Universidade do Minho
Escola de Engenharia

Smart City

Master in Industrial Eletronics and Computers Engineering

Embedded Systems

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Contents

List of Figures

List of Tables

Acronyms

AP Access Point

API Application Programming Interface

BS Base Station

CAGR Compound Annual Growth Rate

CPS Cyber-Physical System

CSI Camera Serial Interface

GPIO General Purpose Input/ Output

GUI Graphical User Interface

IoT Internet of Things

LED Light-Emitting Diode

PWM Pulse Width Modulation

Chapter 1

Introduction

1.1 Problem Statement

Nowadays, the energy crisis is a constant theme because of the inflated energy prices [2]. Furthermore, huge energy consumption is a burden to the environment, as not all means of energy production are non-polluting. According to "Our World in Data"[3], in 2019, 63,3 % of eletrical energy production comes from fossil fuels. It is known that generally, street lamps are continuously switched on at night, most of the time unnecessarily glowing with its full intensity, in the absence of any activities in the street, leading to a great waste of energy. Furthermore, it is in cities where the consequences of using cars are most noticeable. An example of this is the search for a parking space. According to the RAC Foundation [4], in England, an average car is parked 95 % of the time, which explains how hard it can get sometimes when trying to find a parking spot. This struggle leads to an increase in carbon dioxide production as well as fuel and energy consumption.

With that in mind, this project aims the implementation of applications for a Smart City, regarding Smart Lighting and Smart Parking, in order to decrease the energy consumption in public streets, while improving the lives of citizens around the world. The solution will embrace a decentralized system, composed by smart street lights capable of turning on only when they detect movement in the surroundings, at night time, and also, capable of detecting available parking spaces in the street post vicinity.

1.2 Problem Statement Analysis

The main purpose of this system is to control a network of street lamp posts, using for this Raspberry Pi 4B [5]. To reduce the costs associated with this solution, the network is composed by a “primary” lamp post, which implements smart lighting management and smart parking, and controls the remaining lampposts. These are the “secondary” lampposts, which only implement smart lighting management.

When there is no activity detected in the area, the lamp post is at a predefined minimum light level, whereas when a car or pedestrian is noticed in the area, the light automatically activates at full brightness. Therefore, each street lamp post communicates wirelessly with the neighbor lamp posts, allowing to dynamically turn on the lights of the following poles. To detect movement in the vicinity of the pole, a motion detector is used. Since the lamppost will only light up during the night time, the motion detector will also only work during that period. To ensure this, a luminosity sensor is used, determining the ambient light conditions. In order to facilitate the maintenance of the pole, a system that determines the operating conditions of the lamp is also implemented. When this system verifies that the lamp is not in good working conditions, in other words, that it is broken or burnt, this information is transmitted to the entity responsible for the network of lamp posts, through a mobile app. This is also used by the person in charge, to manage all information on the pole network, such as the location and working conditions of each pole.

In order to detect empty parking spots, this system should only be used in an area where there are parking spaces nearby. For this, the lamp post has a camera, turned on all day, and, after Raspberry Pi processes the acquired information, it will be available on a website, so that a user, a car driver, can know where there are empty parking spaces.

Chapter 2

Market Research

2.1 Market Definition

Smart cities have the potential to benefit communities and individuals in a variety of applications across health, transportation, education, government, energy, and power and water. Implemented correctly, smart city applications can reduce costs, simplify services and offer a sustainable solution. [6]

Figure 2.1: Global smart cities market trends.

As one can see, in figure 2.1, according to MarketsandMarkets [7] global smart cities market is expected to grow from USD 457 billion in 2021 to USD 873.7 billion by 2026, at a Compound Annual Growth Rate (CAGR) of 13.8%, during the forecast period. Growing urbanization, need for efficient management and utilization of resources, and also the increasing demand for a healthy environment with efficient energy consumption are expected to be the major factors driving the growth of the smart cities market.

As figure 2.2 shows, there are various applications of IoT technology for smart cities. In this project it will be created a solution that comprises Smart Lighting management and Smart Parking.

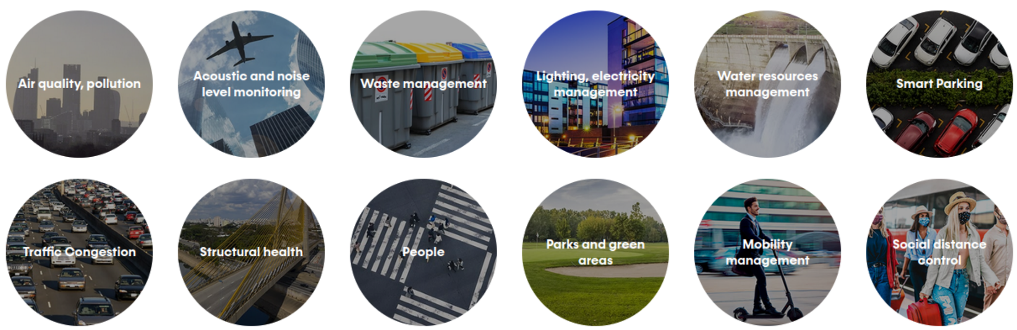

Figure 2.2: Applications of IoT technology for Smart Cities. [1]

2.1.1 Smart Lighting

Smart Street lighting is a rapidly growing lighting market, with an expected CAGR of 20.4 % until 2026 [8], implementing a smart management of public lighting to optimize energy consumption according to lighting needs. This is boosted by regulatory policies that encourage energy efficiency, IoT convergence and the drop of Light-Emitting Diode (LED) prices. This new concept of smart light post is also growing, implementing not only the smart management of street lights, but also features that go from basic LED replacement control, to traffic and video monitoring, environmental monitoring, and others.

Telensa - PLANet

Nowadays, Telensa is the market share leader in smart street lighting with more than ten years of experience.[9] PLANet is an intelligent street lighting system, consisting of wireless nodes connecting individual lights, a dedicated network owned by the city and a central management application, seen in figure 2.3. This system reduces energy and maintenance costs associated with street lighting and also improves quality of maintenance through automatic fault reporting.

