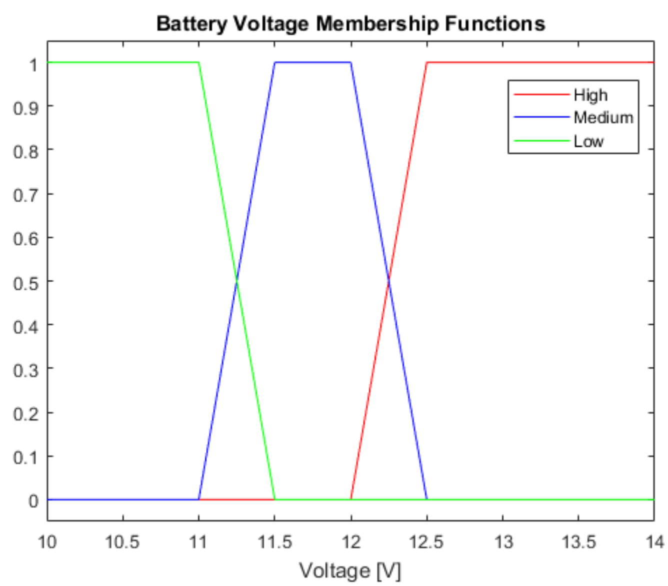

Figure 5.2: Battery Voltage Membership Functions.

Time of the day information was considered to know when the solar charger is expect to work. Figure 5.3 shows four periods: morning, afternoon, night and dawn. The separation of time time in two (night and dawn) helps estimate how long it will take for the solar charge to start working again.

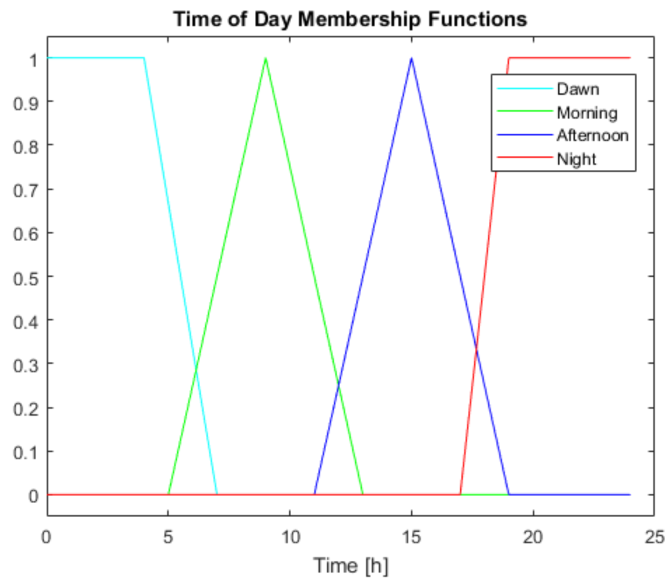

Figure 5.3: Time of the Day Membership Functions.

Rain Probability information will help predicting if, during day time, the solar charger will be working. This information is useful when battery voltage is at a normal level, but, there will be a week long of rainy/cloudy weather ahead. Figure 5.4 shows the rain probability MF.

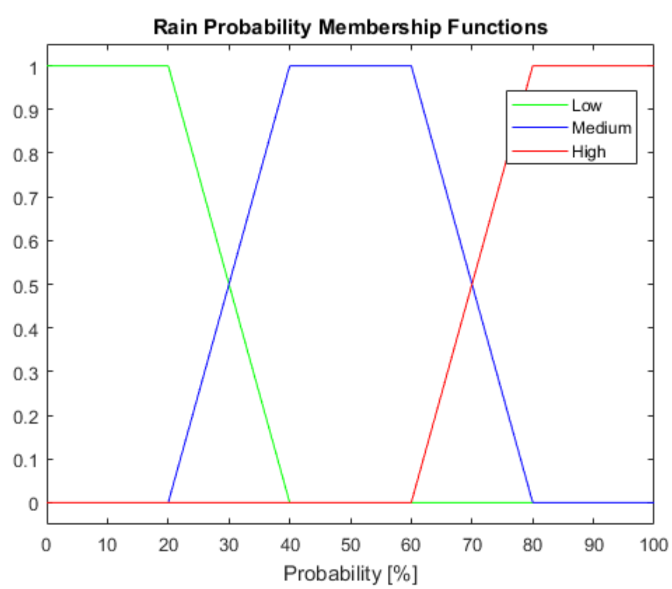

Figure 5.4: Rain Probability Membership Functions.

