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Smart IoT Lighting System for Energy Consumption Optimization

Diogo Alves da Silva

Masters in, Telecommunications and Computing Engineering

Supervisor:
PhD Carlos Eduardo Coutinho, Assistant Professor, ISCTE-IUL

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October, 2024

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TECNOLOGIAS
E ARQUITETURA

Department of Information Science and Technology

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I would like to express my gratitude to everyone who supported me and contributed to make this work a reality.

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I was not really sure what path to choose for this dissertation but Bruno's dissertation from 2019 was an eye opener and I was immediately drawn to it, so i thank him for presenting me to his work.

My proudest moment throughout this experience was when i had the pleasure of presenting my work on the "2024 International Symposium on Sensing and Instrumentation in 5G and IoT Era" conference and I have my paper published on IEEE for posterity, so I would like to thank Prof. Dr. Carlos in particular for introducing me to this conference and helping me with the presentation of the work.

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Resumo

A gestão da energia tem vindo a ganhar grande importância na contribuição deste processo global para o consumo de energia de forma sustentável e para a redução de desperdícios. Este consumo está a crescer com o aumento da urbanização, que está a pressionar as necessidades de eletricidade em edifícios residenciais, comerciais e institucionais, aumentando consideravelmente o desperdício de energia, especialmente nos sistemas de iluminação que, na sua maioria, permanecem ligados independentemente da ocupação ou das condições ambientais de luz. Assim, com o advento da IoT, as soluções de iluminação inteligente oferecem oportunidades para a redução desse desperdício através de sistemas adaptativos que ajustam a iluminação com base em dados em tempo real sobre as alterações ambientais.

Esta dissertação tem como objetivo estabelecer a prova de conceito de um sistema de iluminação inteligente baseado em IoT que visa otimizar o consumo de energia sem comprometer o conforto do utilizador. Os sensores do sistema proposto monitorizam a luz ambiente, a lâmpada inteligente altera a luminosidade, enquanto as peças compreendem o Arduino MKR WAN 1300 e a lâmpada inteligente Tapo L530E conectados usando LoRaWAN e Node-RED para lógica de controlo e processamento de dados. Assim configuradas, as luzes ligam-se e desligam-se dinamicamente de acordo com as condições ambientais em constante mudança e procuram otimizar a iluminação com um consumo mínimo de energia.

Os dados recolhidos sugerem que o sistema tem um bom desempenho em termos de consumo de energia, em comparação com uma configuração de iluminação tradicional. As simulações e os testes efetuados em computador confirmam o potencial de poupança de energia e de redução do consumo de energia.

Palavras-chave: Internet das Coisas, Poupanças Energéticas, LoRa, Sensores, Monitorização de Energia

Abstract

Energy management has gained a lot of importance in the contribution of this global process towards consuming energy in a sustainable manner and the reduction of waste. This consumption is growing with increased urbanization that is putting pressure on the needs for electricity in residential, commercial, and institutional buildings, adding considerable energy waste, especially in lighting systems that mostly remain turned on irrespective of occupancy or ambient conditions of light. Thus, with the advent of IoT, smart lighting solutions offer opportunities for reduction in such wastage by way of adaptive systems that adjust lighting based on real-time data on environmental changes.

This dissertation sets out to establish proof of the concept of an IoT-based smart lighting system aimed at optimizing energy consumption without compromising user comfort. The sensors of the proposed system monitor ambient light, the smart lamp changes brightness, while the parts comprise Arduino MKR WAN 1300 and Tapo L530E smart lamp connected using LoRaWAN and Node-RED for control logic and data processing. Thus configured, lights will switch on and off dynamically according to the ever-changing environmental conditions and strive for optimization of illumination with minimum energy consumption.

Data collected suggests that the system is performing well in energy consumption compared to a traditional lighting setup. Computer simulations and testing confirm the potential for energy savings and drastic peak power reduction. This work falls into the wider group of sustainable smart building systems and points toward further applications of scalable adaptive IoT systems in energy management.

Keywords: Internet of Things, Energy Savings, LoRa, Sensors, Energy Monitoring

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Chapter 1 Introduction

In recent years, society has been experiencing an increasingly fast development when it comes to technology and with that came the need to optimize everyone and everything around us, so we are presented with the idea of making everything around us smart. With that in mind and the constant use of terms like "smart building" or "intelligent system", professionals everyday attempt to develop new ways of monitoring their work and with that optimize their work rate as well as working conditions..

But what is this idea of making technology "smart"? There's a concept nowadays known as the "Internet of Things" which describes every type of physical object connected through the Internet and can collect and transfer data over a wireless network without human interference. This technological advancement led to the development of manufacturing capabilities and the possibility of creating intelligent systems.

We see the use of smart systems everywhere, at home, while walking to work, and basically in every single second of our daily lives. The increasing adoption of smart systems can be linked at a larger scale to the global effects of energy waste, poor medical care, and human intervention in Earth's climate, which has been one of the most discussed topics since the 20th century.

The developed smart lighting system, while tested in a single-room residential environment, is designed to be scalable for applications in public and commercial buildings, such as offices or university campuses, where energy efficiency at scale can yield significant cost savings. Take Fig.1.1 as an example of a study room at ISCTE University where the lights stay ON the entire day, leading to high power consumption and monetary spending.

Figure 1.1 - ISCTE University Library

When it comes to the reduction of energy consumption, a whole range of solutions are available to the public and most of them can be found at your local technology store. With the existence of all sorts of technological objects, it is possible to create a system, even a small one, where, for example, the lights in a room turn on only when a motion sensor detects the presence of a person and after a few moments if there is no motion to detect the lights turn off, and with that, there is no waste of money and resources on an empty room. By using less energy/electricity, we can reduce the demand for energy production, which often involves the burning of fossil fuels like coal, oil, and natural gas. In turn, this leads to lower greenhouse gas emissions and less environmental impact, including reduced air and water pollution, habitat destruction, and contribution to climate change.

Fig.1.2 presents the energy consumption values since 1800 up to 2023 using the "substitution method". The "substitution method" is used by researchers to correct primary energy consumption for efficiency losses experienced by fossil fuels. It tries to adjust non-fossil energy sources to the inputs that would be needed if they were generated from fossil fuels. It assumes that wind and solar electricity are as inefficient as coal or gas.

As can be seen, most of the world's primary energy consumption results from burning biofuels and non-renewable sources, which contributes to global warming, affecting the health of humankind for generations to come and ecosystems around the world.

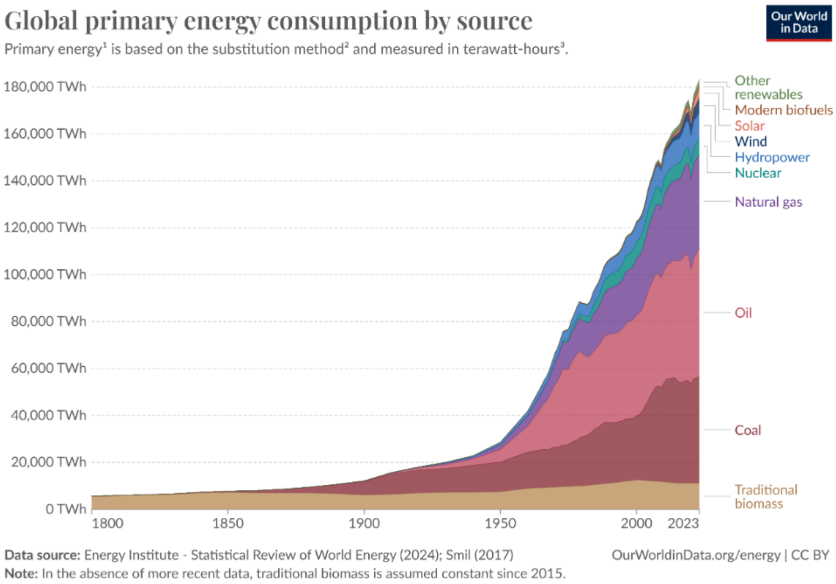


Figure 1.2 - Global direct primary energy consumption [1]

In [2] is stated that since the 19th century, the concentration of C02 on earth has increased by 40 %, and 68 % of this increment is due to energy production. This means that we are seeing an increase in energy demand that is not responded in a balanced way, either through renewable energies or any other solution. With this comes the need to develop smart infrastructures that are much faster to develop and implement. With this in mind is of the most importance, the reduction of CO_2 emissions that affects us all and more importantly future generations.

Demand for energy is growing across many countries in the world, as the communities modernize and have stronger technological needs and populations increase. Global energy consumption has declined in 2020 by 4% according to the Global Energy Statistical Yearbook 2021 [3], mostly due to the global pandemic that affected the entire world and that presented us with lockdown measures, industries and services stopping, and transport restrictions. Energy consumption fell in most countries except for China, which had 24% of the global energy consumption in 2020.

Since 2023, global energy consumption has continued to grow, but it does seem to be slowing – averaging around a 1% to 2% increase per year.

Given this increase in energy consumption, energy management systems are gaining more attention over the years by helping increase productivity and reduce energy costs. Energy management systems (EMS) are one of the emerging technologies that enable an organization, or even a single person, to collect real-time information on energy use through monitoring, assessing, and visualizing energy consumption. This real-time information can be managed using Internet of Things (IoT) systems that can be implemented, recurring to sensors, controllers, software, and others.

In [3] is known that global energy management systems market size was expected to reach $62.3 billion (54.99 million Euros) by 2023, from $25.9 billion (22.86 million Euros) in 2016, growing at a CAGR (Compound Annual Growth Rate) of 13.5% between 2017 and 2023. It ended up reaching approximately $42.13 billion in 2023 with this difference being attributed to economic elements such as the presence of prohibitive capital equipment costs and the sophistication of the technology which may have mitigated the rates of adoption. However, this market has demonstrated strong growth potential and is expected to grow aggressively, attaining $47.55 billion in 2024 at a compound annual growth rate of 13.38% from 2024 through 2030 and then possibly growing to $101.55 billion by that time.

Every industry, small or big, is running with the help of energy, so it is essential to deploy an energy management system. Although technology is advancing at a brisk pace, end-use clients may not adopt it as quickly as before. Most potential buyers of energy management systems are at a stage where they are aware of the benefits of implementing such a system but utilize traditional technology and applications. Financial barriers, limited expertise, and fragmented stakeholders are some of the key challenges for the energy management systems market.

IoT technologies can go from consumer-oriented devices, such as consumer items (smartphones), smart home solutions (Consumer IoT), to connected equipment in enterprises (Enterprise IoT) and industrial assets, such as machines, robots, or even factory workers and smart industrial facilities [4].

1.1. Research Question and Hypotheses

This research was developed towards the need to respond to the following research question:

- RQ: How can the energy in a controlled environment be optimized in order to reduce its consumption without compromising the comfort of its inhabitants?

Considering that the topic addressed by this dissertation has been the subject of analysis in recent years, leading to the development of several solutions for intelligent buildings, an intense search for relevant information on the topic was conducted from the methods used to develop it to the results obtained. With this in mind, several sub-questions were asked, including:

- How can smart lighting systems integrated with sensor data enhance energy efficiency and user comfort in indoor environments?
- What features can a smart lighting system that dynamically adjusts light intensity based on real-time environmental data have to improve efficiency and savings without compromising comfort?
- What type of technology would be most appropriate to collect this type of data for the purpose of energy consumption reduction?

The investigation that took place to respond to the research question started by eliciting a set of hypotheses that would be able to satisfy the question:

- H1: An IoT-based smart lighting system, when configured to dynamically adjust brightness based on real-time environmental data, can reduce power consumption while minimizing additional energy use from system components.
- H2: Real-time monitoring of IoT systems is a good way to demonstrate the impact of the solution in controlling and analyzing power consumption.
- H3: An adaptive lighting system that adjusts brightness and lighting conditions based on real-time artificial and sunlight data can positively influence user comfort and health by reducing eye strain.

These hypotheses aim to provide a comprehensive understanding of the potential and challenges of integrating smart lighting systems with IoT technologies to achieve sustainable energy management.

1.2. Objectives

The primary objective of this work is to develop a low-cost IoT System for Energy management and optimization in a building, represented by a proof of concept in a smaller sample (room) where sunlight and artificial light sensor will be integrated in the environment, connected to a Arduino with a LoraWan antenna and based on the natural light intensity of the room, the system will control an artificial dimmable Lighting by increasing or decreasing its intensity as well as turning it ON and OFF in order to maintain the optimal room lighting while trying to reduce the overall energy consumption of the environment, which will be measured by a Sonoff switch connected to the power grid of said room. LoRaWAN was chosen due to its long-range and low-power properties as well as potential scalability for larger setting like commercial buildings.

As a complement, a mobile application allows users to access the system from a room via a QR code and, based on the type of user, giving permission to interact with the system only to authorized people (admin user), more precisely to change, for example, the state of the smart system (ON/OFF) or the intensity of the lights in a progressive way to accommodate user's needs and at the same time reduce energy consumption, since a light that is 100 per cent ON does not consume the same energy as a light that only needs to be, for example, 40 per cent on at that time of day. All the data collected by the sensors will be displayed in a dashboard to serve as a management tool for the system. All the steps were taken with the goal of implementing this type of solution in a larger scale, like an entire building, and reducing its energy consumption.

The whole project required the implementation of hardware in a controlled environment (private room), where LoRa was the network of choice. This system will work as proof of concept since the implementation of this system at a larger scale would carry a great amount of investment.

1.3. Research Methodology

It was necessary to follow a chain of research methodology, as described on the annex 5 ,which was based in the Experimental Research Methodology and applied to the subject in hand.

This method has four main steps to achieve the desired solution, which starts with determining objectives and ends with the final evaluation of the system developed. This method grants a way of organizing by splitting the dissertation so that the last step taken complements the step ahead. For this one, the stages taken can be described as follows:

1st Step: **Problem Identification and Hypothesis Formulation**, where a definition of the research problem is defined (e.g., energy inefficiency in lighting systems) and hypotheses are articulated to test how the IoT smart lighting system addresses the problem.