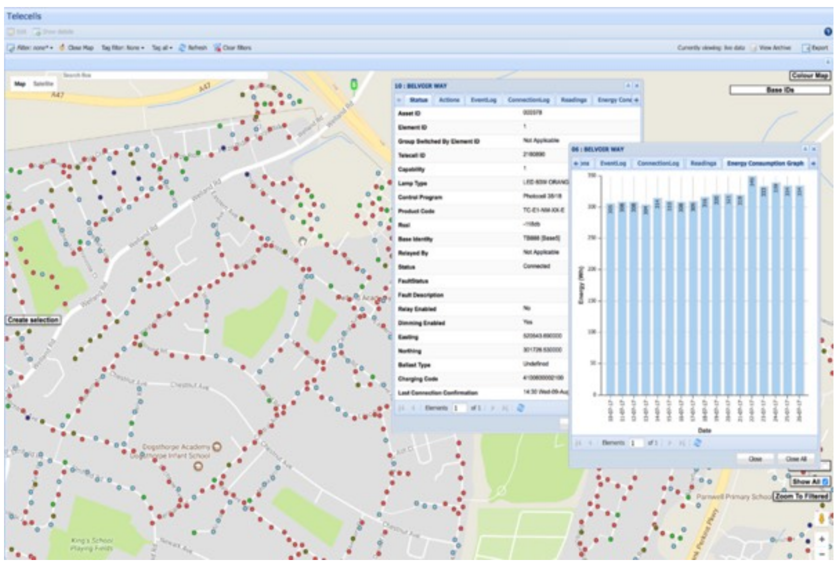

Figure 2.3: Telecells - PLANet's Central Management System.

FLASHNET - inteliLIGHT

FLASHNET is a company focused on developing intelligent systems for smarter cities and better infrastructures and have created a solution that provides the right amount of light where and when needed to lighten the streets, the inteliLIGHT [10].

Using the existing infrastructure, this solution saves money and transforms the existing distribution level network into an intelligent infrastructure of the future, as shown in figure 2.4. Furthermore, the system is integrated with major IoT platforms and provides Application Programming Interface

(API) connectivity with City Management applications, ensuring compatibility with existing smart lighting and smart city initiatives.

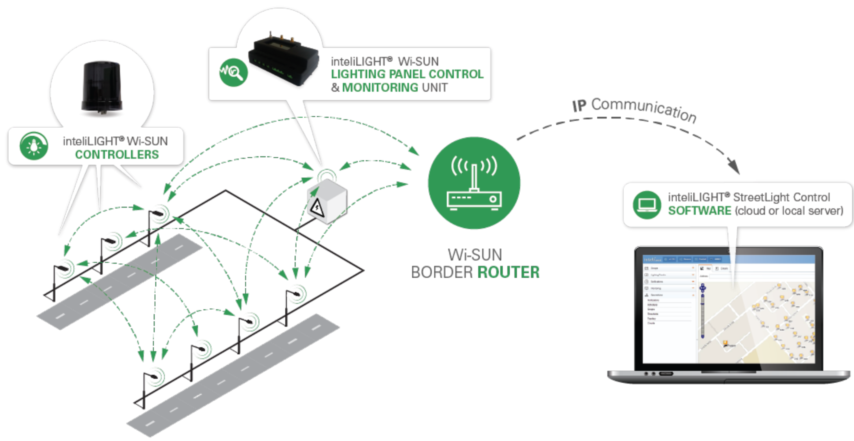

Figure 2.4: inteliLIGHT Communication Technology.

2.1.2 Smart Parking

Smart parking, through the monitoring of parking spaces availability in the city, is also a growing market, expected to grow with a CAGR of 17.85% in the forecast period of 2021 to 2028.[11] The rise in investment in building driverless vehicles and an increase in the government's initiative in building smart cities across the globe, along with the demand and adoption of IoT technology, are the main driving factors for the growth of smart parking market.

intuVision - intuVision VA Parking

Regarding only to the detection of available parking spaces, there is a solution, by intuVision, named intuVision VA Parking, which provides parking lot analytics to determine vehicle count and security, and monitor parking space availability at all times, both for cities and for private parking lots, as one can see in the figure 2.5.[12]

Figure 2.5: intuVision Parking Lot Demonstration.

2.2 Why choose our product

This product aims to decrease power consumption associated with the traditional street light network, and also, using that infrastructure, contribute to the development of a smart city, detecting available parking spaces in the streets. This street lighting solution can be used in residential areas, public spaces or a large outdoor parking lot, feasible of being installed in existent lamp posts, requiring minimum changes to the original infrastructure. Although in this project it is not implemented, aside the parking spaces availability detection, this product can have the ability to monitor and to process various areas of interest using the camera built in, like for example, security purposes.

Chapter 3

System

3.1 Network Architecture

The system to be developed is inserted in a network, more specifically, an infrastructure based network, as shown in figure 3.1. This type of networks are composed by wireless segments of a more extensive network, whose core is usually a wired network. Infrastructure-based networks have a special station, called an Access Point (AP) or Base Station (BS), which serves as an interface between the wireless segment and the rest of the network. Inside the wireless segment, there will be a centralized communication, so that all messages that circulate on the network pass through a central station. That way, the network only supports two transmission directions: the downward direction (downlink), from the base station to the other stations, and the uplink direction, from the stations to the base station. The downlink usually allows the simultaneous transmission of information to a group of stations in the cell (multicast) or to all stations (broadcast).

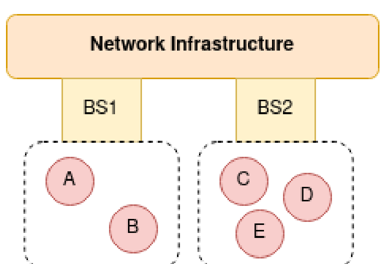

Figure 3.1: Infrastructure based network architecture.

Street lighting is generally divided into sectors, facilitating maintenance and problem solving regarding the lighting network. In figure 3.2, one can see that the base station is a “special station”, since it connects the local network of lighting poles to other base stations, through a remote server, and also because it has a camera for the detection of available parking spaces. The rest of the stations that compose the local network, the local systems, will only do the smart management of their lamps.

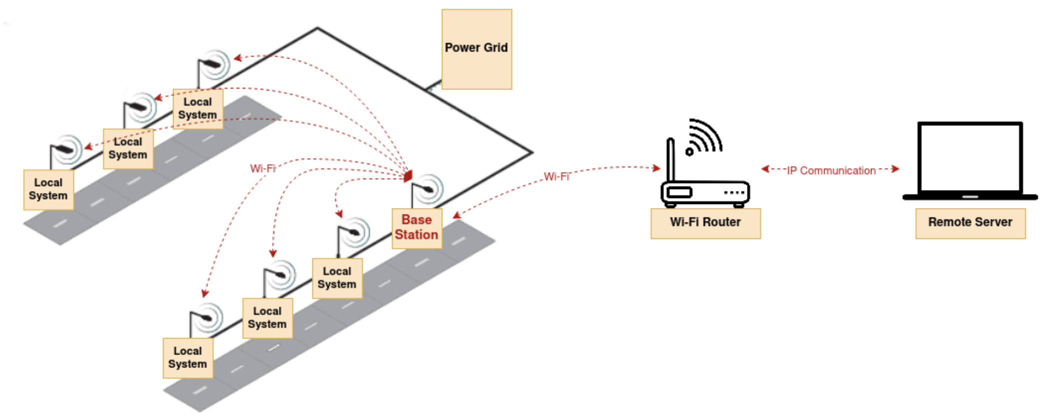

Figure 3.2: Network architecture.