The last environmental parameter to be considered was the local sun irradiation during the year. In Figure 5.6 are the MF related to the local sun irradiation in the city of Bragança in Portugal. This information is seen in Figure 5.5 from Instituto Português de Energia Solar (IPES). Local sun irradiation data helps differentiate summer and winter time, a sunny summer day will have a bigger impact than a sunny winter day when it comes to solar charging.

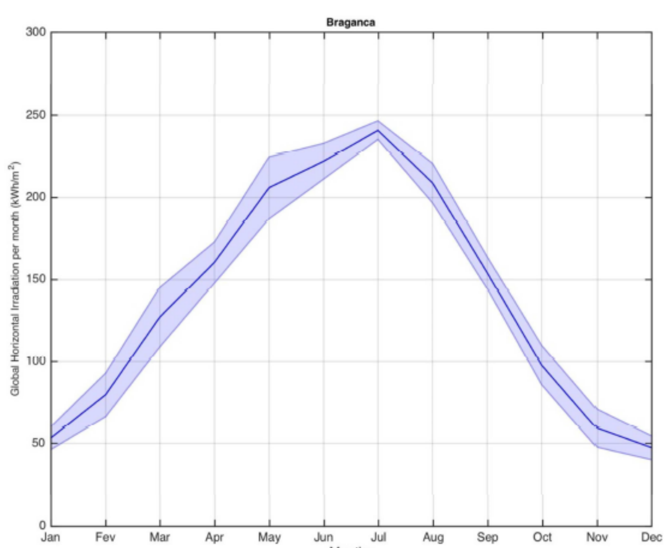

Figure 5.5: Sun Irradiation in Bragança-PT during the year. [41]

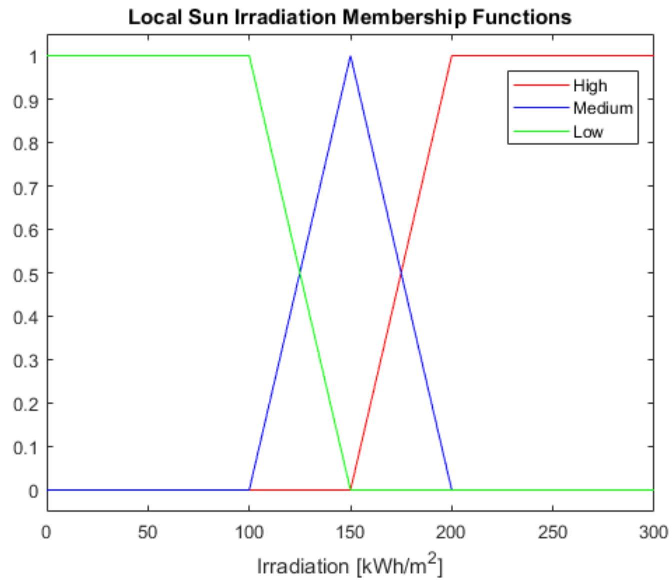

Figure 5.6: Sun Irradiation Membership Functions.

Figure 5.7 shows the control's output MF with all three possible operating modes. Regular mode is how the IoT was designed to work at normal conditions. Save mode will be used when a necessity of saving battery appears for a reason such as a lower battery level or bad environmental conditions. The last mode will be used when a maximum power save is required.