2nd Step: **Experimental Design**, where a plan is made and the experimental setup is defined as well as variables, and methodology for collecting data.

3rd Step: **Data Collection**, where experiments are conducted and data is collected under controlled conditions for each system operational mode.

4th Step: **Data Analysis**, where analysis of the experimental data collected takes place to determine whether the hypothesis are supported.

5th Step: **Interpretation and Validation**, it is the final step taken where final finding are interpreted, hypothesis are validated and limitations or possible improvements are identified.

Check annex 5 for the Research Methodoloy structure representation on a flow chart.

Chapter 2 State of the Art

This chapter intends to present the research behind the development of the system in case, from the sensors and overall hardware technology used, to the description of the system and its logic. Concepts like LoRa Network, smart sensors, system architecture, Node-Red and mobile user interaction interface will be presented and explained.

Several Smart Management Systems were investigated to obtain as much knowledge as possible to deepen the system of this dissertation. As the system consists of several components and computing equipment, given the importance of processing the data and where this is done, research was made with the different types of computation, in order to try to use all equipment correctly and effectively.

2.1. Smart Management Systems

The whole system is predicated on the integration of smart devices in convenient places in order to capture data from said sensors and with that interact with the system/room with the objective to reduce energy costs while maintaining the overall quality of the room and even improve it.

Usually, when talking about smart buildings or smart systems overall, we are talking about an environment that is monitored and controlled by some sort of management system, in order, for example to control the heating, air quality, lighting or even security. Usually, these management systems operate in a way that interacts with the system/environment based on pre-determined established values. For example, if a room presents a high temperature, the system will automatically set the heating to a value defined for every room.

Mataloto [5] developed an IoT system as a solution for a Building and Energy Management System using visualization tools to create automatic savings. Like in this dissertation, LoRa was the communication technology chosen and used a System on Chip system, which is an integrated circuit that integrates most or all components of a computer or other electronic system, to gather battery-operated sensors, such as temperature, humidity, luminosity, air quality, and motion.

Data was collected for 3 years, and in the end, the system developed resulted in a 20% energy saving and improved environmental quality.

There is a range of possibilities to implement these types of systems, since the use of smaller range Wireless Sensor Networks that use ZigBee Module for communication, referenced in [6]-[9], to longer ranges in IoT using GSM/GPRS, which presents an increase in power consumption and range[10]-[11].

Shanmugasundaram, et al. [12] used a NODEMCU to manage devices (home appliances) utilizing IoT. The NodeMCU ESP8266 Wifi Module received commands from the smartphone via the web. They chose Blynk as an IoT Platform to encode the ON/OFF. They reported savings in electricity, time, and money with this system.

Erzi and Aydin[13], developed an IoT based mobile smart home surveillance app was developed aiming the reduction of human intervention and increasing security and energy efficiency. Smart sensors were implemented and were controlled by the web service and mobile application created that allows data collected from the sensors to be stored in a database periodically using quartz.net application and with that keep user informed about the conditions of the smart house. The system created included sensors like motion sensor, heat sensor, gas sensor and temperature sensor and all these sensors were connected to the Wi-Fi Module Esp8266.

Hwang [14], developed a monitoring and controlling system for an IoT based smart home is developed, with the smartphone application providing the user with information from the system based on a Bluetooth module providing communication functions between the Arduino-Uno and the smartphone.

David, Chima, Ugochukwu and Obinna[15], developed a low cost and flexible home control and environment system is developed, based on a microcontroller Arduino Mega 2560 with IP connectivity. The devices can be controlled with a web application or via Bluetooth Android based application. For the web application, Adobe Dreamweaver was used as the programming environment and PHP, JavaScript and AJAX were used as programming languages. The system developed was, as mentioned before, a low-cost system with wires involved and for that reason is a step back on what is being developed in this dissertation, that aims for a more durable wireless network.

Hoes, Hensen,, Loomans, de Vries and Bourgeois[16], showed a different approach to energy savings is presented by the use of occupancy sensors in large commercial buildings, to determine the patterns occupancy patterns in certain areas and thus the creation of a more efficient HVAC that can create reductions of up to 38% in energy consumption while maintaining thermal comfort for the users.

Sanchez-Iborra, Sanchez-Gomez, Ballesta-Viñas, Cano and Skarmeta[17], made studies regarding electricity savings to determine what type of feedback an energy management system should have in order to optimize the results, and the authors came to the conclusion that Real-time feedback systems are more efficient than feedbacks given from time to time.

Marco Jahn [18], developed and deployed a framework for 19 months, where Jahn conducted a variety of studies regarding the conversion of smart buildings into "Innovation Environments". Jahn implemented a HVAC (heating, ventilation and air conditioning) control strategy and showed how the smart building framework increased experimental freedom. The author developed three end user applications in order to validate how end user involvement in a HVAC system can be improved through an API usability evaluation where feedback from users was collected. Marco's research shows that most traditional systems do not involve active user participation while it forms a principal engagement for energy-saving behavior. 'Innovation Environments', a term coined by Jahn, fill this gap, allowing iterative prototyping and testing of innovative applications in actual settings. The framework thus substantiates the necessity for participation in application development to change behavior and interaction.

2.2. Importance of User Feedback

With the evolution of smart systems, also user involvement is becoming a big part of smart environments research. Past researches, [14], regarding this subject take in consideration the existence of what is called building managers and occupants, being the building manager responsible for the administration of the building management systems and the occupant part of the system environment with limited ways to impact the system, in spite of being the most affected by it.

In [16], mentioned before, Hoes, Hensen, Loomans, de Vries, and Bourgeois developed a user feedback mobile application in order to present to the users the conditions of the prototype room created in the project. The interface of the app was very straightforward with a simple look, basic information provided, and minimal capacity of interference in the system in a progressive way since the interaction with the air conditioner, lights, humidity, and security was limited to turning this individual environment characteristics ON and OFF, with no possibility of, for example, control the lights in the room progressively, depending on the natural light coming from the windows and with that reduce the power consumption. The mobile application mentioned can be seen in Fig.2.1.

Figure 2.1 - Mobile Application developed [14]

In [15], the occupant of a system/room is used as a “sensor” and feedback of the room conditions is obtained based on the user feedback. A prototype of a mobile application was developed in the scope of the SEEMPubS project (SEEM-PubS,2014) with the purpose of studying the possible involvement of users in smart buildings.

In reference [19], user feedback on the system results potentially in a maximum of 15% in energy savings. Based on the work developed in [19] and past works, it becomes clear that user behavior and user feedback impact power consumption. The mobile application being developed in this dissertation will help understanding the impact mentioned above.

This dissertation approach aims to perform an automation process of saving energy, whether it is by locally collected data and automatic actions based on that data or through a user interaction system with the use of a mobile application.

2.3. Communication Technologies

All the references mentioned above, regarding the implemented systems, have in common an IoT communication technology that supports all of them. Based on Fig2.2, the choice of which technology to use is an essential step, as it can affect both the quality of the system and its efficiency. For example, if the system is to be applied in a small area like an apartment, office, or any place that presents a range from 10 to 100 meters then the most viable options in terms of communication technology are Bluetooth, ZigBee, or WiFi althought as a proof of concept for larger environments LoRa was chosen for this specific dissertation. The technologies mentioned before are known as Short-range technologies [20] (Bottom left corner of Fig.5) and are specific for local setups since they offer the system the quality that is needed without presenting high costs to the owners when it comes to equipment used or power consumption.

If the objective is to create long distance monitoring systems, then the ideal communication technology is known as Low Power Wide Area Network (LPWAN) (Right side of Fig.5). These technologies offer low power consumption rates and ranges, depending on the technology chosen, from 2 Km to 1000 Km by reducing the data transfer rate to lower values, from 0.3 kbit/s to 50 kbit/s per channel. Technologies like this are used for example in precision agriculture, energy management, and many other activities that are not confined to small areas.

For this dissertation LoRa was the communication technology used due to its long-range and low-power properties as well as potential scalability for larger setting like commercial buildings and even though for this specific proof of concept Zigbee would be a logical choice, since the objective is for this system to be implemented at a larger scale in the future the decision fell on LoRa since it didn’t represent downsides for this particular system and could be used to show how in the Lisbon a system like this would work.

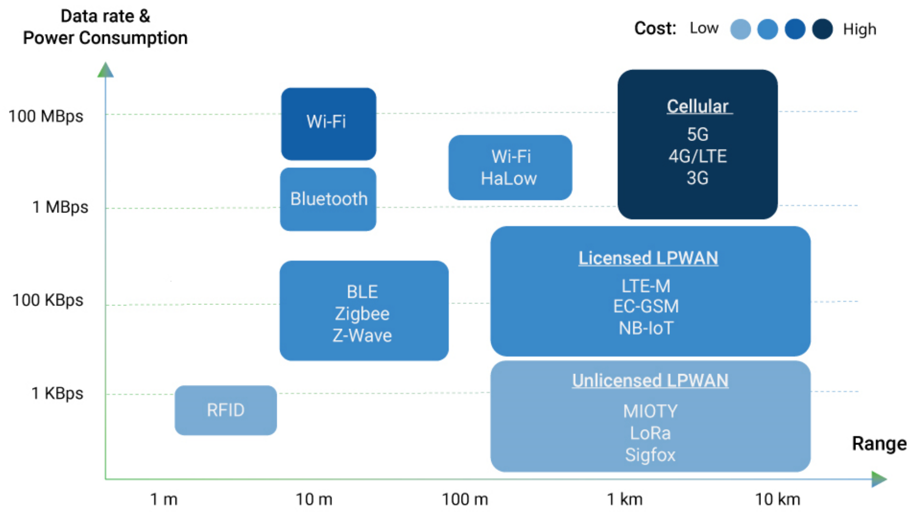


Figure 2.2 - Communication Technologies according to data rate and range. [16]

When it comes to LPWAN technologies, the three more popular are Sigfox, LoRa and NB-IoT. Sigfox offers long-range but at the same time low power consumption, and for this reason is a protocol used for small data transmission. Sigfox uses a frequency band of 868 MHz in Europe and 915 MHz in USA, with a bandwidth of 200 KHz, offering a range of efficiency that goes from 30 to 50 Km in rural areas and 3 to 10 Km in urban areas. In terms of data rate, it can transmit from 10 to 1000 bps, being the ideal value 100 bps for IoT applications, it uses a Binary Shift Keying in the uplink (end points to gateway) and a Gaussian frequency-shift keying in the downlink (gateways to end points). In terms of power consumption, is “uses” about 61 mA at the time of transmission. [20]

LoRa is a wireless modulation technique that encodes information on radio waves using chirp pulses, it offers robustness against disturbances and can be received across high distances. LoRa technology ranges go from 2 to 5 Km in dense urban areas and 15 Km in suburban areas, it works in a frequency band of 868 MHz in Europe and 915 MHz in North America and uses a spread spectrum modulation which uses wide-band linear FM pulses. Each LoRa gateway takes care of thousands of nodes and is a technology that presents a longer battery life.[20]

Narrow Band IoT or NB-IoT was introduced with the aim of providing low-cost, low-power consumption, and wide-area cellular connectivity for the IoT. NB-IoT technology offers a coverage area that can go up to 15 Km in rural areas and 1 Km in urban areas, it works in a frequency spectrum of 700 MHz, 800 MHz and 900 MHz with a bandwidth between 180 KHz and 200 KHz. It supports about 40 devices and 50000 connections per cell with a maximum data rate of 200 Kbps and because it is a very low power consumption technology, it can extend its battery life up to 10 years.[20]

2.3.1 LoRa Technology

Fig.2.3 represents the LoRa architecture, in which devices are connected to gateways, in a one-to-one or one-to-many connections and the gateways serve as a "bridge" between devices and the network server [21]. Gateways forward payload information to the network server acting, as mentioned before, as a bridge connecting to the network server either though Ethernet, 3G, 4G, Wi-Fi or satellite connection.

At the base of all gateways exists a LoRa concentrator, which is a multi-channel demodulator, able to decode all versions (obtained by varying the SF parameter) of LoRa modulation, on an extensive range of frequencies at the same time [22]. The LoRa gateways are capable of decoding up to 9 channels at the same time, with these channels being identified by a specific sub-band and spreading factor [23].

If there are messages being sent, there are messages being decoded. And the responsibility of decoding the message falls to the network server, which performs security checks by filtering duplicate and unwanted packets and finally responding to end devices through one of the gateways that are in range [23].

Finally, the application interface can be provided by the network server, or the data can be sent from the server to a IT solution developed by the user, or an IoT platform (ex. Google Cloud IoT, Cisco IoT Cloud Connect and ThingWorx).

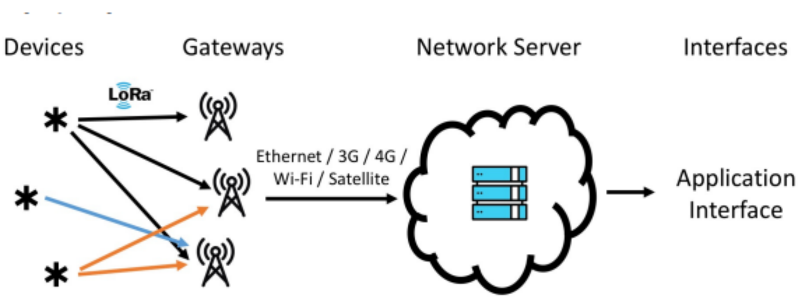


Figure 2.3 - LoRa Architecture [24]

2.4. MQTT

MQTT is a protocol based on publish/subscribe actions that allows devices to publish to a broker, and therefore clients connected to this broker who subscribed to a certain topic will receive a message published by another client associated with that topic. This protocol, represented in Fig.2.4 is nowadays used in most IoT systems [25] and is defined as a very basic/simple protocol and much faster than HTTP protocol and even easier to use. Finally, one of the major pluses of MQTT over HTTP is the simplicity of implementation by the user.