The range of a Wi-Fi network depends primarily on the number and type of wireless access points used to build it, and so, the cost to build and maintain these networks increases significantly as the range increases.

The Wi-Fi signal range of any given access point also varies significantly from device to devices, depending on the specific 802.11 protocol that its used, the strength of its device transmitter and the nature of physical obstructions or radio interferences in the surrounding area. Also, due to laws of physics, 5 GHz Wi-Fi connections are more susceptible to obstructions than are 2.4 GHz. Generally, Wi-Fi routers operating on the traditional 2.4 GHz band reach up to 46 meters indoors and 92 meters outdoors. [13]

Using a router running 802.11n, in open space the wi-fi signal range can be a little over 60 meters. [14] That being said, if each lamppost is spaced by 4 meters, each base station can easily connect with 10 local systems. To communicate with a remote server, the router will be connected to the internet through an Ethernet cable, or similar, that will most certainly already exist near the lampposts, in the telecommunications infrastructure.

3.2 System Overview

Through the system overview diagram, in figure 3.3, it is possible to identify the main modules of the system to be developed, and how they interact. We can divide the system into three subsystems: the local system, which represents a lamp post, the base station, a lamp post that controls a network of street lamp poles, and the remote system, that allows interaction with the system users.

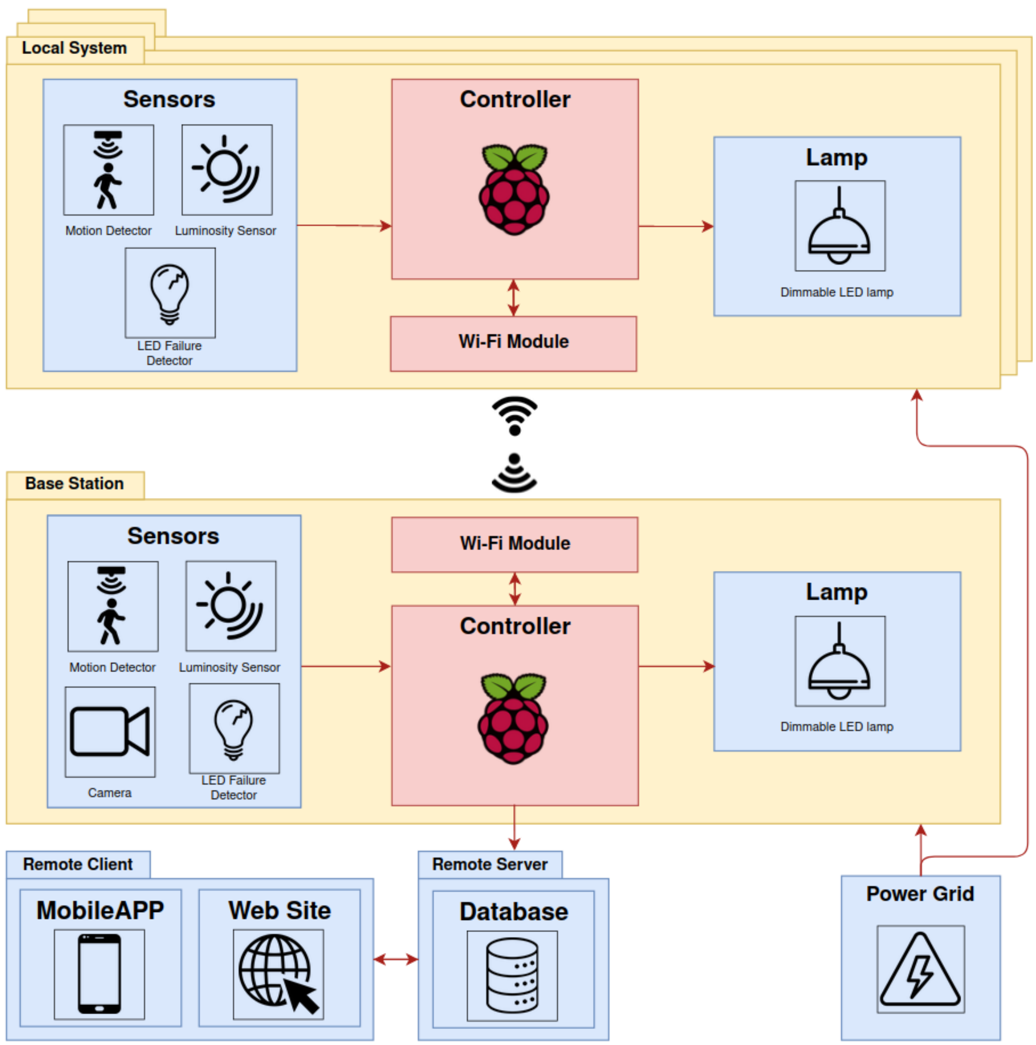

Figure 3.3: System Overview Diagram.

The local system is composed of sensors, a controller and a lamp. Regarding the sensors, there will be a motion detector, to allow the detection of movement in the vicinity of the pole, a luminosity sensor, to detect the light conditions of the pole's surroundings and a LED failure detector to know if the LED lamp is working.

The base station have the same components as the local system but it includes a camera to find empty parking spots. The controllers of the base station and local systems, the Raspberry Pi, use the sensors information and communicate with each other through a Wi-Fi module in order to so that the lights are dynamically turned on. The base station controller also communicates via internet with a remote server.

The remote system is composed by the remote server and the remote client. The remote server consists of a database that stores all information about each lamp post location and operating status. This information can be accessed through a mobile application by the operator in order to carry out the necessary maintenance of the lamp of each pole. Furthermore, the operator when installing a new lamp post can add its location to the database, using the mobile application. In addition, the database stores information on available parking spaces. When a user, a car driver, wants to know where there are empty parking places, he can access a website that informs him of the location of the empty parking spaces.

Knowing that the public lighting network is directly related to the electrical network, this will be used to power each local system.