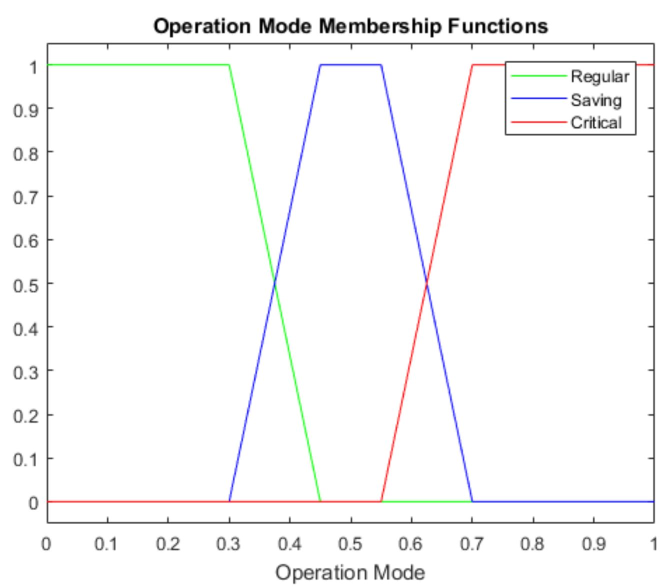

Figure 5.7: Operating Mode Membership Functions.

As mentioned before, the goal was to build a control that suits a wider range of applications. That is the reason why data transmission interval and data amount variation tests were not used for the Fuzzy Control given they are particular to the test node used. If these information were to be used, Figure 5.8 and Figure 5.9 show how their MF would look like. These MF were develop based on Figure 4.5 and Figure 4.6.

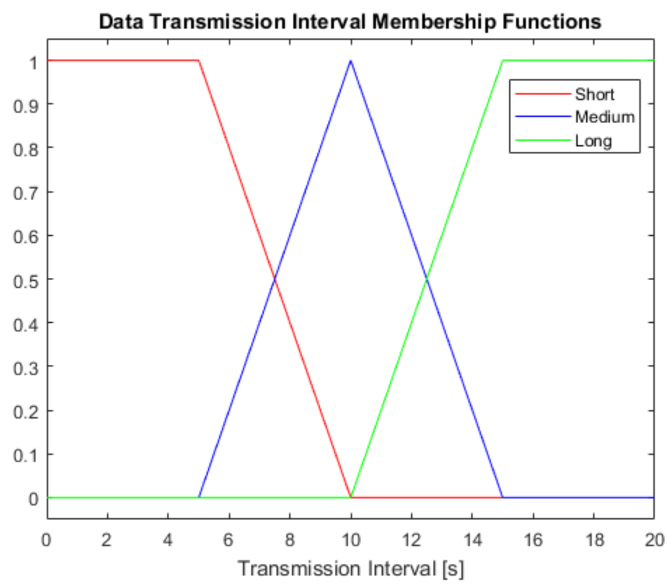

Figure 5.8: Transmission Interval Membership Functions.

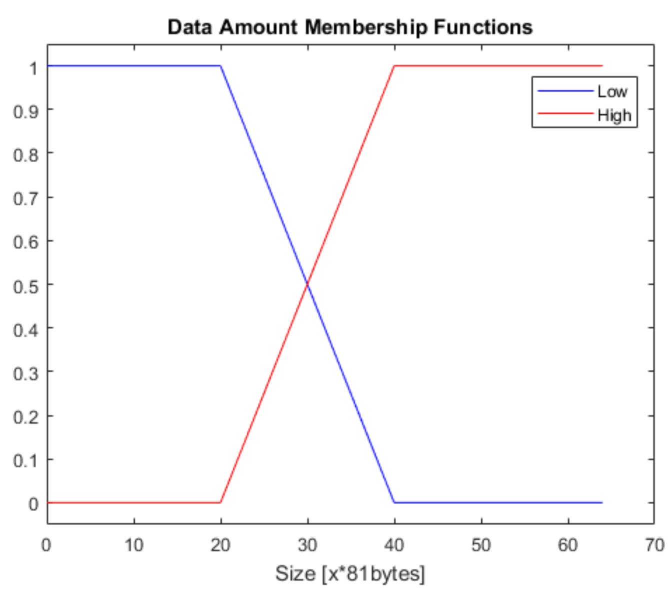

Figure 5.9: Data Amount Membership Functions.