This protocol runs over network protocols that provide reliable bi-directional connections, presenting the following characteristics[26]:

- Subscribe/Publish messages that define to which receivers the message is going to be sent;
- Message quality by the receiver is guaranteed;
- “Debug” mechanism to notify both parts when an abnormal situation occurs regarding the transmission of data.

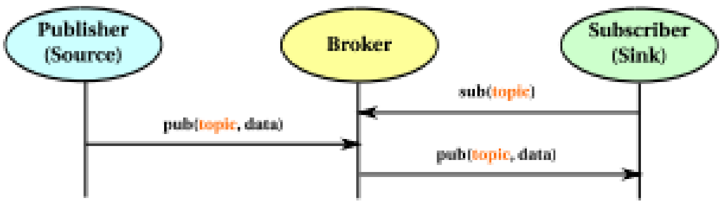


Figure 2.4 - Basic Subscribe/Publish model from MQTT [27]

The subscribe/publish system, shown in Fig.7, is offered as an alternative to the traditional client-server, since in client-server model a client interacts directly with a server. In this case the publisher and the subscriber never “talk” with each other, or even need to confirm the existence of the other to communicate since the connection is handled by a third party, known as broker, who filters all messages received and sends them to the subscribers of interest [28].

Chapter 3 IoT system development

In this particular chapter, a high level overview of the system is depicted. It describes the architecture, basic elements, and communication strategies of the system. This chapter highlights the way, in which sensors, actuators, control algorithms and network communication that form the system work together to enable dynamic lighting. Each section focuses on some particular part of the design, such as system architecture and technical stack and practical implementation and how they all come together for the purposes of energy saving and comfort of the end user.

3.1. System Architecture

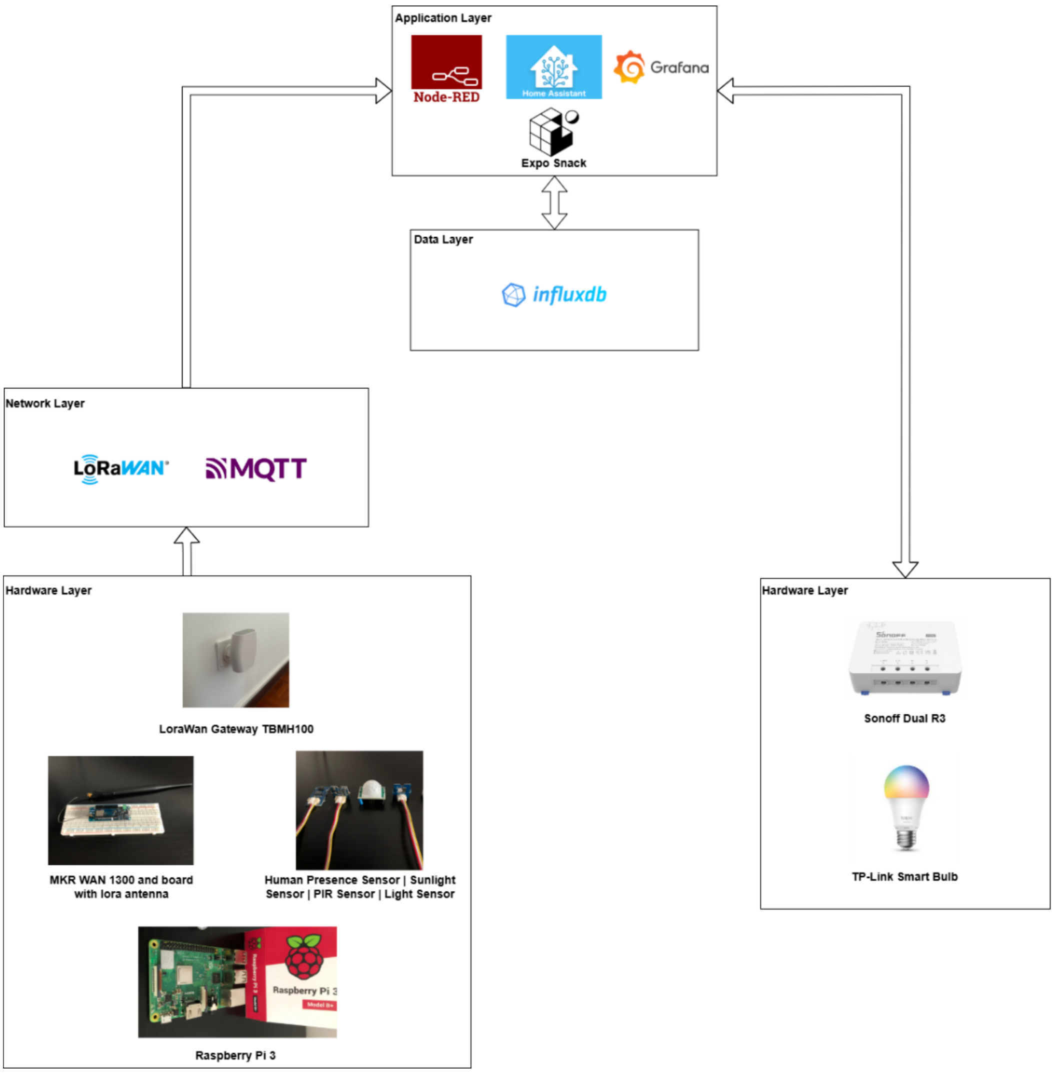


Figure 3.1 - System Arquitecture

The system architecture, described in Fig.3.1, is divided into 4 main layers (Hardware/Sensor, Application, Data and Network):

- **Hardware/Sensor Layer:** Grove Light intensity sensor is interfaced to an Arduino and its board for sensing the light levels in real time. This data is sent through LoRaWAN protocol via LoRaWAN gateway to The Things Network (TTN) who works as a network facilitating the connection of the sensor devices to the internet, allowing them to transmit data wirelessly and interact with the system. The integrated Sonoff Dual R3 device is used to monitor power consumption and maintain energy efficiency. Actuator is a Tapo L530E smart lamp, where its brightness can be controlled by sending control signals from Node-RED to it. In addition to the dynamic modification in the light intensity percentage, the smart light system, through adjustments in the color temperature and scene settings, will take further advantage of the Tapo L530E's features. With such adjustments, the system will thus come up with ambient lighting configured specifically to make the user feel at ease and productive by merely mimicking the normal daylight cycles.
- **Application Layer:** Node-RED gets the data from sensors and calculate how to adjust brightness on the Tapo smart lamp. The control algorithm is using a proportional control mechanism to regulate the room and keep it at a predetermined optimal light intensity. Home Assistant provides power consumption data from the Sonoff device and presents this data on Node-RED and therefore influx and Grafana.
- **Data Layer:** Influx Database used to store data and feed Node-Red and Grafana.
- **Network Layer:** LoraWAN and MQTT network technologies used to integrate all components and merge them into Node-Red.

3.2. Technology Justification

The technologies for system architecture have been chosen considering the project objectives of energy efficiency, scalability, and affordability. The following technologies replied to some needs of the IoT-based smart lighting:

- **LoRaWAN:** Long-range low-power mode communication has been selected as the way of data transmission from the sensors to the primary controller. Such attributes are primary for energy consumption and scalability while other deployments are multi-room and building-wide. Wi-Fi and Zigbee was also evaluated but eventually dismissed due to the objective of integrating this system at a larger scale .
- **Node-RED:** This is a flow-based programming tool which gives a very easy way of bringing together IoT devices and database dashboards, with a drag-and-drop environment. Furthermore, great workflows can be built quickly for controlling data transfer. Node-RED also provides a wide capacity of integration with third party softwares.
- **MQTT:** It is a lightweight publish/subscribe that facilitates real-time communication between components of the system whose operation is very low-latency. It was chosen because of its advantage in overhead against HTTP and is therefore very correct for confined resources in IoT devices.
- **InfluxDB:** This time-series database was adopted to store data from sensors because of its good performance and capacity to grow, and also very well integrates with visualization tools such as Grafana. It is very well-suited for this analysis, as it can handle 30 seconds time-stamped data very efficiently.
- **React Native:** Mobile Application developed using react native for cross-platform compatibility, thus reducing development time and cost hence also meeting the aim of providing a user-friendly and easily accessible interface for interaction and control of the system.

3.3. Node-RED Flow

The smart lighting and energy management system has a central Node-RED flow controller. It collects sensor data, processes, makes decisions based on the rules set and activates smart devices within the system. This flow includes several components such as MQTT for communication, Home Assistant for smart devices, The Things Network (TTN) for LoRaWAN data, InfluxDB for storing of time series data, etc. The flow optimizes energy consumption by controlling the light according to changes in the environment but does not affect comfort of the user. The major components of the Node-RED flow are described below.

3.3.1 MQTT Input Nodes

The flow initiates from the MQTT input nodes. These nodes handle the incoming sensor data from TTN connected to the light intensity sensor through LoRaWAN. MQTT Input Node subscribes to a topic on TTN, which delivers the payload from the sensor attached to the Arduino MKR WAN 1300.

- Ambient Light Intensity Information ("Get TTN Data" node): This is the value coming inside the incoming payload, which will contain the ambient light intensity values coming from a sensor. This value constantly changes in real time to keep the system responsive to the environmental changes.
- Power Consumption Data ("Get HA power consumption" node): This data about power consumption is sent from the Sonoff Dual R3 through Home Assistant. The data lets the system monitor energy use from the lighting system and has valuable insight as to how efficient the system will be over time.

MQTT allows leveraging a lightweight, low-bandwidth transmission efficiently, especially in an IoT environment where minimizing overhead for data transmission is very important.

3.3.2 Data Processing with Function Nodes

Once the data is fetched from sensors, it passes data to the function nodes for processing. The nodes carry out the required logic needed in order to obtain meaningful information out of the payload and prepare it for decision-making.

- Extract Light Intensity Function ("extract_light_intensity" node): The aim of this function node is to parse JSON payload coming from TTN and extract the value of the light intensity from it. Normally, the sensor delivers raw values in the range 0-1023. These raw values are mapped onto a percentage value between 0 and 100%. This is done to make sense for the setting of the brightness of the smart lamp. It can also check whether the value is out of the threshold set.

- Extract Power Consumption Function ("extract_sonoff_power_consumption" node): This function node performs its role, essentially in extracting power consumption values from the payload coming out of Sonoff Dual R3. The data is crucial for monitoring the system's energy efficiency, especially in comparing energy use in different lighting scenarios such as smart system enabled versus disabled.

These function nodes are designed to ensure the system can react efficiently and in a timely manner to changes in the environment. The processing is near real time; thus, this system fits within those environments where the conditions-like natural light-change frequently.

3.3.3 Decision-Making Logic Nodes

Once the data has been processed, the system will need to make a decision as to whether or not it should adjust the smart lamp's brightness. This is designed to flow through more function nodes which handle the core decision-making of our system.

- Brightness Control Logic ("Process Data" node): the main decision logic controls a difference between light intensity in room and target value, which tells how slowly it gets off. In case ambient lighting starts to decrease, for example when the sun goes down or due to cloudy weather), it will increase Tapo L530E smart light brightness.
- Threshold Monitoring ("Check lamp action" node) — Although lamps have been monitored in real time, part of the decision making is that not to let them lamp get wasted. The system uses user-defined and adjustable threshold values. When the natural light levels exceed a certain point (e.g., greater than 80% ambient), lamp controls will automatically dim or shut off, saving energy.
- Time-Based Operation: To optimize energy consumption, a "Time Check" Node was created to ensure that this smart lighting system operates within the defined work hours. The system runs from 6 AM to 9 PM, which are the hours that lighting is required. Other than that time period, the smart system is off, thereby eliminating excess energy usage.

3.3.4 Actuation via Tapo Control Nodes

The system uses Tapo Control Node when the decision step is taken to control the brightness of a smart lamp. This node communicates with the smart Wi-Fi Tapo L530E and issues commands to the brightening percentage. The changes are easily and readily responsive, meaning that after the detection of a change in the environment, the change in light brightness presents undetectable delay in its adjustment. Control mechanisms in place:

- Lamp On/Off Control ("Turn OFF" node): Apart from brightness adjustment, the system is able to turn the lamp on/off according to surrounding conditions. For example, if there is sufficient ambient light, such as during daytime, it can turn the lamp off completely.
- Lamp Brightness Adjustment ("Set Brightness" node): Apart control the lamp state of ON/OFF the system is able to adjust the lamp brightness based on the current light intensity in the room, detected by the sensor connected to the Arduino board.