3.3 System Requirements and Constraints

In order for the system to have the desired performance, these requirements and constraints must be respected:

Functional Requirements

- Sensors data acquisition
- Motion detection
- Control of a street lamp
- Control a network of street poles

- Wireless communication between local systems and base station
- Access system information through a mobile application
- Empty parking spots detection
- Manage system information through a mobile application
- Add lamp post location through a mobile application
- Access available parking spots location through a web site

Non-Functional Requirements

- User friendly mobile application and web site
- Ambient luminosity sensing
- Lower power consumption than actual street lights
- Soft Real-Time Embedded System

Technical Constraints

- Buildroot
- C and C++
- Device Drivers
- Linux
- Raspberry Pi
- Cyber-Physical System (CPS)
- Makefiles
- Pthreads

Non-Technical Constraints

- Two members team
- Project deadline at the end of the semester
- Low budget

3.4 System Architecture

Using the system overview diagram information, one can describe the system in two different architectures. Hardware architecture, as how the hardware modules interfaces with itself, and what are the physical components of the system, and software architecture, which details how the information is processed among different software layers.

3.4.1 Hardware Architecture

In figure 3.4, one can see the diagram that represents the physical connections of the system. The Raspberry Pi is the main component in the system, processing all the information given by the sensors, via General Purpose Input/ Output (GPIO) pins and Camera Serial Interface (CSI) for the camera. The communication with the Wi-Fi module is straightforward since its built-in into the Raspberry-Pi. The power of all system components comes from the power grid and, through an AC/DC converter, will power the Raspberry Pi and its associated sensors. In order to power the lamp and at the same time control its brightness, a driver is used, taking the controller output, a Pulse Width Modulation (PWM) signal, and system power as inputs.

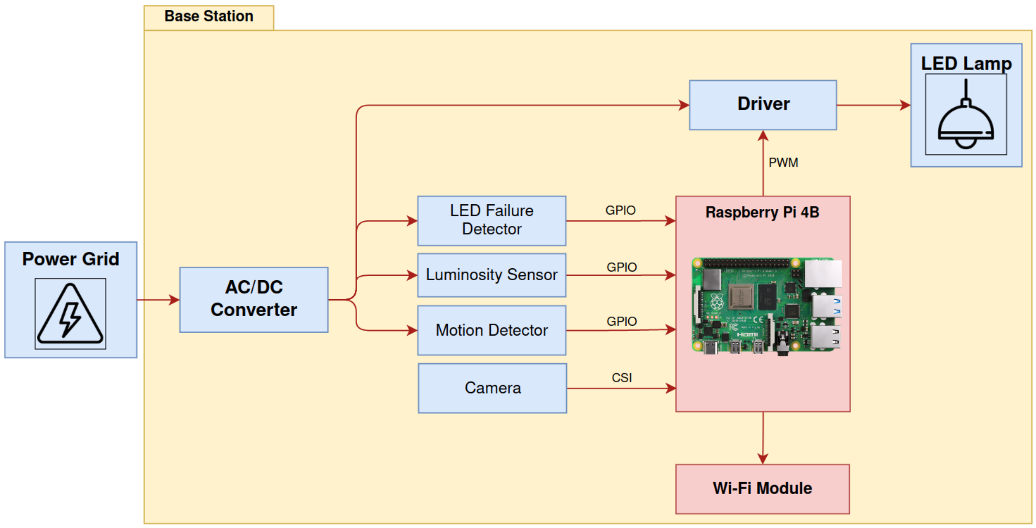

Figure 3.4: Hardware Architecture Diagram.

3.4.2 Software Architecture

The software architecture is divided into three layers:

- The **Operating System** layer, which is composed by the Operating System drivers and Board Support Packages;

- The **Middleware** layer, which includes software for abstracting the lower level layer packages. It works as a pipe since it links two applications, in different layers, so that data can be easily transmitted;

- The **Application** layer, where the core functionality of the program is built, with a resource for the API's in the lower level layers.

As shown in figure 3.5, the operating system layer is composed by the sensor drivers, such as the LED Failure Sensor, the Luminosity Sensor, the Motion Detector which uses GPIO drivers, the camera, that uses CSI drivers and also the Wi-Fi Communication driver. In the middleware layer are the tools needed to process the images from the camera, to multitasking, using PThreads execution model, to acquire data from sensors and to communicate via Wi-Fi with the remote server. Finally, the application layer manages the system database, as well as the Graphical User Interface (GUI), that is the mobile application and the web site, and also all communications with the neighbor street poles.

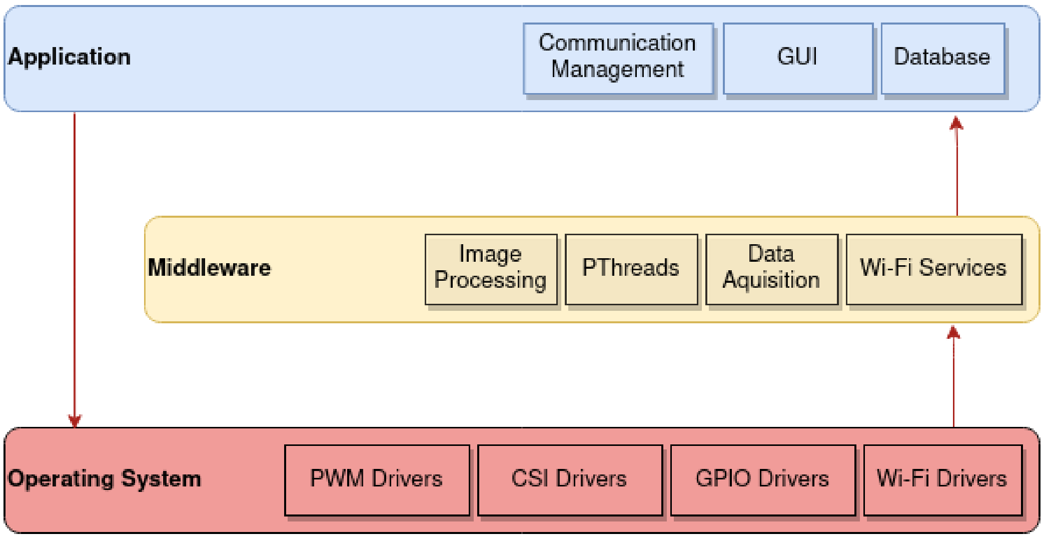

Figure 3.5: Software Architecture Diagram.

Chapter 4

System Analysis

4.1 Base Station

4.1.1 Events

To better understand the base station behavior, it is necessary to be aware of the events that may occur, defining how the system will respond to each one of them, as shown in table 4.1. The asynchronous events are generally triggered from external sources. In contrast, the synchronous events are triggered periodically.

