ASHESI UNIVERSITY

DESIGN AND CONSTRUCTION OF AN IOT-BASED

RETROFITTING UNIT

FOR STREETLIGHT MONITORING

CAPSTONE PROJECT

B.Sc. Computer Engineering

Ted Otchere Asare

2021

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CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Computer Engineering.

Ted Otchere Asare

2021

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:

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Candidate's Name:

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Date:

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I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University.

Supervisor's Signature:

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Supervisor's Name:

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Date:

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Acknowledgements

I cannot express enough thanks to my supervisor, Mr Francis Gatsi, whose tremendous encouragement and academic advice helped me through this capstone project.

I am grateful to the Engineering department and faculty, who have also provided guidance and shared ideas for this project.

Abstract

Streetlights in many parts of Ghana are manually controlled or have circuitry designed to switch the light at preset times. While these configurations allow the streetlights to provide lighting at night, there are cases where the lights remain on during the day when not needed. Due to this problem, electrical energy is wasted, and unexpected costs are incurred. In other cases, the streetlights may become faulty without the notice of authorities or technicians, and this problem may affect the safety of road users at night. This project seeks to retrofit intelligence to streetlights to gather insightful data, monitor and control streetlights, and reduce the energy consumption of streetlights in communities. The project explores a low-cost, energy-efficient system that allows streetlights to communicate in a network and transfer data required for remote monitoring and control of streetlights. The monitoring system implements the management of streetlights through a web application interface that enables an administrator to monitor, control and analyze data from any internet-enabled device. The results from the prototype implementation prove that the streetlight monitoring system is about 80.1% energy efficient when the light source is dimmed to about a fifth of its total capacity when the roads are not busy. The results also demonstrate the prototype fulfils the design requirement to monitor malfunctioning lights by alerting the administrator, technician or user to control or visit the streetlight site for servicing remotely. The testing of the various system components demonstrated the feasibility, functionality, and security of the streetlight monitoring system.

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Chapter 1: Introduction

1.1 Background

Streetlights play a significant role in communities and streets. Streetlights tend to beautify streets and neighbourhoods by providing lighting at night-time. Fundamentally, street lighting helps road users to be able to navigate the roads easily at night. More importantly, streetlights improve safety and security for pedestrians, motorists, and other road users. Proper street lighting is imperative because communities depend on them to extend the day's activities.

However, streetlights in most communities either do not always operate when they are needed to or do not work correctly to illuminate streets and cities. Traditional street lamps were designed to be controlled by a central switch that control streetlights in a particular area. This means that the streetlights would be difficult to operate when the streetlights could not be manually accessed, such as during bad weather situations. Some newer streetlights use a timer system or photocells to turn the streetlights on or off, depending on the time of the day. Even though these streetlights reduced manual control, these streetlights follow a strict time pattern to operate without regarding other times of the day. More recently, a more intelligent streetlight function uses sensors to detect how dark an area is. Despite these improvements, streetlights appear to be dumb; they cannot see changes and interact with the environment.

The design of streetlights makes them ineffective and unreliable in communities. Overly lighted streetlights and streetlights that follow a strict time pattern, which stays fully on when not needed, tend to be significantly energy inefficient. Streetlights that remain on longer than needed tend to waste a lot of power and generate a lot of heat without doing any beneficial work. Aside from the energy costs, unintelligent streetlights generate high carbon dioxide emissions to the atmosphere in communities, enlarging the carbon footprint in communities [1]. The most related issue to these problems is the inability to automate the control of streetlights intelligently. These problems influence the effectiveness of streetlights and the activities of pedestrians and motorists as it creates inconveniences for these road users at night [1].

Moreover, concerning maintenance, faulty streetlights or those that are likely to fail may go undetected. As such, repairs may be delayed while creating an unsafe environment for people in a community. On the other hand, faulty streetlights may remain on in the daytime or may not even function. These faulty streetlights cause significant energy wastage and incur high economic costs on the government [2].

1.2 Problem Definition

Faulty streetlights in communities either cause energy wastage or jeopardise the safety of road users at night. Crimes on the roads have become an increasingly alarming threat. Thieves and robbers commonly use dark spots to rob and harm people in communities. Additionally, poor street lighting is also one factor contributing to the high number of road accidents in communities today. Therefore, these problems highlight the need for an intelligent, energy-efficient and low-cost unit to monitor streetlights in communities.