3.3.5 State Management and User Control Nodes

A notable characteristic of the intelligent system is the ability for system control, for administrator users, to switch the system on or off via the mobile app developed. This is accomplished with the help of additional nodes which control the state of the system:

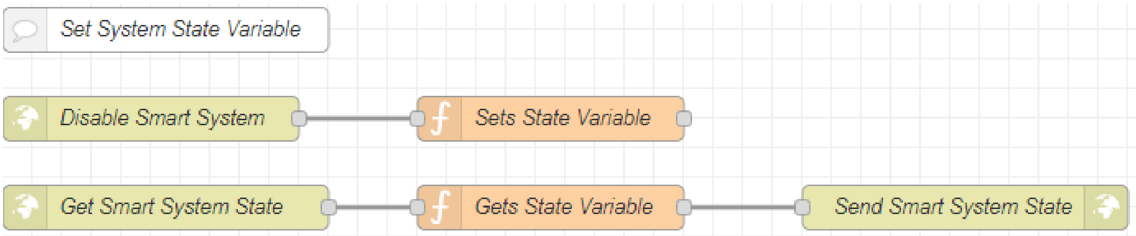


Figure 3.2 - Set System State

The first flow starts with the interaction of the admin on the app changing the state of the switch from enable to disable or vise-versa. For whichever action, the Node-RED receives the state and sets a global variable on Node-RED that will then be used on the main system flow to stop it or let it run. By having the ability to enable/disable the system the privileged user(admin) is able to determine the lamp brightness or lam state(ON/OFF) that he wants without the smart system interfering every 30 seconds. Current state switch on the mobile application developed presented on Fig.3.3

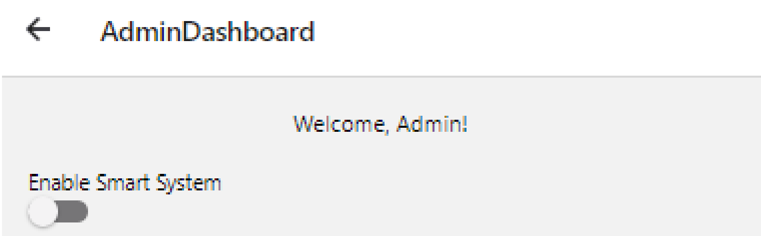


Figure 3.3 - Mobile App system state toggle

3.3.6 Data Storage and Visualization Nodes

Data related to light intensity, power consumption, and lamp settings are sent to an InfluxDB database for storage so that further historical analysis may be performed. This information is highly useful in carrying out an effective study of the performance of the system over time and also with regard to energy savings. This data also feeds the mobile application.

- Data Logging (“Send Light Intensity and Power Consumption Data” Node): InfluxDB stores the timestamped data points for later visualization via Grafana or mobile app. This helps draw out graphs to show the trends in light intensity and energy usage, hence giving a very detailed analysis of the system’s performance- including how frequently the adjustments of the lamp were made and the amount of energy saved by the smart system.
- Performance Monitoring: The data stored in the InfluxDB will enable the system for long-term performance monitoring. Afterwards, the user will be able to consult metrics such as the total consumption of energy and the efficiency of the smart lighting system in maintaining the best lighting levels within the room.

The structure of the database is such that it includes: “current light intensity”, “current lamp intensity”, "power consumption" and "Action taken". Each measurement item comprises of a time and values for each of the records mentioned above, which is truly the most critical feature required to be included to enable time-based queries to be accurate.

Fig.3.4 shows the resulting output of a query responsible for retrieving the last 10 records of the system data. Since there's a 30 second interval between data collection these 10 records represent the light and energy consumption values of the last 5 minutes.

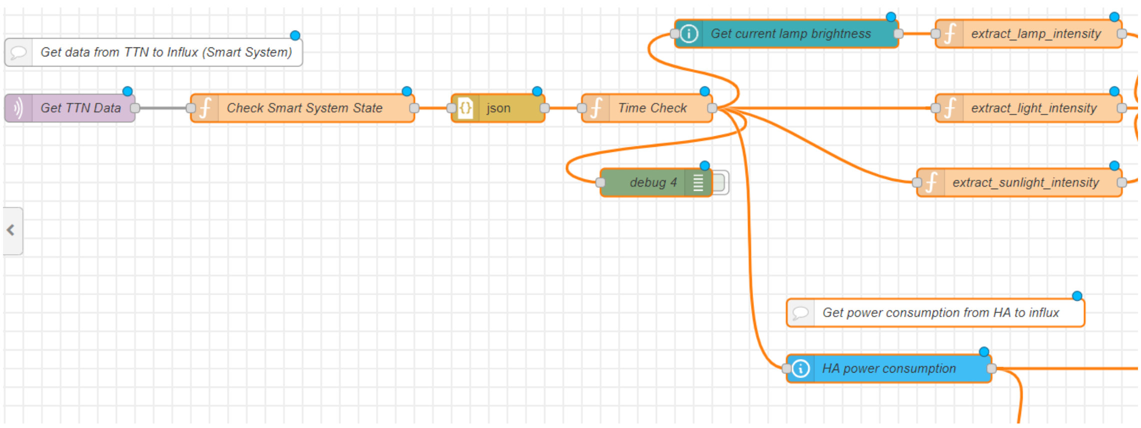
```
>
> SELECT * FROM light_and_power_data ORDER BY time DESC LIMIT 10
name: light_and_power_data
time                lamp_action    lamp_new_percentage_intensity light_intensity power_consumption
----                -----------    ----------------------------- --------------- -----------------
1724875182250000000 set_brightness 100                           22              6.6
1724875151213000000 set_brightness 100                           19              6.59
1724875089312000000 set_brightness 100                           19              6.52
1724875058282000000 set_brightness 100                           19              6.57
1724875027317000000 set_brightness 100                           21              6.54
1724874996330000000 set_brightness 100                           22              6.59
1724874965342000000 set_brightness 100                           23              6.55
1724874934449000000 set_brightness 100                           20              6.56
1724874903451000000 set_brightness 100                           22              6.56
1724874872747000000 set_brightness 100                           22              6.56
>
```

Figure 3.4 - Data Collection on InfluxDB

The data collected and stored on InfluxDB is then displayed on Grafana for a friendlier user experience and interaction with the data. The image below shows two of the current Grafana graphs on the smart system dashboard.

The main flow, presented in Fig.3.5, was designed to be modular, whereby each component performs a specific function of the whole system. This modularity makes future extension or integration quite simple to execute with additional devices or sensors(HVAC sensors). As such, one, for example, could even consider adding new sensors to track the temperature or occupancy to further develop the system working on optimizing energy consumption based on several environmental factors.

It is optimized for real-time decision-making where latency among data collection, processing, and actuation is minimum. It will be very suitable for dynamic environments such as homes, offices, colleges, or libraries, where the changes in lighting conditions occur quite often.



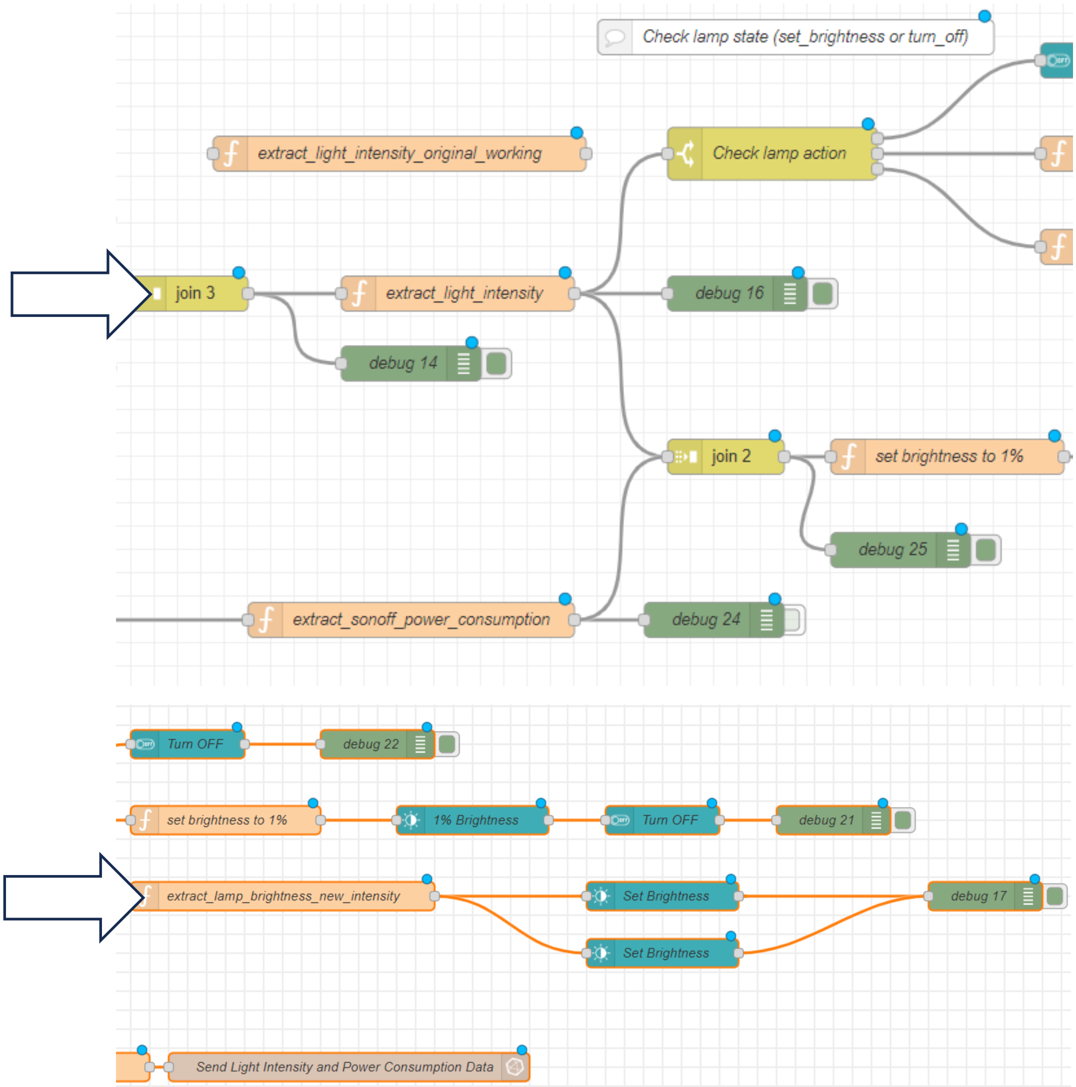


Figure 3.5 - Node-RED system flow

3.4. Data Collection Process

Arduino MKR WAN 1300 is one of the primary hardware lines, along which the data collection is done for the smart lighting system. The Arduino focuses on collecting the sensor data, like the values for room sunlight and ambient light in real-time, and then through wireless protocol transmits the information to the central system (Node-RED) through LoRaWAN to the server on TTN. We will proceed by explaining how the hardware and software are configured on the Arduino and the communication protocol implemented.

Hardware Setup: The Arduino MKR WAN 1300 reads data from the following sensors:

- Grove Light Intensity Sensor: Determines the amount of light in a room and outputs a raw analogue value (0-1023);
- Grove Sunlight Sensor: Measures the intensity of visible light, infrared and ultraviolet light using the SI114X library.

The sensor readings are then computed on the Arduino and converted to a more meaningful scale (0 – 100 %) for control of the brightness of the smart lamp.

Software Setup: The sketch, which is loaded into the Arduino controller, is designed for reading sensor measurements, interpreting this data, and connecting to the LoRaWAN system. The code sets up the sensors, connects to The Things Network (TTN), and finally transmits sensor readings at regular 30-second intervals. This enables the constant flow of data but in a low power mode. The sketch uses Over-The-Air Activation (OTAA) method of connecting to TTN in order to ensure the content-addressable network is safe and operates with very minimal delays.

Data Transmission: Data which is processed from the sensors is packed into a 5 byte payload and sent using the LoRaWAN protocol. Given that low-power wide-area networks (LPWAN) are often associated with M2M applications, the need for such characteristics in the use of LoRaWAN is evident. The transmission of the data is done also every 30 seconds in order to maintain a near real-time performance while power consumption is kept at an optimum level.

3.3. Experimental Setup

The experimental setup aimed to replicate a real-life scenario and, in this case, the take up was done in a bedroom environment where a central ceiling light was used as the smart lamp under control. This arrangement provided the ability to test the system in its normal indoor operational conditions which can then be scaled up to big indoor operations such as office buildings, universities, etc.

- **Environment**

- The tests were carried out in a bedroom with standard lighting and ambient conditions with sunlight coming though one lateral window. This setup, although smaller in the overall measurement as compared to a commercial or institutional space, offered enough scope to highlight the core functionalities of the system such as occupancy detection, ambient light adjustment, and power consumption utilization tracking.

- **Equipment and Sensors:**
  - The principal lighting element used was a dimmable TAPO lamp. A grove light and sunlight sensor as well as a PIR sensor were connected to the system to control ambient light and provide data of a detected person's presence within the vicinity respectively.
  - A Sonoff Dual R3 was attached to the room electric circuit to monitor its power usage for different operational modes.

- **Testing Procedure:**
  - Duration and Data Collection: The data was collected over two distinct periods resulting in 3 different datasets, one month with the smart dimmable feature and another with the basic ON/OFF system. A separate dataset was established for modeling purposes where the dataset consisted of all lights being on state ON for the entire duration of the experiment which served as an energy baseline without any IoT system involvement.
  - Assessed Variables: The system recorded multiple parameters like ambient light, lamp intensity, occupancy, and energy consumption. These parameters were recorded every 30 seconds to account for changes throughout the day.

- **Operation Modes**
  - Dimmable Mode: The system was designed to control and change the brightness of the lamp depending on the level of ambient light, wherever there are people present. This mode's objective was to conserve energy by reducing the brightness of the lamp when consistent natural light was provided.

- On/Off Mode: The lighting conditions were kept either fully in one extreme of the spectrum or in the other, that is in the dark, based solely on the occupancy of space and disregarding changing any levels of brightness. This served as a reference to the dimmable mode in terms of no energy savings.

This setup enabled thorough evaluation of power consumption parameters of the system and its response time. The experimental setup also showed the potential of energy optimization provided by the IoT lighting system in other operational modes than 100% lighting.

3.4. Mobile Application

A mobile application was developed on JavaScript with the use of React Native framework and is an essential part of the system, offering the possibility of system control with real time response and system analysis with data information presented in graphs. The mobile application grants admin users real-time control of the system, while it keeps the unprivileged users updated on the key metrics, such as light intensity and aggregate energy consumed. The application is developed using React Native and Expo Snack to enable access through both Android , iOS devices and even web. This application allows privileged users to toggle the smart lighting system on/off, change the light intensity, and display key data like power consumption and historical trends of light intensity.

3.4.1 Mobile App Architecture

The design of the mobile software incorporates an easy-to-operate layout, considering two major users of the system: an Administrator and a Regular User.