Event	System Response	Source	Type
Luminosity detector OFF	Power the lamp	Environment	Asynchronous
LED failure detector ON	Notify remote system	Base station	Asynchronous
Motion detected	Turn on the lamp	User	Asynchronous
Requested to turn on the lamp	Turn on the lamp	Local system	Asynchronous
Camera sample	Image processing	Timer	Synchronous
Update system information	Send data to remote system	Local system	Asynchronous

Table 4.1: Base station events.

4.1.2 Use Cases

The base station use cases are presented in figure 4.1. A street passerby, a car or a pedestrian, can interact with the base station by moving in the vicinity of the lamppost, triggering it's motion detector, or by clearing a parking space.

When movement is detected, the base station lights up the lamp and requests to the neighbor lampposts to turn on their lamps. The opposite can also happen, when a neighbor local system, with the lamp already on, requests the base station to turn on its lamp. At the same time, in both situations, the information that the lamppost was activated is sent to the remote server. Since the base station is the "primary" station of the network, a third scenario can be put, when there is a local system requesting the base station to turn on the lamp of that local system neighbor lampposts.

Moreover, the base station is frequently doing image processing through the capture of camera frames. So when the street passerby clears a parking space, the system will detect that, sending that information to the remote system.

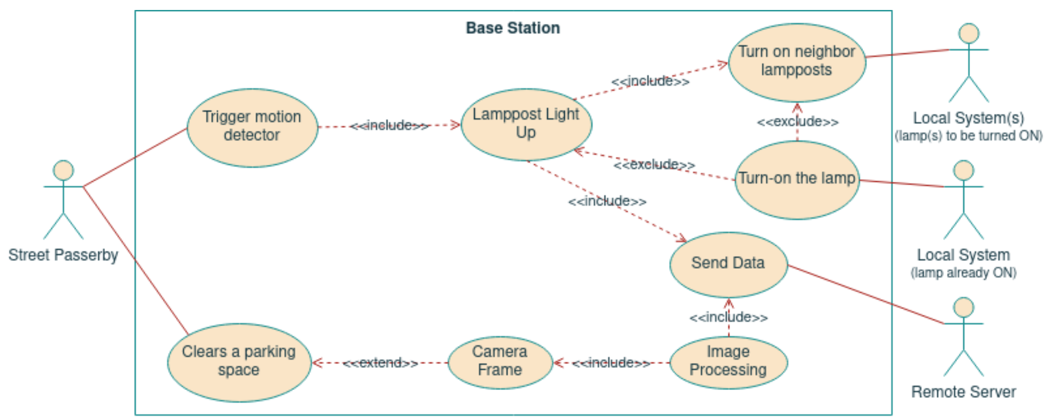

Figure 4.1: Base station use cases.

4.1.3 State Chart

In figure 4.2 its represented the state chart of the base station. It initiates with the system configuration, initializing all subsystems inside the base station, as the Wi-Fi communications management, sensors data acquisition, image processing. After that, the system enters an idle state.

To do the sensors data acquisition, it is used a sample period, that periodically triggers the execution of the function "SampleSensors", detailed in figure 4.3. When the base station is requested to turn on its lamp, the lamp is turned-on and a timeout is started, named "turn off time" on the diagram. This timeout makes sure that the lamp stays on for a predefined period of time, after being triggered for being on. To do the image processing, it is also used a sample period to get image frames through the camera. If there is an available parking space detected, that information is sent to the remote server, as well as when the lamp is turned on or off, or when a LED failure is detected.

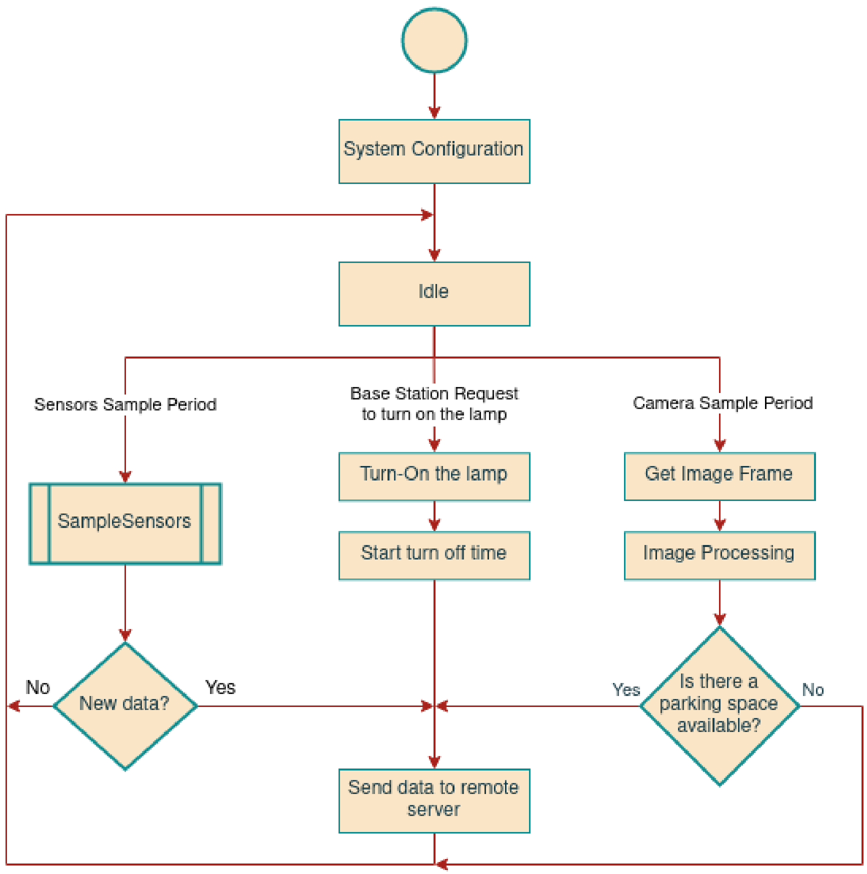

Figure 4.2: Base station state chart.

Sample Sensors

The sampling of the sensors is represented through the state chart detailed in figure 4.3.

Firstly, the LED failure detector is checked. If it is on, means that is detecting that the lamp has a failure, if not, the other sensors can be checked.

When low luminosity conditions are detected, through the luminosity sensor, the lamp is powered on, putting the lamp at a predefined minimum bright level. If motion is detected, the lamp is turned on to its maximum bright level, and a timeout is started, as explained before. Besides that, the base station requests the neighbor lampposts to turn their lamps on. When motion is not detected, it is checked if the timeout for the lamp light being on has already ended. If that is true, the lamp is turned-off.