1.3 Objectives

This project aims to design and construct an intelligent retrofitting unit deployed on existing streetlight infrastructure for monitoring and control using the Internet of Things (IoT). To address the highlighted problems, features like switching on or off and controlling the intensity of lighting automatically for energy saving would be incorporated in the design. Additionally, the unit design would implement the feature to allow communication to a central station. This communication would send information and alerts about the street light infrastructure's status to facilitate infrastructure maintenance and ensure anti-theft measures. To make the unit more intelligent and smarter, sensors would be deployed on the streetlight to monitor the number of vehicles that use the streets. All this information would then be passed to the control centre for valuable data analytics and processing to provide suitable and better street lighting at all times.

1.4 Expected Outcome of Work

This capstone project's expected outcome is to design and construct IoT prototype unit that can be deployed in a community street lighting system. The result of this project is to have a unit that can be deployed or replicated in a real-life setting with the following features:

- Intelligent
- Energy Efficient
- Low Cost
- Automatic control of the streetlight
- Communication to a control centre or base station

1.5 Scope of Work

The design, construction, and testing of this capstone project would be implemented on a smaller scale replicating the real-life setting. However, this project is designed to allow it to be deployed to monitor an existing street lighting system in communities and cities. As such, similar but more compatible components would be needed to implement this project in communities and towns.

Chapter 2: Literature Review

Regarding streetlight monitoring, scientists and engineers have used different approaches and technologies to improve street lighting systems. While most of the methods focus on using energy-saving means, these systems are built to provide good performance and effectiveness in communities. For example, the design in the paper by Chun et al. implements remote streetlight monitoring and control through a web interface and by use of SMS (Short Message Service) via wireless communication technologies like mobile General Packet Radio Service (GPRS) [3]. The paper by B. Kul implements a backup power supply to ensure continuous and effective streetlight control and monitoring at all times of the day [4]. The design also includes using the cloud to store data that can be easily accessed across devices. The design implementations by others are comparable to what this capstone project design seeks to adopt and improve.

The Internet of Things (IoT) adopts sensors and actuators to make the object "smart" to sense and detect changes in the environment by use of sensors and actuators. These smart objects' main features include a processing unit, sensors or actuators, a communication unit, and a power supply unit. As devices become more intelligent, the goal is to improve the devices' capabilities by reducing power consumption while increasing processing power and communication features.

The communication modules of IoT devices enable smart objects to communicate with each other over long distances. The desired features concerning communication include long-distance communication, ease of deployment, cost, reliability, speed and the effect on power consumption. Most of the work that others have done deploy communication technologies such as GPRS, Wi-Fi, Zigbee [3], [5], among others. Although the technologies used in the various designs reviewed are functional, there are a few limitations and design constraints that come with these technologies to provide streetlight monitoring. One of these constraints includes power consumption. Since IoT devices are usually battery-operated, power consumption is an essential factor for any IoT-related project. For instance, Wi-Fi consumes a lot of power for smart devices; for this, reason devices that use Wi-Fi are frequently charged or directly connected to power. In the same vein, the use of SMS to receive status information and issue commands would be expensive since network operator charges may apply. This highlights the significance of cost on the usability of technology.

Most scientists and engineers design the best way to bring about energy-saving technologies to prevent energy waste in our communities. The High-Intensity Discharge (HID) light bulbs used for traditional streetlights are energy-inefficient as they consume and waste a lot of power. Energy-efficient LEDs with a wireless sensor network provide streetlight monitoring and automation through energy-saving means [6]. With this capstone project, energy can be conserved by putting the retrofitting IoT unit in sleep mode when the smart device is not actively in use. When motorists and pedestrians hardly used the roads at times like dawn, the streetlights' light intensity could be set to a dimmed state or could be put off. In contrast, the lights at dangerous corners or spots that could be a hotspot for criminal activities could be left on to ensure the security of safety of road users who may be present.

Another feature that could be adopted in this capstone project is using a mesh network topology for communication among the devices from streetlight to streetlight to the central control centre [7]. A mesh network would allow leaf nodes to conserve energy or, better still, a mesh network would significantly reduce the sole dependence on one node to transmit data to all network nodes. Such a topology would accommodate higher amounts of traffic since each device can send or receive at the same time. Additionally, it would increase scalability. If there is a need to add another streetlight, another unit will not interrupt data flow among other smart devices in the network.