- Administrator: This role has complete and unrestricted control over the system either by being capable to enable or disable the smart system as well as manually change the brightness of lamp. Admin users can also view up-to-date as well as historical data information and check this same data over a defined time frame.

- Regular User Role: Regular users are allowed to view data such as current light intensity, and energy being used but cannot adjust system parameters. This distinction makes sure that system critical operation is safeguarded from unintended modification.

The application makes use of HTTP requests to send instructions to the Node-RED server, which interacts with a database InfluxDB to ensure changes in the system, as well as retrieving information. React's useState and useEffect hooks maintain state, thus making an application interactive with changes according to changes in the information it displays.

This application architecture can be seen on the figure 3.6 below.

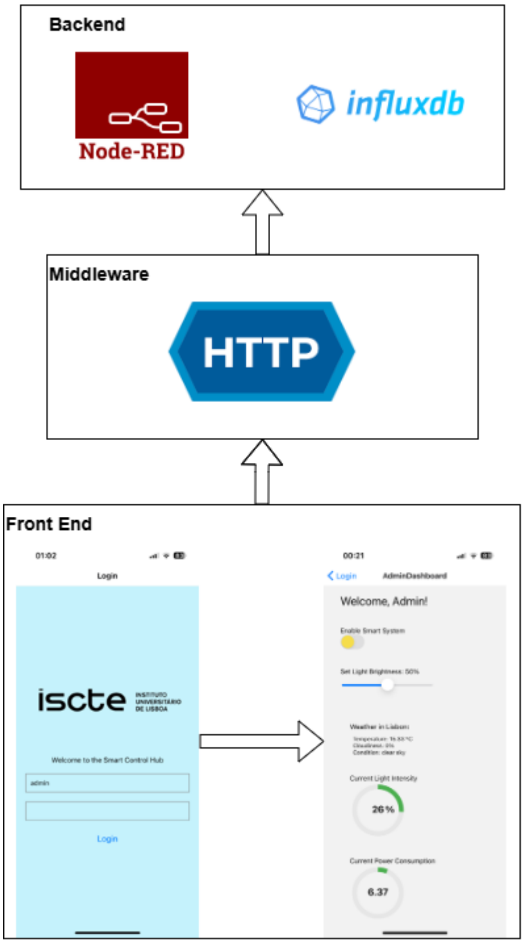


Figure 3.6 - App Architecture

3.4.2 Development Process

React Native was chosen as the application developing tool for the following reasons:

- Cross-platform capability: React Native enables it to run on iOS devices and also Android devices, as well as web browser interface.
- Easy integration to the backend: React Native allows standard HTTPs requests and WebSockets, thus paving the way for easy integration with the Node-RED and InfluxDB backend.
- Developer Tools: Expo Snack is a great environment to test and develop in, with fast iteration and live updates while developing.

3.4.3 Mobile App Interface

The application was designed to be as simple and clear as possible to allow the user to perceive the data and manage the system. Check the full code developed on github repository (annex 3) The following are its main interface elements that can be seen in Fig.3.7:

- Login Screen: The user logs in with his credentials in order to see or control the smart system. In the case of an administrator, the system adds more functions of control, while for a regular user, it limits them to only data visualization.

Dashboard:

- Light Intensity Gauge: It shows the present light intensity as a percentage, 0-100%. It fetches data from the Node-RED backend every few seconds because an API call is fired every few seconds.
- Energy Consumption Indicator: This reflects the current power consumption of the system in watts. The data is fetched from InfluxDB via Node-RED.
- Control Switches: A toggle switch can be used by an administrator to turn the smart system on or off. On turning this system off, it will not automatically adjust the light.

- Brightness Control: This can be done manually by an administrator using a slider. In the case of a smart system turned off, the slider directly controls the intensity of the light.

<u>Admin Dashboard</u>

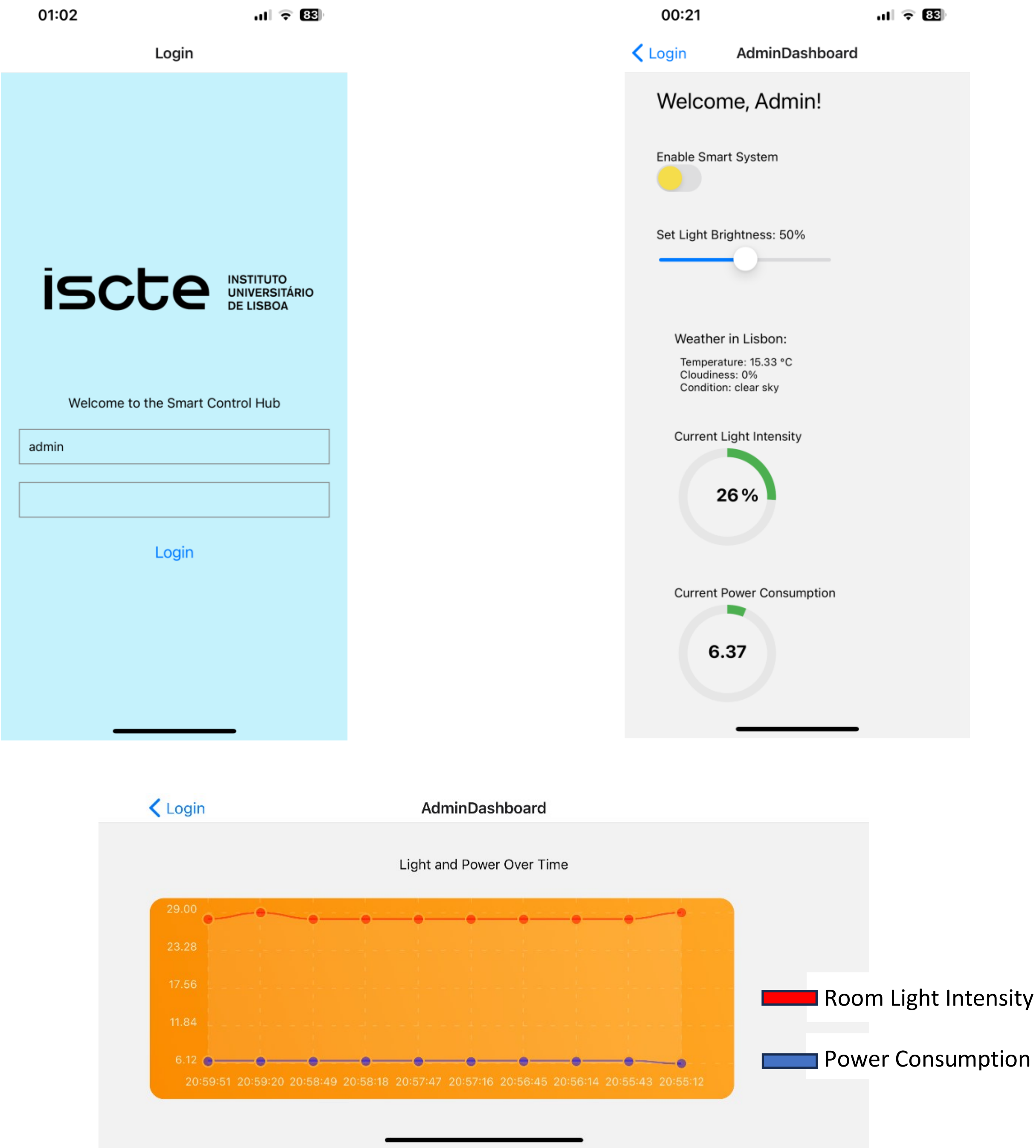


Figure 3.7 - Mobile Application UI (Admin)

User Dashboard

The user dashboard, Fig.3.8, differs from the admin by having the button and the slide removed due to the lack of interaction permissions with the system.

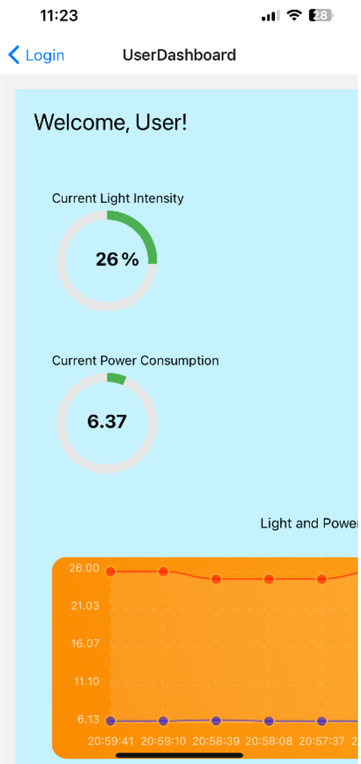


Figure 3.8 - Mobile Application UI (User)

3.4.4 Backend Communication

As mentioned before, the application submits HTTP requests to the Node-RED server through the mobile app for processing, which contains commands either to the smart lamp or to retrieve data from the InfluxDB database.

- Fetching Data from InfluxDB(Fig.3.9): The current light intensity and power consumption are retrieved from InfluxDB through an external API created on Node-RED. This enables the display of updated metrics in the application dashboard.

```
// Function to fetch light intensity data from Node-RED/InfluxDB API
const fetchLightIntensity = async () => {
  try {
    const response = await fetch('https://176.78.110.146:1880/get-light-intensity'); // Node-RED endpoint
    const data = await response.json();
    return data[0].light_intensity; // Accessing the light intensity
  } catch (error) {
    console.error('Error fetching light intensity:', error);
    return null; // Return null in case of error
  }
};
```

Figure 3.9 - Fetch data function

- Control Commands(Fig3.10): The smart lamp is controlled by administrators who send HTTP requests to Node-RED to increase or decrease the brightness level or even to disable the smart system. In case of a toggle-off, it sends a POST request to Node-RED, which stops the automatic control of the system.

```
const toggleSmartSystem = async (value) => {
  console.error(isSmartSystemEnabled);
  try {
    const response = await fetch('http://176.78.110.146:1880/disable-smart-system', {
      method: 'POST',
      headers: {
        'Content-Type': 'application/json',
      },
      body: JSON.stringify({ status: value ? "enabled" : "disabled" }), // Set to "enabled" or "disabled"
    });

    if (response.ok) {
      console.log(`Smart System ${value ? "enabled" : "disabled"}`);
      const data = await response.json();
      setIsSmartSystemEnabled(data[0].state === "true"); // Update local state based on API response
    } else {
      console.error("Failed to change Smart System state");
    }
  } catch (error) {
    console.error("Error:", error);
  }
};
```

Figure 3.10 - Switch system state function

3.5. Hardware Setup

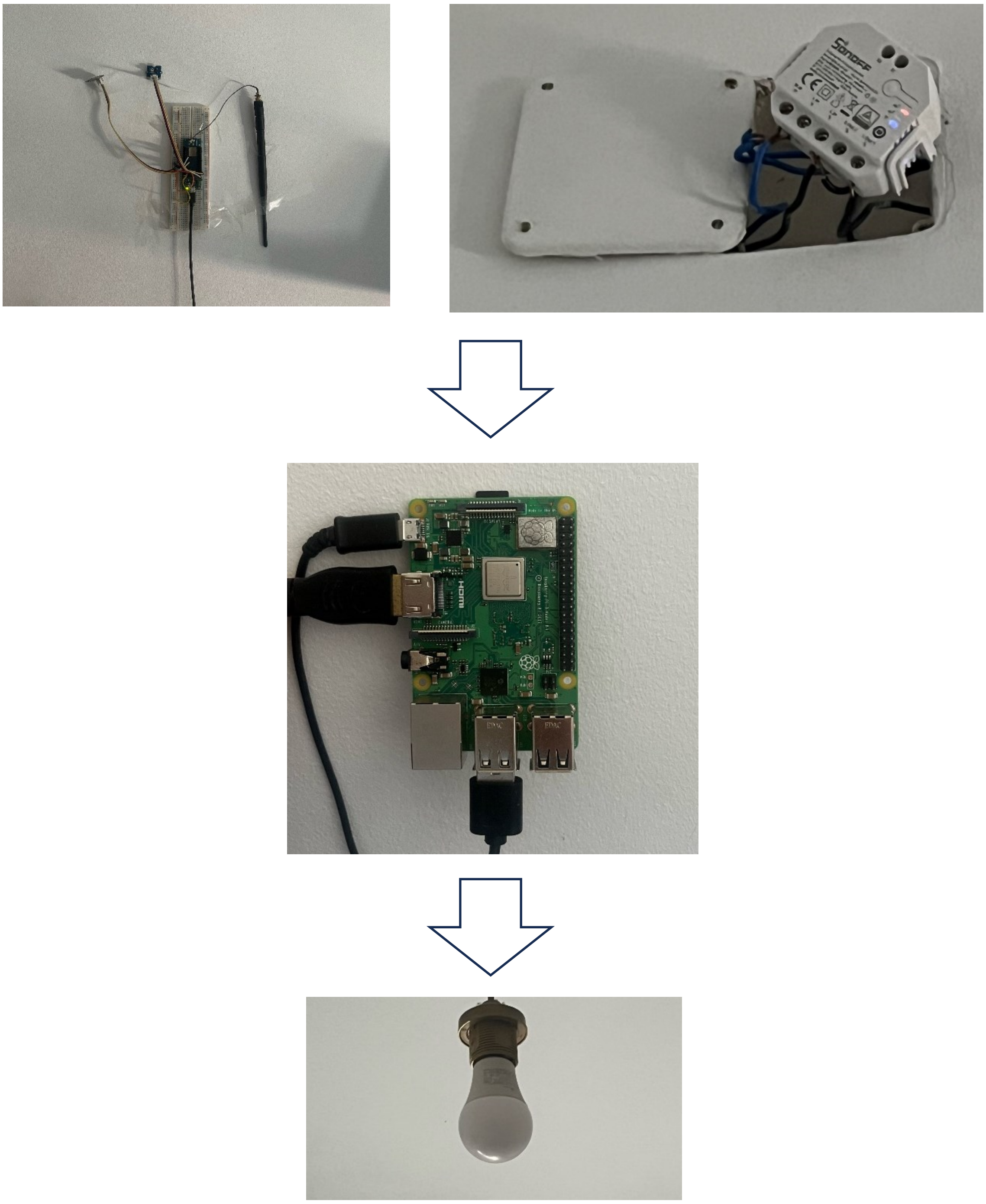


Figure 3.11 - Real system implementation of the developed proof-of-concept

3.6. Raspberry Pi Configuration

Raspberry Pi 3 is the main platform in this smart lighting system, which carries out data processing, storing, and controlling the system. This will be set up to run Node-RED, InfluxDB, and Grafana in fetching the flow of data from sensors, controlling the smart lamp, and storing historical data for future analysis. It also interacts with several external devices, including Arduino MKR WAN 1300 and Sonoff Dual R3, through LoRaWAN, MQTT, and Wi-Fi protocols.