Note that, regarding the lamp control, one will use "turn on" to represent the lamp bright transition from minimum bright level to maximum bright level, and use "turn off" to represent the opposite, the transition from maximum bright level to minimum bright level. The lamp is only off when low luminosity conditions is not verified, i.e, during the day.

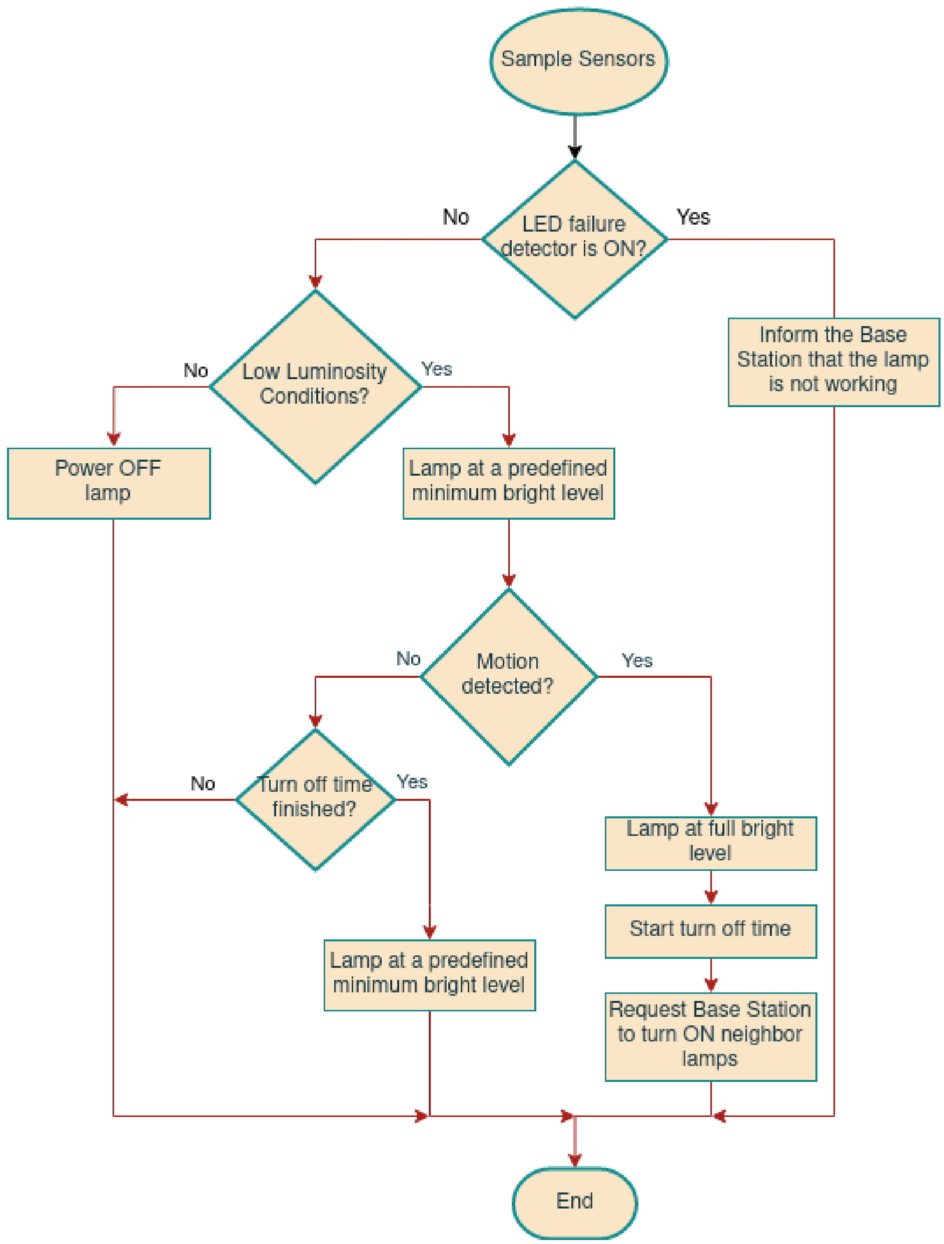

Figure 4.3: Sampling of the sensors state chart.

4.1.4 Sequence Diagram

In figure 4.4 it is shown the base station sequence diagram. When a street passerby triggers the motion detector, the base station turns on its lamp, and at that moment that information is updated in the remote server. After that, the communication management of the base station is free to communicate with the neighbor local systems to turn on their lamps. If however no more movement is detected, the lamp turns off after a predefined time (turn off time), and again, the lamp status is updated in the remote server.

An alternative of an interaction with the base station is when a local system requests the base station to turn on its lamp, this being processed in a similar way to the previous example.

Finally, the base station can also be requested to turn on the neighbor local systems of the local system that is requesting that.