2.1 Existing Designs from Related Works

Before specifying this project's design details in the next chapter, similar projects must be reviewed to gain meaningful insights that could be implemented or avoided in this project.

The design of related projects implemented an improved control of streetlights using photocells and microcontrollers. Additionally, existing designs focus on power-efficient and environmentally friendly designs such as LEDs in place of high energy bulbs. While these designs improve on previous limitations, some shortcomings are related to the existing street lighting monitoring designs. For instance, access technologies like GSM and Wi-Fi consume a lot of power and have bandwidth limitations for communication. This project aims to adopt the most efficient design that would make the system efficient and effective.

Chapter 3: Design

This chapter provides details about the technical specifications and design decisions for the proposed system. This project's design is essential to guide how the final system has to work and what features and must be included in the system.

3.2 Use Case

The primary actors of this system's use case scenario are the system administrator at the control center and the streetlight technician.

A streetlight technician is tasked to perform maintenance services on streetlights at Adenta every two months. Until the technician visits the assigned streetlights for maintenance or a report is made by a passer-by, faulty streetlights remain unnoticed by the technicians and the system administrator. With the help of the streetlight monitoring system, the system administrator and technician can monitor faulty streetlights and control streetlights remotely from a control center. From the dashboard, the administrator can see if an individual streetlight is on or off at a particular time. A critical alert is delivered to all the users for on-site maintenance or remote management in the event of a critical issue, such as all streetlights on a specific street being off.

The system's users can achieve the desired results and obtain data from the streetlights from the hardware on the streetlight to the user interface. With the system's help, the administrator can save energy consumed by unmonitored and faulty streetlights.

3.2 Design Requirement

The design requirement entails the specifications that the system is supposed to meet.

Function

The system should be able to monitor and control the streetlights in a location. The unit should be deployed on a streetlight to manage and measure light intensity and communicate to a control station and other network nodes. Additional functionalities such as street surveillance, anti-theft measures, and using sensors to detect the number of cars that use the road are features to be also considered.

Target Customer

This project's target customer is a community or city with inadequate street lighting monitoring and control with the need to create a safe and convenient environment.

Performance

The product would be used on the streets, specifically on mounted streetlight that border streets in urban communities or other communities with few and distanced streetlights. The outcome would have to be low cost, easy to use, efficient, and durable.

Materials and Environment

The product should be made up of materials that would protect the smart device against harsh weather conditions. The product's material should also be a material that does not affect the functionality of other components like sensors and communication modules. The unit should be made up of environmentally friendly parts and materials to protect the environment.

3.3 Requirement Specification

This capstone project requires designing and constructing a retrofitting IoT prototype unit that can be deployed in a community street lighting system. The result of this project is to have a unit that can be deployed or replicated in a real-life setting with the following features:

- Intelligent
- Energy Efficient
- Low Cost
- Automatic control of the streetlight
- Communication to a control centre or base station

3.4 Design Decisions

The first design decision concerns the underlying elements needed to make up the smart object – a microcontroller development board. The microcontroller would allow for the intelligent device to interface the sensors and actuators, a communication module, processing unit and power that the system would need to function. With the smart device's help, the streetlights can be connected to the internet and the streetlight monitoring network.

The favourable microcontroller device should be less expensive, power-efficient, available on the market and easily compatible with the proposed system design. A Pugh analysis determines the best microcontroller choice and best alternative based on the preferred criteria.

Table 3.0.1: Pugh matrix for microcontroller selection

Microcontroller/ Development Board		Weights	NodeMCU ESP32	ATMEGA 328P (Arduino Uno)	Raspberry Pi 4b	NXP FRDM-KL25Z
Criteria						
1	Cost (Less Expensive)	3	+4	+5	+1	+2
2	Compatibility	2	+2	+1	0	0
3	Power Consumption	5	+4	+3	+1	+3
4	Availability	4	0	0	0	0
Total			**+36**	**+32**	**+8**	**+21**

Considering the Pugh matrix above, the best option from the results is the NodeMCU ESP32 board due to its compatibility and features for the project. The next best alternative appeared to be the low-cost ATMEGA 328P microcontroller option coupled with the required sensors and components for the project.

3.4.1 NodeMCU ESP32

The NodeMCU ESP32 is a low-power, low-cost microcontroller board with numerous peripheral interfaces that support multiple IoT applications. The ESP32, the ESP8266 microcontroller's successor, comes with an integrated Bluetooth and Wi-Fi module, 520 KiB SRAM and a 32-bit Xtensa microprocessor that can execute up to 600 MIPS [8]. It also features about 20 Analog-to-Digital Converters (ADC) and Digital-to-Analog Converters (DAC) interfaces that support a large set of sensors compatible with the microcontroller.