This section describes the assembly and installation of hardware, together with the configuration of software, that will transform the Raspberry Pi into a strong and multi-capable IoT Controller to support the whole smart system.

3.6.1 Hardware

Raspberry Pi 3 Model B was chosen because it provides very affordable, power-saving, flexible IoT development. Compared to the latest generation Pi 4, RP3 has relatively lower computation capability, however, this was not a problem since all the software running on RP3 was light weighted, including Node-RED, InfluxDB, and Grafana.

- LoRaWAN Gateway: This serves as the connection to TTN; it receives data from the Arduino MKR WAN 1300 sensor using LoRaWAN. LoRaWAN provides low-power, long-range communication with a sensor network.
- Wi-Fi Network: Wi-Fi network for wireless communication of the Sonoff Dual R3 and the Tapo L530E smart lamp with raspberry.
- USB Peripherals: Wireless mouse, Keyboard and HDMI monitor were employed.
- Power Supply: 5V micro-USB was used as the raspberry power supply in order to keep it stable.

Raspberry is connected to the same local Wi-Fi network, which optimizes the communication with sensors and smart devices and vice versa, as well as the backend services that work together, like Node-RED, InfluxDB, Grafana, Home Assistant and mobile app.

3.6.2 Software Setup

The Raspberry Pi has a lightweight Raspbian GNU/Linux 11 Operating system installed, optimally utilized in the Raspberry Pi hardware. Several key services have been installed on the Pi for driving the smart lighting system:

- Node-RED: Node-RED is the brain of this system, processing all sensor information from the Arduino, controlling its logic and sending commands to the smart lamp. Node-RED was configured as a "systemd" service(Fig.3.12) so that it automatically starts at boot and it also offers an optimized log/journal system for, among other things, troubleshooting:

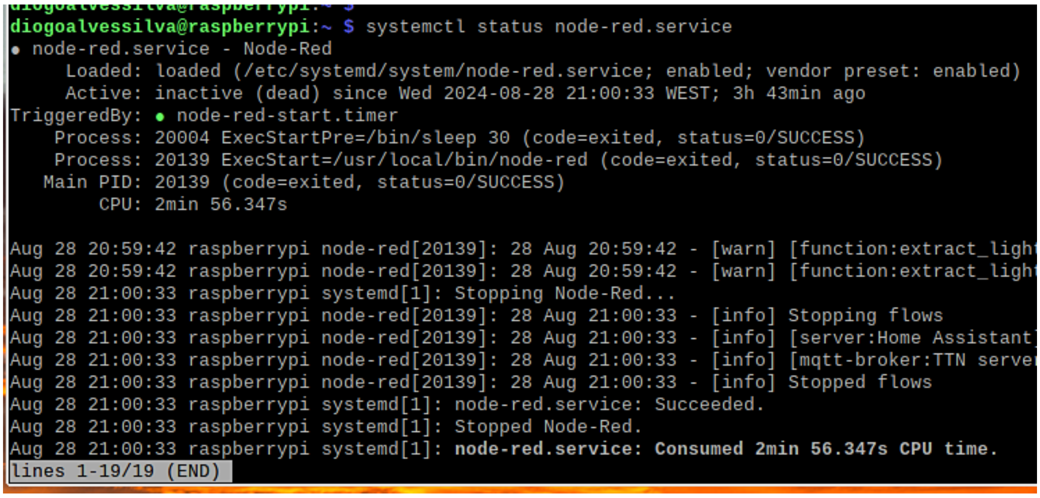


Figure 3.12 - Node-RED status

- InfluxDB: Sensor data, light intensity, and power consumption are persisted in an InfluxDB time-series database, which resides on the Raspberry Pi. InfluxDB is configured to start automatically and continuously run in the background to ensure that at all times, data is logged that can later be analyzed over time. For Retention policies were set up for managing disk space by deleting data older than 3 months automatically, to avoid overloading its limited storage space. InfluxDB was installed by running the following commands:

```
sudo apt-get update
sudo apt-get install influxdb
sudo systemctl enable influxdb
```

- Grafana: Grafana was installed to allow data visualization stored in InfluxDB. An intuitive web interface shows the historical trends of light intensity and power consumption. Grafana was also configured to run as a service(Fig.3.13):

```
diogoalvessilva@raspberrypi:~ $
diogoalvessilva@raspberrypi:~ $
diogoalvessilva@raspberrypi:~ $ systemctl status grafana-server.service
● grafana-server.service - Grafana instance
     Loaded: loaded (/lib/systemd/system/grafana-server.service; enabled; ven
     Active: active (running) since Sun 2024-10-20 19:25:03 WEST; 1 day 5h ag
       Docs: http://docs.grafana.org
   Main PID: 510 (grafana)
      Tasks: 16 (limit: 1595)
        CPU: 6min 44.649s
     CGroup: /system.slice/grafana-server.service
             └─510 /usr/share/grafana/bin/grafana server --config=/etc/grafan
```

Figure 3.13 - Grafana process

- Home Assistant: Home Assistant was installed as a Docker to facilitate integration with the Sonoff Dual R3 power monitoring device to provide real-time power consumption data that would then be passed to Node-RED and InfluxDB and as a docker it prevents the HA system from colliding with other running services.

3.6.3 Automation with Systemd Timers

In order to minimize power consumption and increase the efficiency of operations, systemd timers were implemented, Fig. 3.14, with the responsibility of turning on and off the Node-RED application at certain intervals. The system was defined to be active from 6 AM to 9 PM, after which the Node-RED is turned off, in order to reduce wastage of computational resources. This interval was defined in order to try and capture as much data as possible during the usual working hours.

```
diogoalvessilva@raspberrypi:~ $ sudo cat /etc/systemd/system/node-red-stop.timer
[Unit]
Description=Stop Node-Red at 9 pm

[Timer]
OnCalendar=*-*-* 21:00:00
Unit=node-red-stop.service

[Install]
WantedBy=timers.target
diogoalvessilva@raspberrypi:~ $
```

Figure 3.14 - Stop timer

The Raspberry Pi has been set up in a manner where it can be accessed externally for purposes of monitoring and controlling the operations:

- Remote configuration of the Raspberry Pi is facilitated by enabling SSH.
- Enables access via the browser to the Node-RED and Grafana dashboards for control and monitoring of the system in real-time.
- Use of static IP assignment and DNS configuration ensures that the Raspberry Pi is reachable at the same address on the local area network.

3.6.4 Cloud Backup System

Automated cloud backup solution was used to build an additional layer of protection for the Raspberry Pi and facilitate the operationality of the smart lighting system. The backup safeguards data from InfluxDB and Node-RED configuration and files, against the unforeseen loss of the system due to factors like SD card no longer being viable or overall raspberry pi malfunctions.

These backups run every day at 11PM, sending data to a private Google Drive account via Rclone. Rclone is an open source command line application for cloud file management. Rclone works with Google Drive and allows files from the raspberryPi to be easily filtered to the drive spare. Backups were automated through crontab processes (Fig.3.15) running every day.

```
#Create Raspberry, Arduino and Influx backups
23 00 * * * /home/diogoalvessilva/Documents/Backups/influxdb_backup.sh
23 00 * * * /home/diogoalvessilva/Documents/Backups/backup_nodeRED_to_cloud.sh
23 00 * * * /home/diogoalvessilva/Documents/Backups/backup_arduino_to_cloud.sh
```

Figure 3.15 - contrab -e command output

3.7. Arduino

As mentioned before, the Arduino MKR WAN 1300 is a must-have device as it allows to capture the environmental data and transmit it to a backend through the LoRaWAN. In this respect, the physical set up, software programming, and the connection from Arduino to the whole system will be explained below.

3.7.1 Physical Setup

The Arduino is powered using a USB cable connected to the sensors using jumper wires. The light sensor has been connected to analog pin A0 while the sunlight sensor has been connected to the correct I2C pins. The whole setup was designed to consume as low power as possible to enable it to endure its primary function of IoT devices for a long period. Wiring details:

- **Grove Light Sensor:**
  - Signal pin connected to A0.
  - VCC to 5V, GND to GND.
- **Grove Sunlight Sensor:**
  - I2C communication with SDA and SCL pins connected to the Arduino's corresponding I2C pins.

3.7.2 Arduino Code Overview

The Arduino Software is coded in C++, which collects measurements through sensors and calibrates the light intensity readings into the percentage range (0-100%). The information is afterwards sent to The Things Network (TTN) although using the LoRaWAN protocol.

The following code sippet shows how the data is retrieved from the sensors, prepared and then sent to TTN:

```
// Get data from Grove Light Sensor
  int sensorValue = analogRead(lightSensorPin);
  int lightIntensity = map(sensorValue, 0, 1023, 0, 100);


  // Get data from Grove Sunlight Sensor
  unsigned short sunlightIntensity = SI1145.ReadVisible();


uint8_t sunlightIntensityHighByte = highByte(sunlightIntensity);
  uint8_t sunlightIntensityLowByte = lowByte(sunlightIntensity);
  uint8_t payload[5];
  payload[0] = 0x02;
  payload[1] = lightIntensity;
  payload[2] = 0x03;
  payload[3] = sunlightIntensityHighByte;
  payload[4] = sunlightIntensityLowByte;


modem.beginPacket();
```

3.7.3 Data Transmission

LoRaWAN Low power long range communication between Arduino and the central system node red is made possible through LoRaWAN. The lightweight and robust header structure for transmitting information carries light intensity and sunlight data concatenated together.

The connection to TTN is made possible by the OTAA scheme in order to protect and keep the data transmission effective. The payload is sent by TTN to an MQTT broker which is then processed by Node-RED allowing manipulation of the lighting system within the premises.

```
Serial.println("Joining Network…");

 if (!modem.joinOTAA(appEui, appKey)) {

  Serial.println("Failed to join network");

   while(1);
```

Network Flow:

1. Data is read from sensors.
2. Processed and packaged into a 5-byte payload.
3. Transmitted via LoRaWAN to TTN.
4. TTN forwards the data to Node-RED using MQTT.

Chapter 4 Discussion & Results

This section features a summary of the key results and findings of the smart environment created in this dissertation. The system contains many components, where sensors are connected using LoRa technology, data is processed using MQTT, Node-RED and HomeAssistant software and data is stored in InfluxDB, which is all displayed on Grafana platform. Moreover, the outcomes include the evaluation of the system, the analysis of resources used on a Raspberry Pi, and the assessment of user interaction with the system through a mobile interface.

- **Scalability and Real-World Potential**

Although the system was design for a single lamp in a controlled environment, it represents a proof of concept that shows how the model would scale upwards for wider applications. Architecture can easily be scaled up to several lights, rooms, and even whole buildings. Such scalability is of great essence since even moderate reductions in energy usage, if extended on large scales, add up into significant savings. It is thus fitting for application even in university campuses and office buildings.

Scalability, for example, on a university building, could be achieved by adding lamps, light sensors, and Arduino MKR WAN 1300 to extend this system into bigger-sized spaces such as a multi-room office or building. The core components such as Node-RED server, MQTT broker, and InfluxDB database were built not to require major upgrades and can be used just like it was used on this proof of concept. For example, to scale to 10 rooms with the same size, this would require about 10 Tapo L530E lamps (about 10/15 euros a piece), 10 Grove Light Sensors (about 2/5 euros each), and 10 Arduinos MKR WAN 1300 (40/50 euros) resulting in a initial cost between 520 and 700 euros. If we substitute the sensors to sensor that don't require the direct connection to Arduino we would be able to reduce the Arduino cost.

With the last values in mind, it's reasonable to assume that the energy savings would eventually pay off the initial investment and make it suitable for both small and large implementations equally cost-efficient and energy-efficient with scalability been justified from the perspective of long-term operational savings and environmental sustainability.

4.1. System Performance

4.1.1 Energy Consumption Monitoring

In order to evaluate the effectiveness of the smart lighting system, energy consumption data was gathered for two different modes of operation on two months period: Dimmable Smart System (August 19 - September 19) and ON/OFF Smart System (September 20 - October 20). Each mode was also compared to a baseline scenario, used on the university mentioned in the "Motivation" scope, where the lamp would be 'Always On' at all times. A Sonoff Dual R3 power consumption sensor was employed to monitor energy usage with data being recorded at intervals of thirty seconds and saved on an InfluxDB time series database. This arrangement made it possible to monitor the power usage at all times and display the information in Grafana dashboards and mobile application. The dashboards could visualize the energy consumption, the dimmable mode of operation showed variations consistent with the ambient light variations outside.

The images that follow, Fig.4.1 and Fig.4.2, present high level visualization of the system with data spanning 1 week for each system and with 30 seconds interval for each collection. The images below show a more readable analysis of both models with data spanning one week to better understand the differences in in both lamp intensity and power consumption.