5.3 Simulation

In order to test how the Fuzzy Control would function in a practical application, a MATLAB simulation was created using the Fuzzy Logic Toolbox. Since all the required MF were created, the next step was to determine the rules for the Fuzzy control to operate based on.

Table 5.1 shows all possible outputs based on the four parameters used: battery voltage, rain probability, local sun irradiation and time of the day. The outputs were set based on information acquired during all the performed test and based on researcher experience.

Battery Level		Time												Rain Probability
		Dawn			Morning			Afternoon			Night			
	Irradiation	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	
Battery Level	Low	C	C	C	S	R	R	C	C	S	C	C	C	Low
		C	C	C	C	S	R	C	C	S	C	C	C	Medium
		C	C	C	C	C	S	C	C	C	C	C	C	High
	Medium	S	R	R	S	R	R	S	R	R	C	S	S	Low
		S	R	R	S	R	R	S	S	S	C	C	S	Medium
		S	S	S	S	S	R	C	C	S	C	C	C	High
	High	R	R	R	R	R	R	R	R	R	S	S	S	Low
		S	R	R	R	R	R	S	R	R	S	S	S	Medium
		C	S	S	S	S	R	S	S	S	C	C	C	High

R	Regular Mode	S	Save Mode	C	Critical Mode

Table 5.1: Fuzzy States

For the first simulation using MATLAB's Fuzzy Toolbox, rain probability was set at 50%, battery level at 12V, sun irradiation at 150kWh/m^2 and time of the day at 12h. The equivalent value in the MF of the rain probability is Medium, battery level is Medium, sun irradiation is Medium and time of the day is Morning/Afternoon.

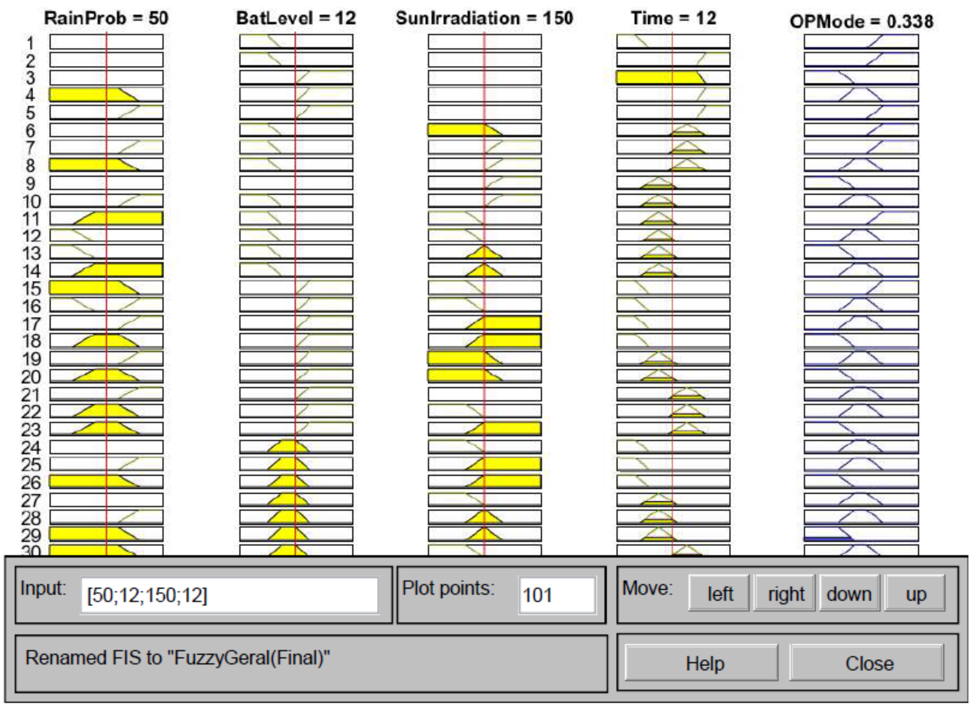

Figure 5.10: Fuzzy Simulation 1.