Figure 3.1: NodeMCU ESP32 (ESP-WROOM-32) microcontroller development board

Source: Adapted from [8]

The following design idea concerns IoT connectivity. The IoT access technology is the technology that connects IoT-enabled devices and other devices such as routers and gateways to share IoT data across an IoT network. For this streetlight monitoring system, the most suitable access technology should be one that fits the design requirements. The access technology should be inexpensive, has a long-range for connectivity, has lower consumption, reliable, and available and supported in the country. With the help of a Pugh matrix, the best option among the IoT access technology that matches the required criteria can be determined for selection.

Table 3.0.2: Pugh matrix for access technology selection

IOT Access Technology		**LoRa Technology**	**Wi-Fi**	**Bluetooth**	**Zigbee**	**NB-IoT**
Criteria						
1	Cost (Inexpensive)	+1	0	+1	+1	+1
2	Range	+3	+1	0	+1	+2
3	Power Consumption	+1	0	+1	+1	+1
4	Availability	+1	+3	+2	+1	0
5	Reliability	+2	+2	0	+2	+2
Total		**8**	**6**	**4**	**6**	**6**

From the results, LoRa scored more points in relation to the design requirements in the Pugh Matrix. The next best access technology alternative was a tie between Zigbee and NB-IoT. Among these two access technologies, Zigbee is more preferred because NB-IoT mobile technology is not available in Ghana; therefore, Zigbee would be the ultimate alternative to LoRa. The power consumption and range of Wi-Fi do not match the requirements of the deployment of this monitoring project, but its use could suffice a prototype design of the capstone project. On the other hand, Bluetooth can connect a small number of devices (about a dozen devices) and has a short connectivity range, making it incompatible with the streetlight monitoring project.

3.4.2 LoRa Technology

LoRa is a long-range, low-power wireless access technology used with the LoRaWAN protocol used for various innovative IoT applications in cities, agriculture, healthcare, and industrial domains. The compatibility of the LoRaWAN and LoRa technology with lossy, low power networks has made it possible for advancements in many IoT use cases [9].

One of the key features of the LoRa technology is the long-range for connectivity of devices. A single LoRa gateway device can connect about a hundred devices that may be up to 48 kilometres apart in rural areas for long-range communications. The long-range access technology can penetrate through tall buildings and obstacles in urban communities. As a result, LoRa technology supports a high capacity of data transmissions from many devices on an IoT network to a single base station [10].

LoRa requires minimal power as a communication technology. This feature reduces battery replacements in battery-operated smart devices. The low power consumption of the LoRa technology can extend battery life for about ten years [10]. These features significantly reduce maintenance costs and contribute to the popularity of LoRa in IoT applications. LoRa is also compatible with other small power sources like solar power sources because of its low power requirements.

LoRa uses end-to-end AES128 encryption to provide secure communication channels in a network. LoRaWAN includes encryption and authentication at various layers in an IoT network for complete authentication, integrity and confidentiality. In the back end, LoRaWAN uses two layers of symmetric cryptography to share network and application session keys between end devices, network server, gateways and the application layer. This design enables LoRaWAN to secure and provide data privacy at the application and network levels [11].

3.4.3 Streetlight Monitoring System Design

The streetlight monitoring project would connect many streetlights along streets in a network to share data and be controlled. Each streetlight unit along a road would be a node in the IoT network with the ability to share data and be controlled remotely. For better identification, each streetlight would have an ID to distinguish each streetlight from the others, allow easier identification for analysis and fault detection.

Each streetlight node would be a smart device that would enable communication through a LoRa transceiver module on each streetlight. A single LoRa gateway can connect at least about a thousand LoRa modules in a 15 km – 20 km range in a massive deployment. The LoRa gateway serves as an intermediary or central device in the LoRaWAN network that allows data to be sent to the cloud over an IP network.