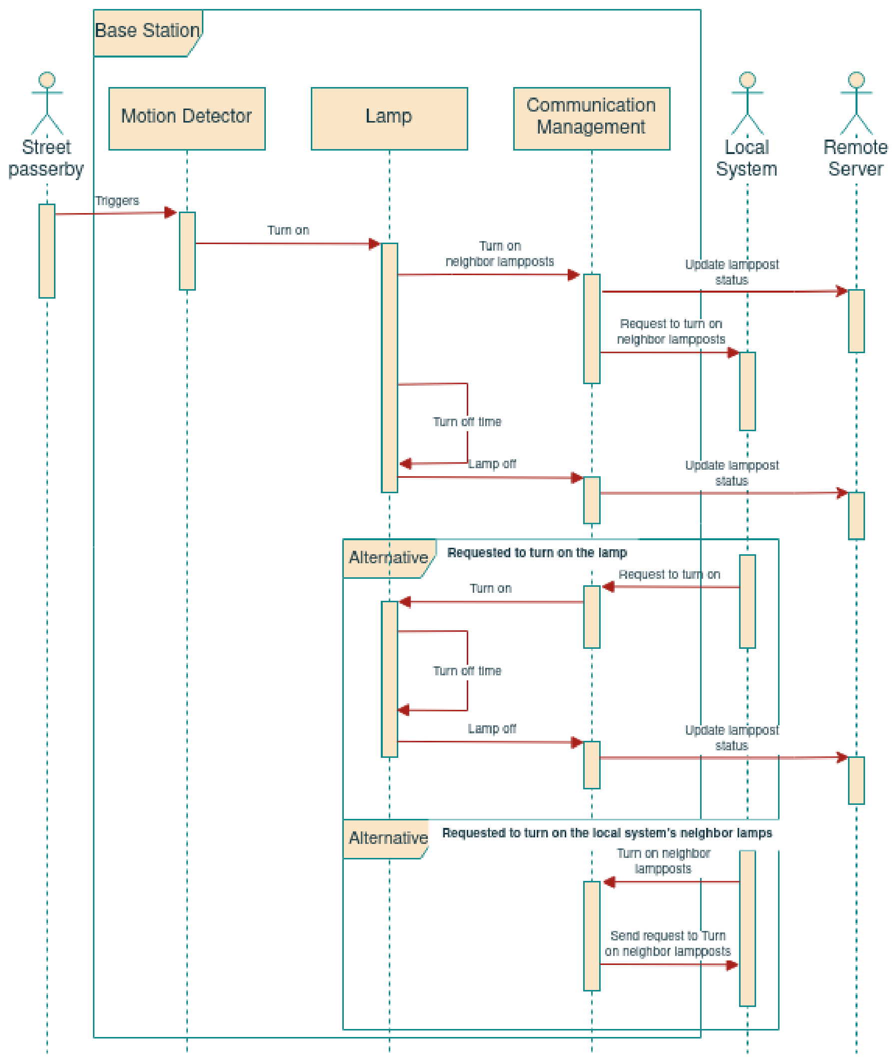

Figure 4.4: Base station sequence diagram.

4.2 Local System

The local system's analysis is very similar to the base station analysis. Comparing to the base station, this system doesn't implement the parking spaces detection, since it doesn't have a camera, and only communicates with the base station. As in the base station, one can say that this is a passive system since it is most of the time waiting for something to happen.

4.2.1 Events

Listed in the table below, table 4.2, are the main events that will occur in the local system and will affect its behavior.

Event	System Response	Source	Type
Luminosity detector OFF	Power the lamp	Environment	Asynchronous
LED failure detector ON	Notify remote system	Local system	Asynchronous
Motion detected	Turn on the lamp	User	Asynchronous
Requested to turn on the lamp	Turn on the lamp	Base station	Asynchronous
Update system information	Send data to remote system	Base station	Asynchronous

Table 4.2: Local system events.

4.2.2 Use Cases

The local system use cases are represented on figure 4.5. Like the base station, a street passerby, can interact with the local system by moving in the vicinity of the lamppost, triggering it's motion detector.

When movement is detected, the lamp is turned on and requests the base station to turn on the local system's neighbor lampposts. At the same time, the information that the lamppost was activated is sent to the base station, for this to send to the remote system.

Also, the local system can be asked, by the base station, to turn on its lamp.

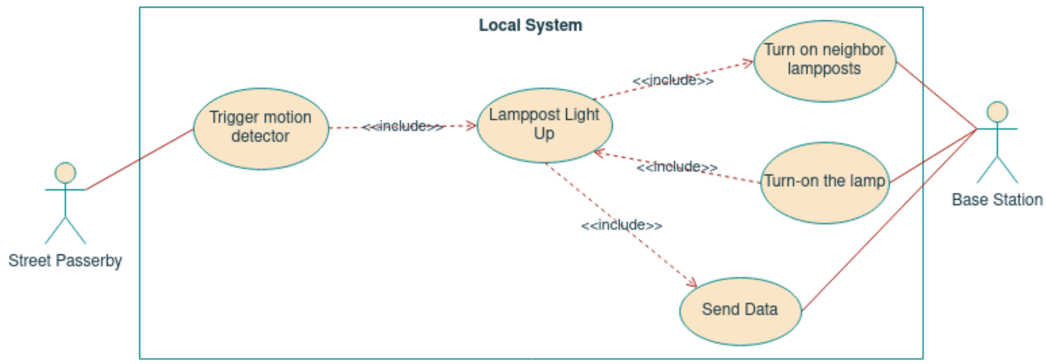

Figure 4.5: Local system use cases.

4.2.3 State Chart

In figure 4.6 is represented the state chart of the local system. After the system configuration, which initializes the wi-fi communication management, sensors data acquisition, the system enters an idle state. To do the sensors data acquisition, like in the base station, it is used a sample period, that periodically triggers the execution of the function "SampleSensors", presented previously, in figure 4.3. When the local system is requested by the base station to turn on its lamp, the lamp is turned-on and a timeout is started (turn off time, as mentioned before). The lamppost status is then sent to the base station, in order to get to the remote server.

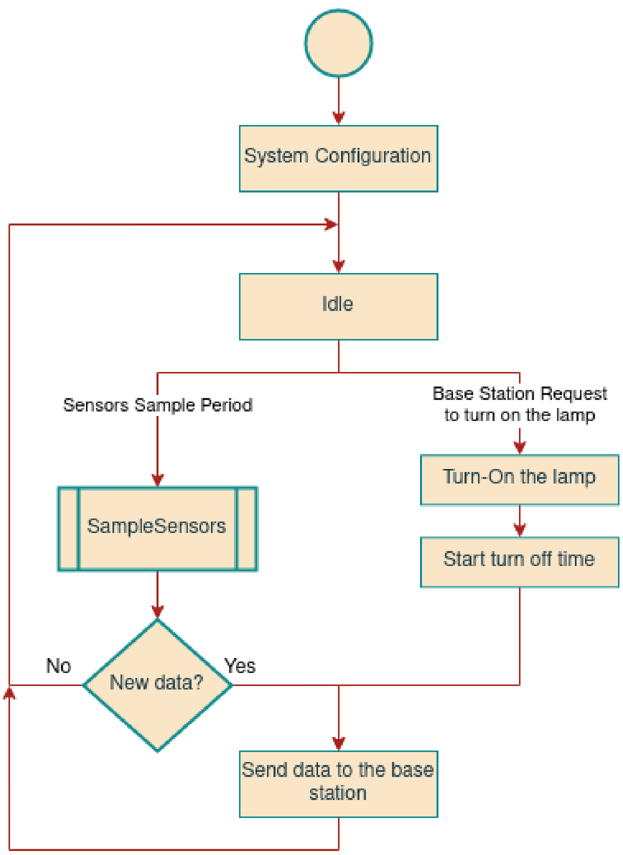

Figure 4.6: Local system state chart.

4.2.4 Sequence Diagram

The sequence diagram for the local system is represented in figure 4.7. Again, this diagram is analogous to the one shown on the base station (figure 4.4), having the differences that the local system only communicates with the base station, so any request that the local system wants to make to another local system has to go through the base station, and, due to that, the local system doesn't have the power to request another local system to turn its lamp on.