The result of the first simulation, illustrated in Figure 5.10, shows the output value is 0.338, checking figure 5.7 is is possible to see that 0.338 is equivalent to Regular Mode. In row 5 and column 5 from table 5.1 shows that the result should be Regular Mode, this proves the simulation was accurate. Since time of the day is between Morning and afternoon other result that would be acceptable is Save Mode in row 5 column 8.

The parameters for the second test were rain probability at 75%, battery level at 12V, sun irradiation at 150kWh/m^2 and time of the day at 15h. The equivalent in the MF of rain probability is High, Time of the day is Afternoon, battery level and sun irradiation are both at Medium.

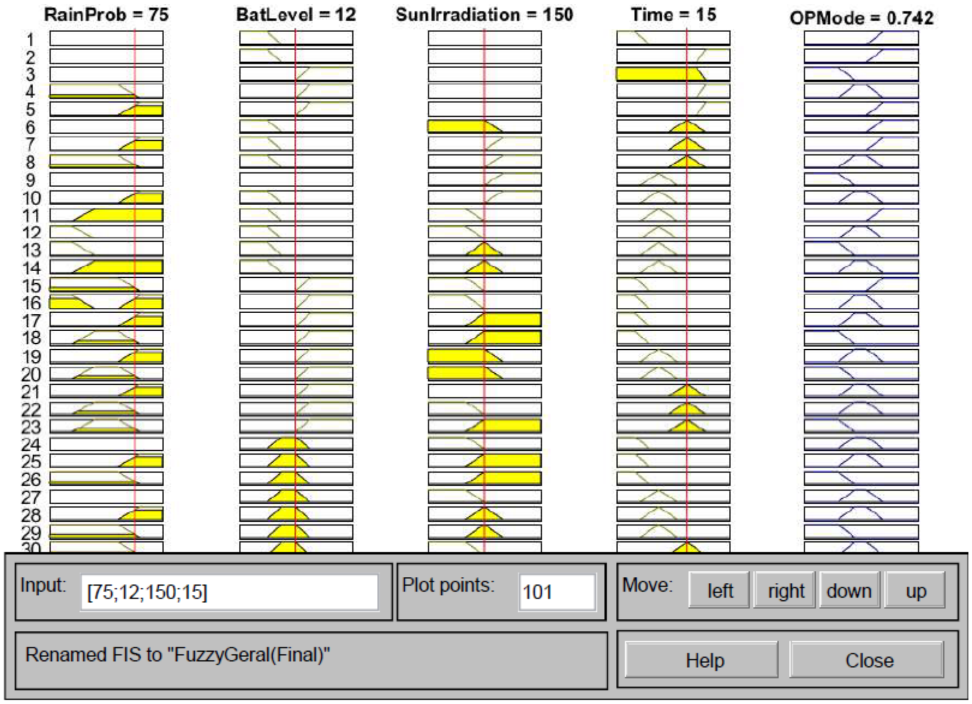

Figure 5.11: Fuzzy Simulation 2.

The output value in Figure 5.11 is 0.742 that is equivalent to Critical Mode. In Table 5.1 this scenario is in row 6 column 8.

The last situation to be tested was with rain probability at 75%, battery level at 12.5V, sun irradiation at 200kWh/m^2 and time of the day at 9h. The MF equivalency is Morning for the time of the day and High for all the other parameters.