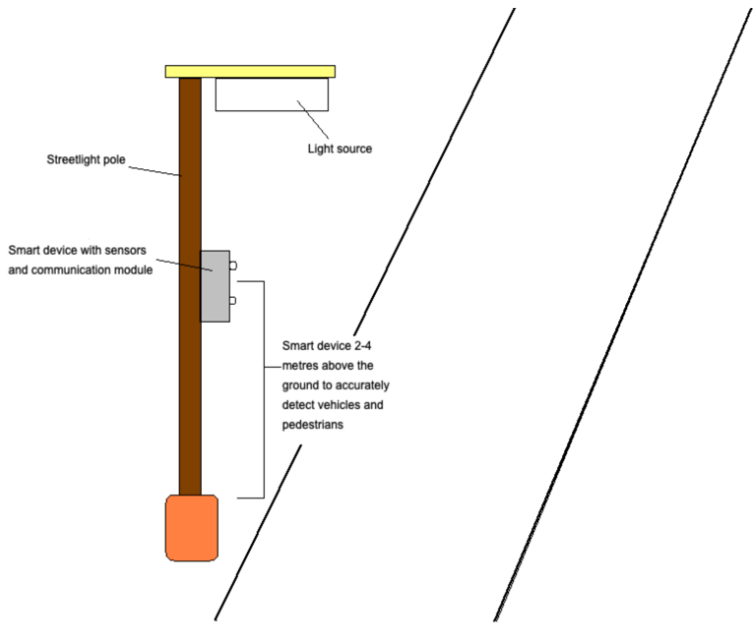

Figure 3.2: A single streetlight in the streetlight monitoring system

The retrofitting smart device would be placed 2-4 meters from the ground on the streetlight pole. This design would enable the sensors to detect passers-by and vehicles while ignoring wandering animals accurately. The detection would cause the unit to dim the brightness of the streetlight at open locations after midnight or less busy hours to conserve energy. Many of the existing streetlights use photocells to turn on at night and off during the day. However, this project's design would explore Pulse Width Modulation generated by the smart device to dim the light source.

To dim the light source and conserve energy at inactive hours, an ultrasonic sensor would be included in the smart device circuit to reduce the brightness of the streetlights when the distance measured by the sensor is in range of a vehicle or a passer-by. If the ultrasonic sensor does not detect any obstacles in range after a while, the unit will dim the light source to save energy. A photoresistor sensor would also measure the light intensity of the light source to record data at the base station to allow details like faulty streetlights, duration of on-time of the streetlights, and busy hours of streets at a specific location, among others, to be analysed.

3.4.4 Power

The smart device would share the same power source as the streetlight unit. Additionally, the smart device's backup power source would be a small solar-rechargeable battery to supply a maximum of about 4.5 V to 5.5 V to the microcontroller and sensors. The backup battery power source is to serve as redundancy and keep the smart device alive to send data to the control station when a streetlight is faulty.

The connection to the streetlight's main power feed would require a step-down transformer to effectively reduce the voltage from the main supply from about 230 V to 5 V for the smart device circuit. The number of turns in the primary and secondary coils of a step-down transformer can be calculated with the following equation, where $N_p > N_s$:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

$Where,$

$Vp\ is\ the\ input\ voltage\ ot\ the\ voltage\ in\ the\ primary\ coil$

$Np\ is\ the\ number\ of\ turns\ in\ the\ primary\ coil$

$Vs\ is\ the\ output\ voltage\ or\ the\ voltage\ in\ the\ secondary\ coil$

$Ns\ is\ the\ number\ of\ turns\ in\ the\ secondary\ coil$

However, the transformer would output Alternating Current (AC); therefore, the AC has to be converted to Direct Current (DC). A rectifier with a diode bridge circuit can be used to convert the AC to DC. A voltage regulator circuit arrangement can be then used to stabilise to the required voltage, as shown in the circuit below.