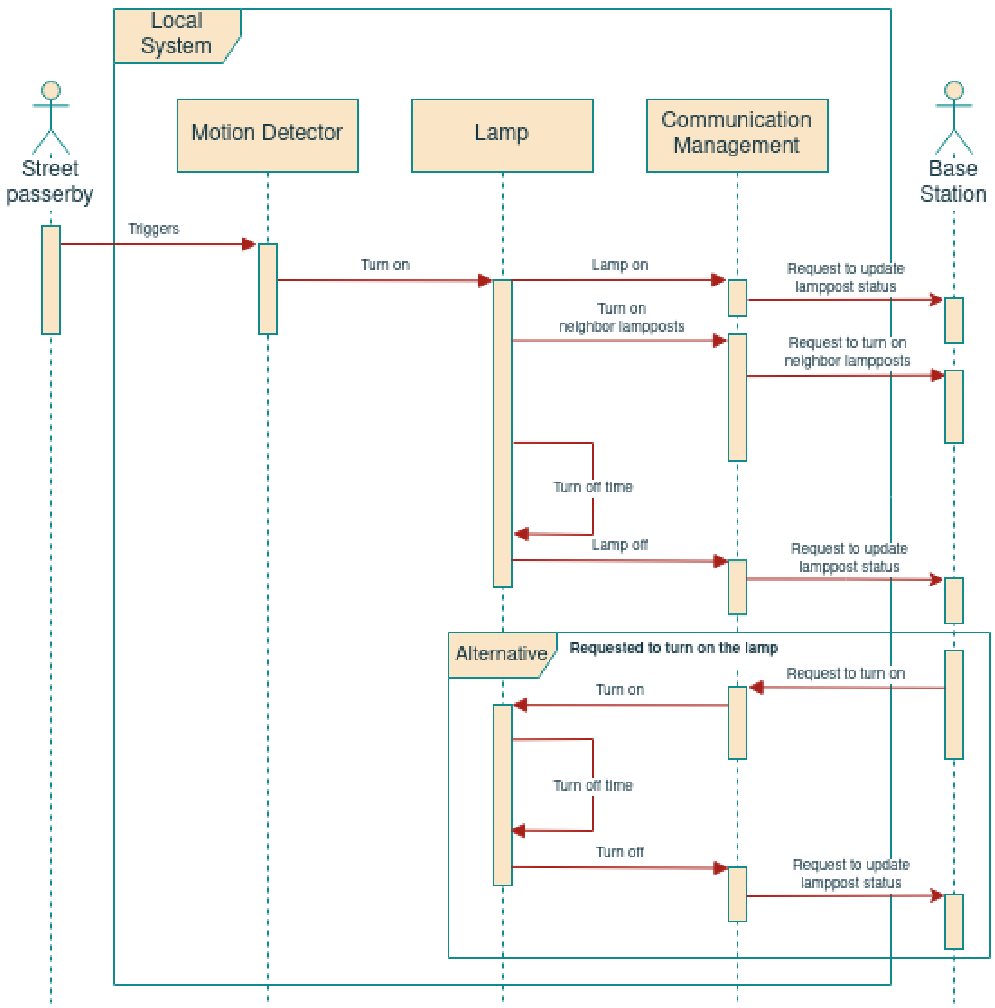

Figure 4.7: Local system sequence diagram.

4.3 Remote System

4.3.1 Events

Event	System Response	Source	Type
Login	Show application main screen if successful	Operator	Asynchronous
Obtain geolocation	Request device geolocation	Mobile device	Asynchronous
App notification	Notifies the operator about the lamppost status	Remote Server	Asynchronous
Register operator	Add operator information to databas	Operator	Asynchronous
Modify lamppost	Update lamppost information to database	Operator	Asynchronous
Register lamppost	Add lamppost information to database	Operator	Asynchronous
Insert location	Show parking spots	User	Asynchronous
Obtain geolocation	Request device geolocation	Mobile Device	Asynchronous

Table 4.3: Remote system events.

4.3.2 Use Cases

4.3.3 State Chart

4.3.4 Sequence Diagram

4.4 Estimated Budget

In table 4.4 is shown the estimated budget of a base station, excluding the external casing of this system.

Product	**Price(€)**
Raspberry Pi 4B	63,50
Industrial power supply 12 V	5,00
Video camera	8,86
Motion detector	4,60
Luminosity sensor	1,69
LED lamp 12 V	3,63
Driver (MOSFET)	1,00
Basic Eletronic Components	5,00
Total	**93,28**

Table 4.4: Estimated budget.

4.5 Task Division and Gantt Chart

In figure 4.8, is represented the Smart Street Lighting project schedule in form of a Gantt chart.

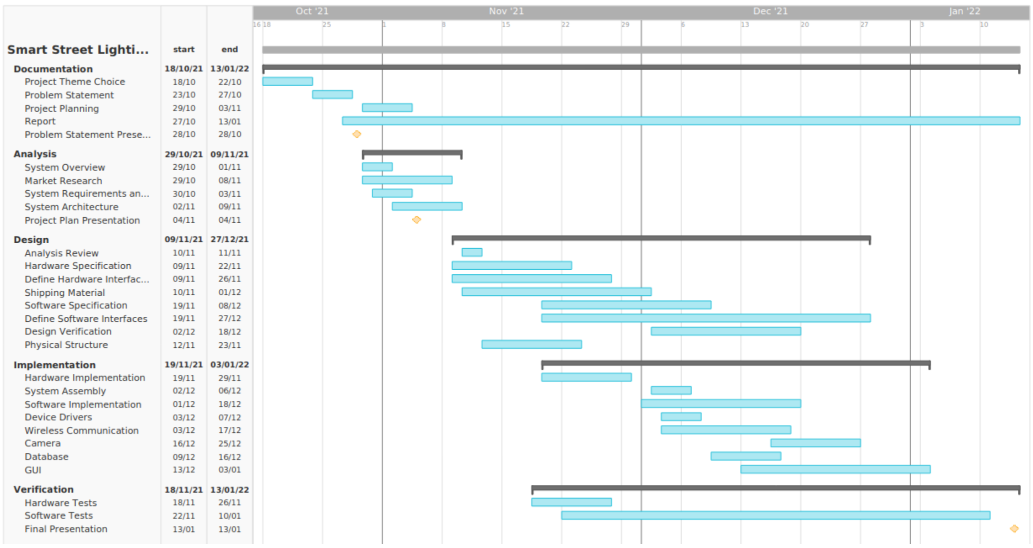

Figure 4.8: Gantt chart.

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