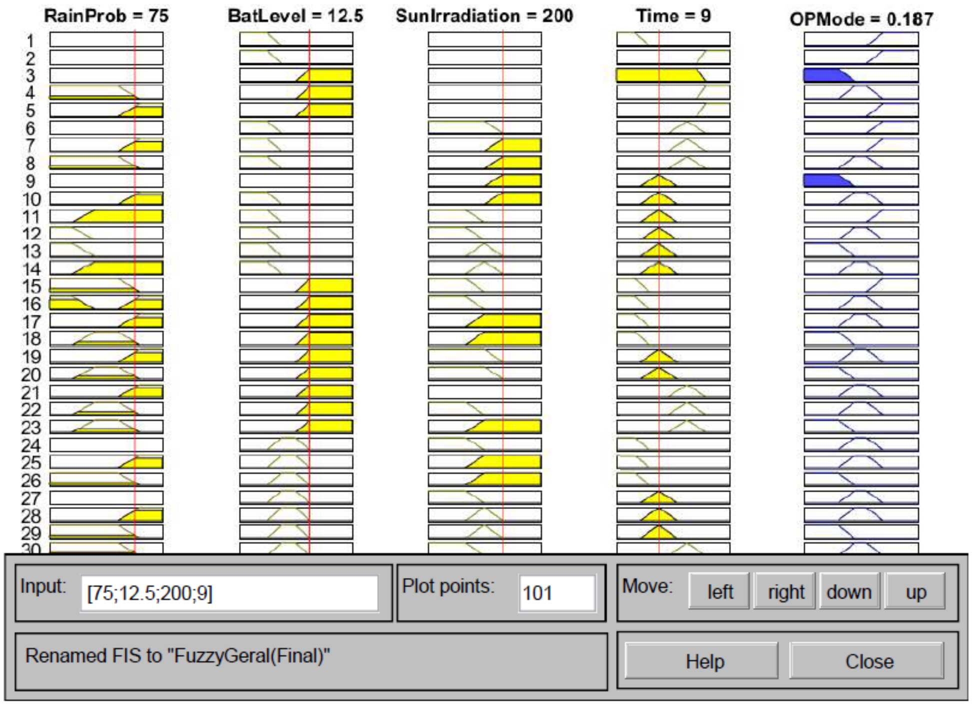

Figure 5.12: Fuzzy Simulation 3.

The output is 0.187 5.12 that is Regular Mode, and in table 5.1 the result can be found at row 9 column 6.

An example of how each operating mode would work for this test node is:

- Regular: Send data every 5s using standard transmission mode;
- Save: Change the interval to 30s and the transmission mode to Wi-Fi sleep;
- Critical: Increase the interval even more, use deep sleep or even stop the transmission completely.

An algorithm could be developed to monitor sensor data values. In the case of a relevant fluctuation in these values, data could be transmitted before the set timer in save and critical modes for example. This was a generic example of each operating mode. They would have to be designed differently for other applications.

5.4 Summary

As conclusion of this chapter, it is possible to use Fuzzy control to make an IoT sensor node intelligent. Three simulations showed positive results in different scenarios. The use of this BMS could make battery lifetime of IoT devices longer. This will reduce cost with maintenance and make applications more reliable especially in critical applications. In this case battery and environmental parameters were used as inputs, but, other applications may require different information in order to manage their battery.

Chapter 6

Conclusions and Future Work

In the overview section 1.1 of chapter 1 was questioned: How can an IoT node manage it's battery more efficiently?

In order to find a solution for this question, this work had as main objectives: develop an IoT sensor node, study it's power consumption and develop a strategy to make the node intelligent in terms of energy efficiency.

Tests were run successfully providing better understanding on battery consumption and data transmission parameters. Results showed that data transmission frequency and amount variation have a impact is battery lifetime.

A Fuzzy logic control was developed to make the IoT sensor node more energy efficient. The control used battery and environmental data in order to change how the node operates in order to optimize battery usage. Simulations showed it is possible to have an operating strategy chosen based on key parameters.

The major difficulty faced during this work was Internet quality. The connection was unstable/slow during a relevant period of time. This caused tests to be rerun multiple times and data to change considerably during tests with the same setup.

Overall the results showed it is possible to make an IoT intelligent and improve it's energy efficiency.

6.1 Future Work

This section has the goal of suggesting future work that could help improving the solution proposed in this work.

- Implement and test the Fuzzy control in a real application and test it in different conditions;
- Optimize hardware and software usage for better results;
- Run new tests based on different parameters and scenarios;
- Use different transmission technologies and hardware in order to test and compare which is more efficient;
- Test different transmission mode such as deep sleep;
- Build nodes with more sensors for testing;
- Develop new intelligent BMS based on other techniques such as Machine Learning and compare.

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Appendix A

Documentation

In the link below codes and files used are available.

https://github.com/Guilherme-F-da-Luz/MestradoIPB