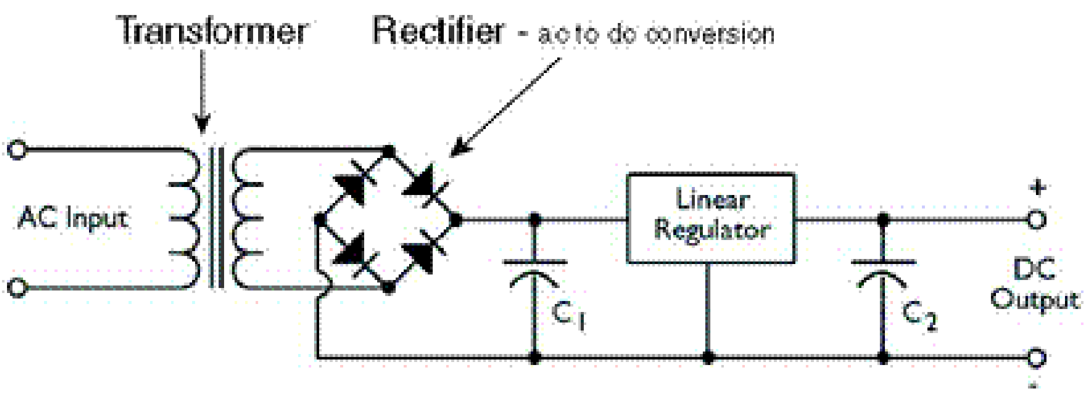

Figure 3.3: Main power feed connection circuit

3.4.5 IoT Network

The IoT network design for this project comprises a star topology with a LoRa gateway as the central node connected to streetlight nodes with LoRa as communicating devices. The LoRa gateway device would be placed on a midpoint streetlight node in the streetlight network such that all the nodes in the range can connect to the gateway.

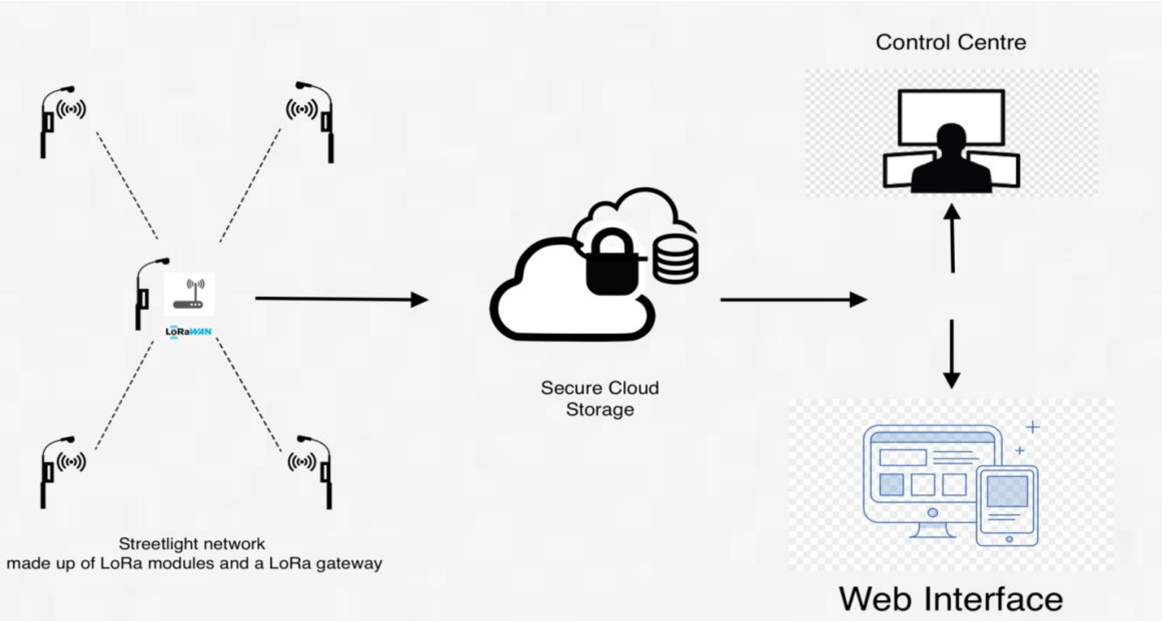

Figure 3.4: IoT network design

The streetlight nodes store data in a secure cloud database over the IP network provided by the gateway. At the control centre, the data can be monitored and analysed. The information can also be accessed via a web interface on devices. The data of interest for this project is data about how long a particular streetlight at a location has been on, when it came on and when it went off. Such data would help the remote monitoring unit tell if a streetlight is faulty and how to make the streetlights more energy efficient.

To avoid network congestion in the constrained IoT network, data would have to be transmitted periodically to control network traffic in deploying this monitoring system.

The data from the sensors stored in the database can be pre-processed for every data captured in about 10 minutes at the node to reduce network congestion.

The block diagram representation of the system shows the connections between the main components of the monitoring system.