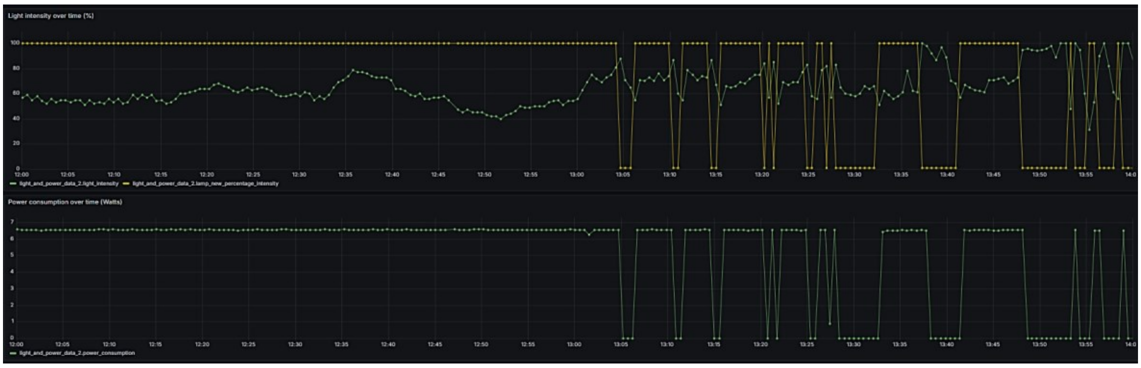


Figure 4.1 - ON/OFF System Dashboard (1 week)

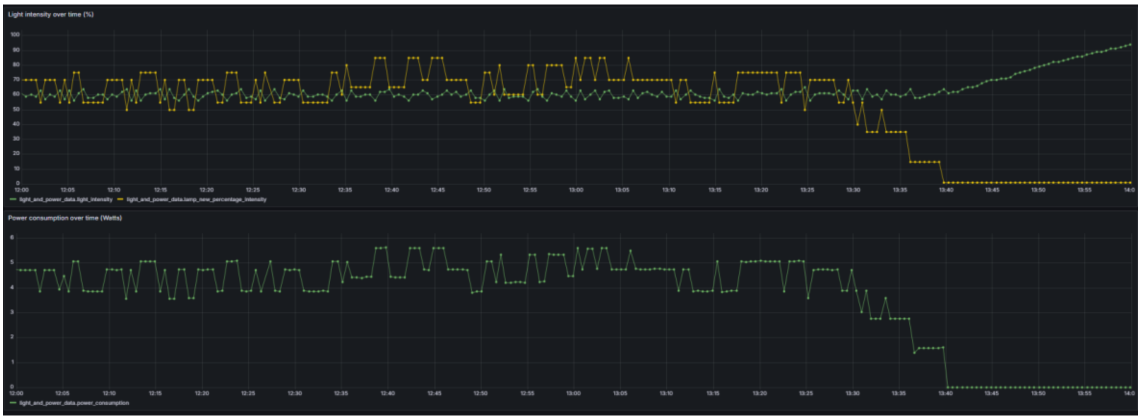


Figure 4.2 - Dimmable System Dashboard (1 week)

Making a comparative analysis of both modes:

<u>First graph of each figure</u>

- Light Intensity (Green Line)
  - ON/OFF System: The green line observes a drastic variation in adjusted room light intensity which is indicative of the control being in a binary state of ON or OFF. In this case, where the adjustable lamp is controlled straight to the ON or OFF switch without any wide range amplitude control, the light is either completely on or off with no intermediate level which would be the target level of operation.
  - Dimmable System: The green line represents the room light level contained within narrower vertical margins suggesting a better control achieved in maintenance of the user's wish for the room light level. The system controls the output of the lamp based on the amount of light in the room, thus providing more even lighting.
- Lamp Intensity (Yellow Line)
  - ON/OFF System: The yellow line shows that there are only two possibilities which are dependent on the lamp being either at full brightness or off. The lack of any intermediate levels means that the risk is there that the lamp will be either on at maximum power wasting power, or off as well as presenting more uncomfortable conditions to the people in the room.
  - Dimmable System: The yellow line changes progressively while the purpose of the lamp is to keep an even brightness within the room. The required lighting is achieved with substantially reduced energy spikes by adjusting the level of light depending on the external conditions. As it can

be seen in Fig.4.2 in the first graph the green and yellow lines present much closer values to one another which indicates a more effective usage of the lamp lighting.

Second graph of each figure

- Power Consumption (Second graph of each figure, Green Line)
    - ON/OFF System: Power consumption here is reflective of the ON/OFF pattern with low power consumption at the end where the sunlight intensity is sufficient and high when the lamp is switched on. This approach creates higher spikes in energy use whenever the lamp is required.
    - Dimmable System: Power consumption is managed along with the dimming resulting to lower total power consumption. The system does provide lighting whenever necessary but manages to save energy by dimming the light as much as possible.

Overall, the Dimmable System (second image) has more control in terms of lighting used in the room and is also economical on energy compared to the first image as it exhibits less drastic changes and rarely uses 100% of the lamp intensity.

4.1.2 System Reliability and Response Times

The performance of the smart lighting system which was developed to be adaptive to ambient lighting conditions in real-time was assessed by means of the response time with regards to sensor reading input to lamp adjustment and the feasibility of further operating the system after prolonged use.

Both in the dimmable and ON/OFF mode, the system increased or decreased brightness depending on the ambient light levels every 30 seconds. The system was reliable, and response times were not significantly delayed with some form of latency experienced a few times usually associated with network constraints or RAM utilization. These were, however, limited in number, and the efficiency of the entire system was not affected.

4.2. Challenges and Optimizations

4.2.1 Hardware

A notable limitation of the current smart lighting system lies in the restricted brightness adjustment range of the Tapo L530E smart lamp. Specifically, the smart lamp can only increase the room's ambient light intensity by a maximum of 22% of the total desired lighting. This limitation becomes particularly evident when the ambient light level in the room is low.

The target light intensity in this system was established at 60% to achieve an optimal balance for comfort and visibility. However, if the initial ambient light intensity in the room is below 36%, the smart lamp's maximum contribution (an additional 22%) is insufficient to meet this target, as it only raises the intensity to a maximum of 60%. Hence, in situations where there is low ambient light, the system will operate at its full brightness (100% lamp output) without any further capacity for adjustment due to the low light output of the Tapo lamp.

Practically, this implies that in some unfavorable lighting conditions, the smart light bulb is already operating at the maximum power without reaching the designed light output. This limits the system's design and energy efficiency since it is almost impossible to adjust the lighting in most instances that are very low or even completely dark.

This restriction emphasizes a potential aspect for improvements in the present systems, where a luminaire with deeper dimming capabilities would be incorporated, or any other luminaires in order to increase the adaptability of the system to all ambient light situations.

4.2.2 Mobile Application

During the development process, a number of obstacles had to be overcome such as ensuring effective real-time state changes, workaround the network delay by using a network extender , and making sure that the mobile application worked seamlessly on both the iOS and Android platforms. In view of the above, the following optimizations were carried out:

- State Management: Functional components built using React Native framework utilized the useState and useEffect hooks to keep track of the current app's status in real-time. These hooks ensure that updates in the backend systems are updated in real-time in the app.

- Error Management: In order to deal with situations where the mobile device was unable to connect to the backend because of unavailability of the Internet error management was implemented. When the connection to the backend is lost, the application informs the user of the problem with appropriate error messages.
- Performance: Since the Raspberry Pi is already on the verge of being overloaded, the data fetching was tailored in such a way that optimally, it would take place only at the point the user starts the application or refreshes the screen. Thus, preventing the system from unnecessary API relays.

4.3. Final Results

This section will present the final results and comparisons between systems, showing every step needed to reach a final monetary cost for each one.

Given that we used a low-power smart lamp for this proof of concept the power consumption presents lower values than the ones expected on an office building or university.

4.3.1 Results Analysis

Comparative Table for Daily and Monthly Costs

Operational Mode	Total Power Consumption (kWh)	Total Active Time (hours)	Monthly Cost (€)
Always-On Baseline	2.8123	434	0.613
ON/OFF Smart	2.1045	325	0.458
Dimmable Smart	1.334	257	0.291

Table 1 - System Results

Analyzing Tab5.1 The ON/OFF system consumes more energy than the dimmable system in this single-room scenario even if it was also active for a longer time, but the difference is modest due to the small scale of the system developed with only one smart lamp Applying the dimmable system across a hundred rooms or lecture halls would result in substantial savings, so in a larger-scale environment, this difference would grow significantly, showing more substantial energy savings.

Making a simple extrapolation, for the same amount of active time (325 hours) on the Dimmable system we would get a monthly cost of 0.367€ which is still lower that the ON/OFF system and in a larger scale would still present considerable savings when comparing to the system ON/OFF.

The queries and calculations below summarize the data extraction processes employed to compute the total power consumed and the period of time the system was active for the three operational modes, with the table light_and_power_data for the dimmable system and the light_and_power_data_2 for the ON/OFF system

Total Power Consumption

SELECT SUM("power_consumption”) FROM "light_and_power_data" WHERE time >= '2024-08-18’ AND time <= '2024-09-18’ AND "power_consumption" > 0

Output: 160,178.66

SELECT SUM("power_consumption”) FROM "light_and_power_data_2" WHERE time >= '2024-09-19’ AND time <= '2024-10-19’ AND "power_consumption" > 0

Output: 252,642.78

Total Active Time

SELECT COUNT("power_consumption”) FROM "light_and_power_data" WHERE time >= '2024-08-18’ AND time <= '2024-09-18’ AND "power_consumption" > 0

SELECT COUNT("power_consumption”) FROM "light_and_power_data_2" WHERE time >= '2024-09-19’ AND time <= '2024-10-19’ AND "power_consumption" > 0

Calculate Total Energy Consumption in Wh

Each entry represents 30 seconds (or 0.00833 hours). With the total power consumption sum in watts, the energy consumption in watt-hours (Wh) is:

Total energy (Wh) = 252,642.78W × 0.00833hours = 2,103.53Wh

Total energy (Wh) = 160,178.66W × 0.00833hours = 1334.29Wh

Convert Watt-Hours to Kilowatt-Hours (kWh)

Total energy (kWh) = 2104.51436 / 1000 = 2.10451kWh

Total energy (kWh) = 1334.29 / 1000 = 1.334kWh

Monthly Cost Calculation

Monthly cost = 2.10353kWh×0.218€/kWh = 0.458euros

Monthly cost = 1.334kWh × 0.218€/kWh = 0.291euros

In order to evaluate power consumption and operational efficiency reliably data was collected every 30 seconds during the assessment periods. The values were deposited in the column "power_consumption", check Fig.3.4, which recorded the usage of power in watts.

4.3.2 Proof of energy efficiency through automation

The results show that the system leads to energy savings by dynamically controlling light brightness based on ambient light input. This form of real-time regulation allows only the amount of energy actually needed to be consumed, and this can be generalized for a wide range of lighting fixtures. Automating this control may ensure consistent energy savings whereby the system shall automatically adjust for different ambient lighting during the day and without human intervention.

4.3.3 Projecting Data for a Larger Scale

The findings obtained from this pilot project will be analyzed and evaluated to make, in other words, broader projections as far as the implementation of similar projects in more complex settings is concerned. For example, if this system is capable of bringing down the energy usage of one room by these percentages, then applying the system to many such rooms, or even entire floors or buildings, may bring in greater savings. Such a forecast indicates the possible extent to which the system in question can help meet electric power consumption targets when implemented in wider scales.

4.3.4 Environmental and Economic Benefits

Aside from the energy savings obtained from this proof of concept and in scope of the motivation presented in the beginning, the system's potential for extension has environmental and economic advantages that are apparent. For institutions that want to reduce the impact of their operations on the environment (carbon footprint), minimization of electricity consumption is a beneficial measure towards accomplishing that goal. Furthermore, this system is suitable for sustainable building management because potential energy cost savings are a strong motivating factor.

CHAPTER 6. CONCLUSION

This dissertation set out to investigate the influence of smart lighting systems based on the Internet of Things (IoT) to curtail energy consumption in controlled environments without compromising the user. The primary research question that directed this study was: How can the energy in a controlled environment be optimized to reduce its consumption without compromising the comfort of its inhabitants?

The outcomes obtained after successful execution and deployment of the IoT-based system confirmed that all the three hypotheses were upheld. The following outlines the findings concerning each hypothesis:

- H1: The experimental data demonstrates the effectiveness of the IoT system in decreasing energy usage, therefore the hypothesis that the IoT system can achieve energy efficiency without major energy consumption is refined.
- H2: The analysis of the data collected through monitoring demonstrated that the use of monitoring systems can be efficient in controlling and evaluating energy consumption in a dynamic manner.
- H3: When tested under controlled conditions, the adaptive lighting system controlled brightness as per the ambient light variations. Auto adjustments like these in reaction to real time changes in the environment indicate how the system can limit possible eye strains while increasing user interactions in varying light settings. While user satisfaction was not evaluated within the scope of the study, due to cost and space limitations, the behavior of the system is consistent with the expected improvements in comfort levels of the users.

Concerning the main research question, the study has been able to prove that energy optimization can be achieved in an environment without compromising the comfort of the occupants. The results suggest that real-time controlled adaptive IoT systems are effective tools in the realization of sustainable energy. While the results indicated not so significant energy savings being a proof of concept on a small environment with only one lamp, there are also indications that this system can be scaled up for wider use, where it can be employed in saving energy in bigger buildings, institutions or even cities.