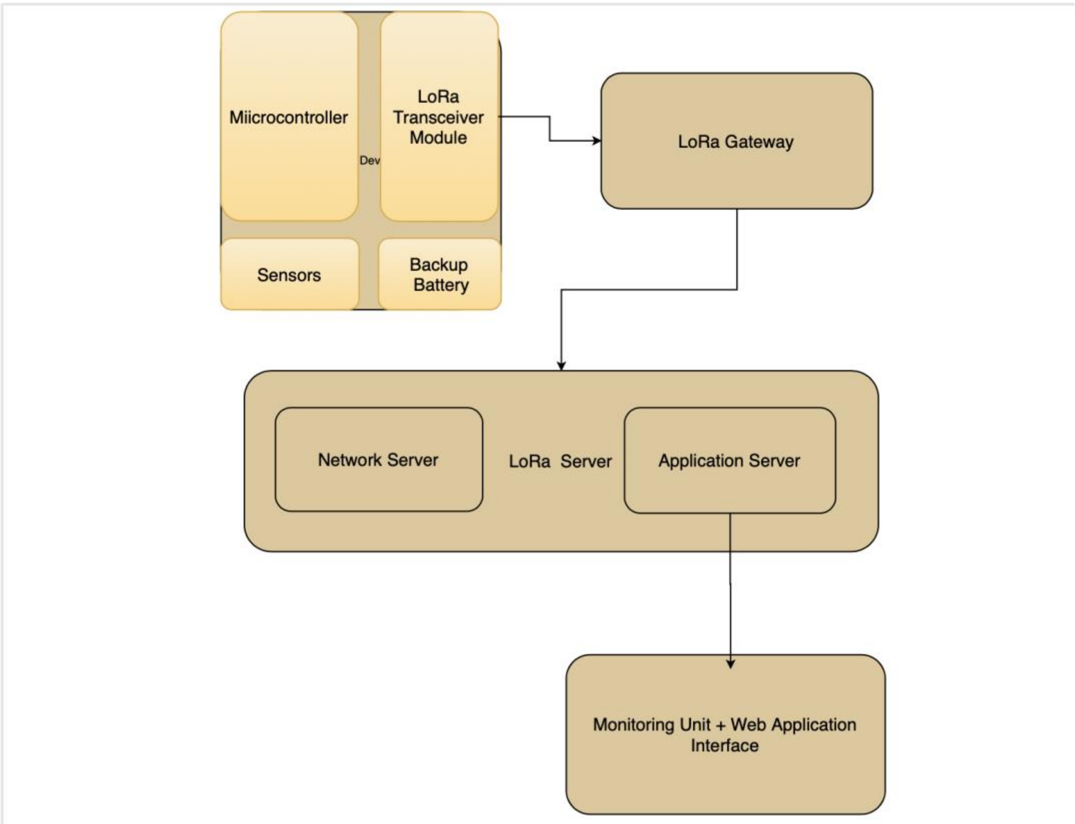

Figure 3.5: Block diagram of the design of the system

3.4.6 Prototype Design

Figure 3.6 illustrates the schematic design of the circuit for the smart device node on the streetlights. The schematic in Figure 3.6. shows the connections among the various electrical components of the retrofitting unit.