In the present time, the system has reached the goals that were set out but there are a number of future research and development avenues:

- **Addressing Limitations:** The insufficient brightness scope of Tapo L530E prevents its use in larger environments. In the future new luminaries with even wider adjustment or higher brightness output may be provided and used in this system. The scenario to be tested is single-room only; it will not provide an insight into constraints such as network congestion or even scalability. Testing needs to extend into test cases of multi-room or building width area.
- **Integrating Predictive Algorithms:** The existing system uses a direct sensor to vary lighting. Future developments may include the application of machine-learning algorithms for prediction of needs based on user behavior and historical data in order to achieve more energy savings.
- **Enhancing User Interaction:** The mobile app will be ready for basic functionality, but future versions should include extended features that may even involve voice control (Voice Assistants like Alexa, etc), detailed energy usage analytics, or user-configurable settings for lighting preferences.
- **Scalability to Commercial Applications:** It is possible to scale the system for commercial or public buildings: for offices, schools, or libraries, energy efficiency at scale may equate to considerable cost savings.
- **Integration with Renewable Energy:** Future research could focus on integrating the system with renewable energy sources, for example, solar panels, in an effort to enhance the entire concept of sustainability even further.
- **Integration of shades (window blinds)**: The system could also improve it by being able to not only interact with the lighting system but also interact with the amount of sunlight and with that reduce the use of artificial lights

This study finally asserts that the use of IoT for adaptive lighting system can indeed facilitate energy saving without compromising on comfort. In the future, the ambition of the research is likely to enlarge the system to the aims of solving multi-room or building scale applications, allowing energy savings in more sophisticated areas.

Bibliographical references

[1] Energy Institute - Statistical Review of World Energy (2024); Smil (2017) – with major processing by Our World in Data. Retrieved from https://ourworldindata.org/global-energy-200-years

[2] IEA (a). (2018). CO2 emissions from fuel combustion 2018 overview. OECA/IEA, Paris.

[3] Enerdata (2021). Global Energy Statistical Yearbook 2021. Enerdata. Retrieved from https://yearbook.enerdata.net

[4] Rehman, A., Rauf, A., Ahmad, M., Chandio, A. A., & Deyuan, Z. (2019). The effect of carbon dioxide emission and the consumption of electrical energy, fossil fuel energy, and renewable energy, on economic performance: evidence from Pakistan. Environmental Science and Pollution Research, 26(21). https://doi.org/10.1007/s11356-019-05550-y

[5] Mataloto, B. (2019). IOT*(AMBISENSE) – SMART ENVIRONMENT MONITORING USING LORA. https://www.iscte-iul.pt/tese/10109

[6] Abo-Zahhad, M., Ahmed, S. M., Farrag, M., Ahmed, M. F. A., & Ali, A. (2016). Design and implementation of building energy monitoring and management system based on wireless sensor networks. Proceedings - 2015 10th International Conference on Computer Engineering and Systems, ICCES 2015. https://doi.org/10.1109/ICCES.2015.7393051

[7] Nguyen, N. H., Tran, Q. T., Leger, J. M., & Vuong, T. P. (2010). A real-time control using wireless sensor network for intelligent energy management system in buildings. EESMS 2010 - 2010 IEEE Worskshop on Environmental, Energy, and Structural Monitoring Systems, Proceedings. https://doi.org/10.1109/EESMS.2010.5634176

[8] Byun, J., Hong, I., Kang, B., & Park, S. (2011). Implementation of an adaptive intelligent home energy management system using a wireless ad-hoc and sensor network in pervasive environments. Proceedings - International Conference on Computer Communications and Networks, ICCCN. https://doi.org/10.1109/ICCCN.2011.6005942

[9] Han, J., Choi, C. S., Park, W. K., Lee, I., & Kim, S. H. (2014). Smart home energy management system including renewable energy based on ZigBee and PLC. IEEE Transactions on Consumer Electronics, 60(2). https://doi.org/10.1109/TCE.2014.6851994

[10] Wang, J., Huang, J., Chen, W., Liu, J., & Xu, D. (2016). Design of IoT-based energy efficiency management system for building ceramics production line. Proceedings of the 2016 IEEE 11th Conference on Industrial Electronics and Applications, ICIEA 2016. https://doi.org/10.1109/ICIEA.2016.7603712

[11] Gao, M., Shaoliangshan, Huixiaowei, & Sunqingwei. (2010). The system of wireless smart house based on GSM and ZigBee. 2010 International Conference on Intelligent Computation Technology and Automation, ICICTA 2010, 3. https://doi.org/10.1109/ICICTA.2010.118

[12] Shanmugasundaram, Ramalingam, Khan, Bharath, Kalikumar and Kishore (2022). IEEE Xplore. Smart Lighting System Using the Internet of Things. Retrieved from https://ieeexplore.ieee.org/document/9785327

[13] Erzi, H. M., & Aydin, A. A. (2020). IoT Based Mobile Smart Home Surveillance Application. 4th International Symposium on Multidisciplinary Studies and Innovative Technologies, ISMSIT 2020 - Proceedings. https://doi.org/10.1109/ISMSIT50672.2020.9255303

[14] Hwang, S. (2017). Monitoring and Controlling System for an IoT Based Smart Home. International Journal of Control and Automation, 10(2). https://doi.org/10.14257/ijca.2017.10.2.28

[15] David, N., Chima, A., Ugochukwu, A., & Obinna, E. (2015). Design of a Home Automation System Using Arduino. International Journal of Scientific and Engineering Research, 6(6).

[16] Hoes, P., Hensen, J. L. M., Loomans, M. G. L. C., de Vries, B., & Bourgeois, D. (2009). User behavior in whole building simulation. Energy and Buildings, 41(3). https://doi.org/10.1016/j.enbuild.2008.09.008

[17] Sanchez-Iborra, R., Sanchez-Gomez, J., Ballesta-Viñas, J., Cano, M. D., & Skarmeta, A. F. (2018). Performance evaluation of lora considering scenario conditions. Sensors (Switzerland), 18(3). https://doi.org/10.3390/s18030772

[18] Jahn, M., 2016. [online] Publications.rwth-aachen.de. Available at: https://publications.rwth-aachen.de/record/682274/files/682274.pdf

[19] Buchanan, K., Russo, R., & Anderson, B. (2014). Feeding back about eco-feedback: How do consumers use and respond to energy monitors? Energy Policy, 73. https://doi.org/10.1016/j.enpol.2014.05.008

[20] Mekki, K., Bajic, E., Chaxel, F., & Meyer, F. (2019). A comparative study of LPWAN technologies for large-scale IoT deployment. ICT Express, 5(1). https://doi.org/10.1016/j.icte.2017.12.005

[21] de Carvalho Silva, J., Rodrigues, J. J. P. C., Alberti, A. M., Solic, P., & Aquino, A. L. L. (2017). LoRaWAN - A low power WAN protocol for Internet of Things: A review and opportunities. 2017 2nd International Multidisciplinary Conference on Computer and Energy Science, SpliTech 2017.

[22] Lavric, A., & Popa, V. (2017). LoRaTM Wide-Area Networks from an Internet of Things perspective. Proceedings of the 9th International Conference on Electronics, Computers and Artificial Intelligence, ECAI 2017, 2017-January. https://doi.org/10.1109/ECAI.2017.8166397

[23] Centenaro, M., Vangelista, L., Zanella, A., & Zorzi, M. (2016). Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios. IEEE Wireless Communications, 23(5). https://doi.org/10.1109/MWC.2016.7721743

[24] Costa, A. G. V. (2018). Internet of Things for the Smart Home (Master's dissertation). Instituto Superior Técnico - Universidade de Lisboa.

[25] Ma, H., Du, N., Yu, S., Lu, W., Zhang, Z., Deng, N., & Li, C. (2017). Analysis of typical public building energy consumption in northern China. Energy and Buildings, 136. https://doi.org/10.1016/j.enbuild.2016.11.037

[26] Raatikainen, M., Skön, J. P., Leiviskä, K., & Kolehmainen, M. (2016). Intelligent analysis of energy consumption in school buildings. Applied Energy, 165. https://doi.org/10.1016/j.apenergy.2015.12.072

[27] Hunkeler, U., Truong, H. L., & Stanford-Clark, A. (2008). MQTT-S - A publish/subscribe protocol for wireless sensor networks. 3rd IEEE/Create-Net International Conference on Communication System Software and Middleware, COMSWARE. https://doi.org/10.1109/COMSWA.2008.4554519

[28] Mataloto, B., Ferreira, J. C., & Cruz, N. (2019). Lobems—IoT for building and energy management systems. Electronics (Switzerland), 8(7). https://doi.org/10.3390/electronics8070763

[29] Yadav, Ankush. "Energy Management Systems Market" May 2018. Retrieved from https://www.alliedmarketresearch.com/energy-management-systems-market

[30] Sütterlin, B., Brunner, T. A., & Siegrist, M. (2011). Who puts the most energy into energy conservation? A segmentation of energy consumers based on energy-related behavioral characteristics. Energy Policy, 39(12). https://doi.org/10.1016/j.enpol.2011.10.008

[31] Gölz, S., & Hahnel, U. J. J. (2016). What motivates people to use energy feedback systems? A multiple goal approach to predict long-term usage behaviour in daily life. Energy Research and Social Science, 21. https://doi.org/10.1016/j.erss.2016.07.006

[32] Houde, S., Todd, A., Sudarshan, A., Flora, J. A., & Armel, K. C. (2013). Real-time feedback and electricity consumption: A field experiment assessing the potential for savings and persistence. Energy Journal, 34(1). https://doi.org/10.5547/01956574.34.1.4

[33] Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. Journal of Environmental Psychology, 25(3). https://doi.org/10.1016/j.jenvp.2005.08.002

Annexes

1. ### Arduino Code

The complete arduino code for the smart lighting system is available in the following GitHub repository on the folder **Arduino/Arduino Code**:

https://github.com/diogoalvesdasilva1998/iot-smart-lighting-system/tree/108aa7038a61396a648e0fa4e59d6de563775d44/Arduino

2. ### Node-RED Flow

The complete Node-RED flow for the smart lighting system is available in the following GitHub repository on the folder **node-red-flow**:

https://github.com/diogoalvesdasilva1998/iot-smart-lighting-system/tree/108aa7038a61396a648e0fa4e59d6de563775d44/node-red-flow

You can import the flow into Node-RED by following the instructions provided in the README.md on the GitHub page.

3. ### Mobile App Code

The complete mobile application code for the smart lighting system is available in the following GitHub repository on the folder **mobile-app/src**:

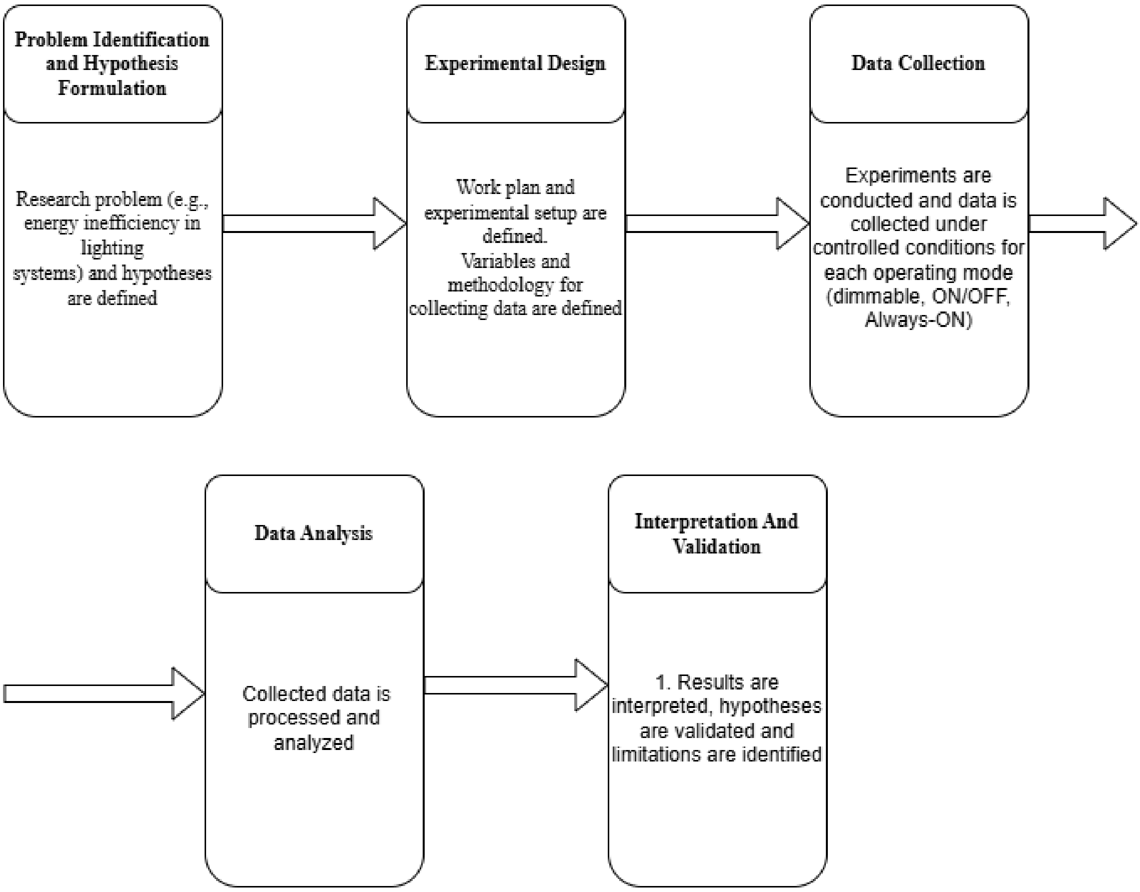
https://github.com/diogoalvesdasilva1998/iot-smart-lighting-system/tree/108aa7038a61396a648e0fa4e59d6de563775d44/mobile-app/src

4. ### Backups Code

The complete code responsible for every backup is available in the following GitHub repository on the folder **Backups**:

https://github.com/diogoalvesdasilva1998/iot-smart-lighting-system/tree/108aa7038a61396a648e0fa4e59d6de563775d44/Backups

5. ### Experimental Methodology Process Model



6. ### International Conference

I presented my paper on a international conference named "2024 International Symposium on Sensing and Instrumentation in 5G and IoT Era" and had the paper published on IEEE: https://ieeexplore.ieee.org/document/10720489