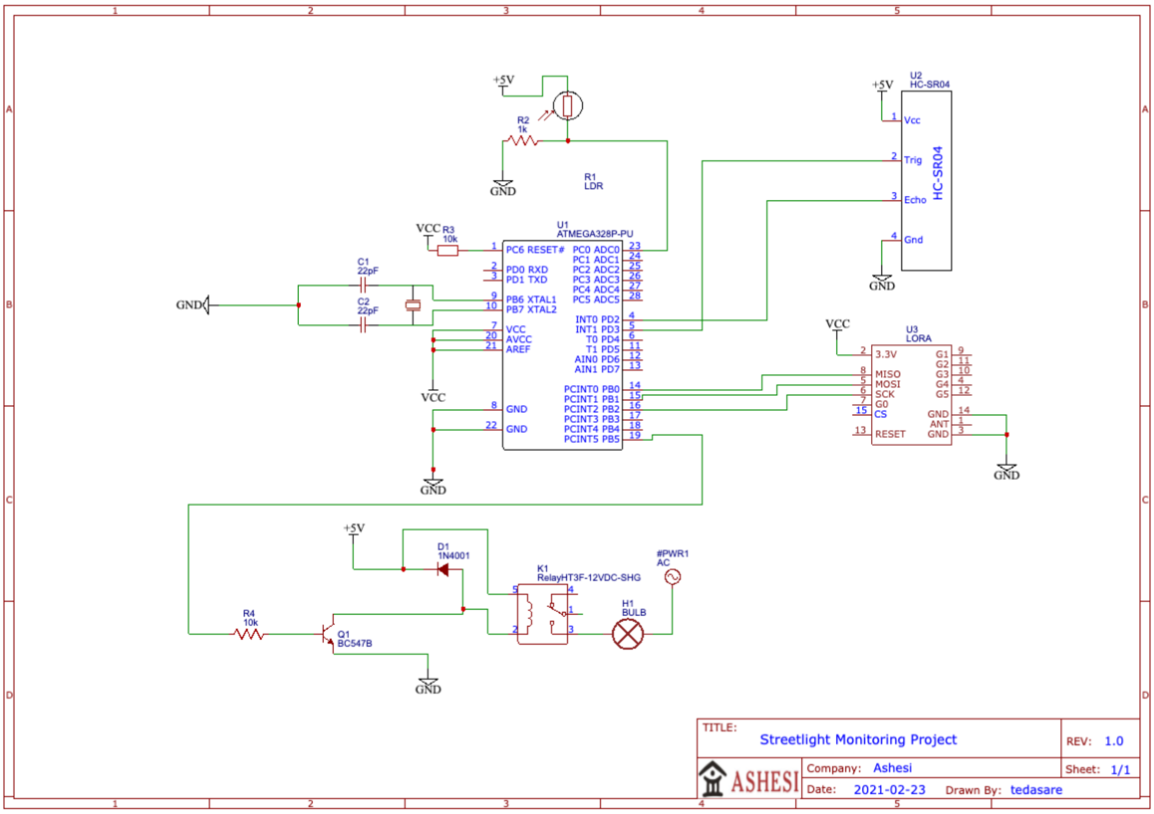

Figure 3.6: Schematic of the smart unit

Chapter 4: Implementation

4.1 Overview

This chapter provides the details and procedure involved in executing the design decisions for the capstone project. A prototype of the systems proposed in the design would be developed as valid, reproducible and expandable units. Also, the systems and components for an actual deployment would be discussed and referenced.

4.2 Prototype

The IoT retrofitting streetlight monitoring system prototype comprises a smart device node, a wireless access network, database, dashboard, and control center. Some alternative designs that were highlighted in the Design chapter were incorporated in the prototype design for this capstone project due to constraints. The following sections of this chapter describe the different parts of the prototype, the reasons they are present in the prototype, and how they collectively work together to meet the project's problem specification and design requirements.

4.3 Alternative Prototype Designs and Constraints

In this prototype, the IoT smart device comprises a NodeMCU ESP32 board, an ultrasonic sensor, a photoresistor, and LEDs as a light source. Given this project's low-cost requirements, the ATMEGA 328P microcontroller would be a good option for the intelligent device. However, it would require a few components like 22 pF capacitors, a 16 MHz crystal oscillator to provide a clock input for the microprocessor, and a voltage regulator like the L7085 regulator to supply a fixed power supply of 5V to the ATMEGA328P, as shown in Figure 4.1.

Regarding the wireless access technology and IoT network, the more affordable and available alternative was used, a home Wi-Fi network in place of the long-range LoRaWAN access technology network. As mentioned earlier, a Wi-Fi network can be used to prototype and connect a small-scale streetlight monitoring system. However, the LoRa Technology would allow long-range communication from the streets to the remote-control center on a larger scale.

4.4 Smart Device – End Node Implementation

The ESP32 board was used for this prototype because of its earlier mentioned features, which are compatible with this project. The ESP32 board's internal Wi-Fi module allows the board to be used both as a soft access point and in station mode for deploying web servers and connecting to other Wi-Fi networks at the same time. The prototype also uses the ESP32's Real-Time Clock (RTC) to track the day's time for streetlight control and monitoring. The ESP32 is powered by USB, a battery or a breadboard supply to supply 3.3V to its input voltage pin.

An LDR (photoresistor) was used to measure and record the light intensity from the light source. An HC-SR04 ultrasonic sensor was also used to measure and record distances of approaching vehicles and passers-by. The other electrical components that make up the prototype are LEDs and current-limiting resistors for the sensors. Both sensors are powered with 3.3 V from the ESP32. The trigger and echo pins of the HC-SR04 sensor are connected to the GPIO pin. The LDR, on the other hand, was connected to the ADC1 pins, which are the functional pins when the Wi-Fi module of the board is in use.

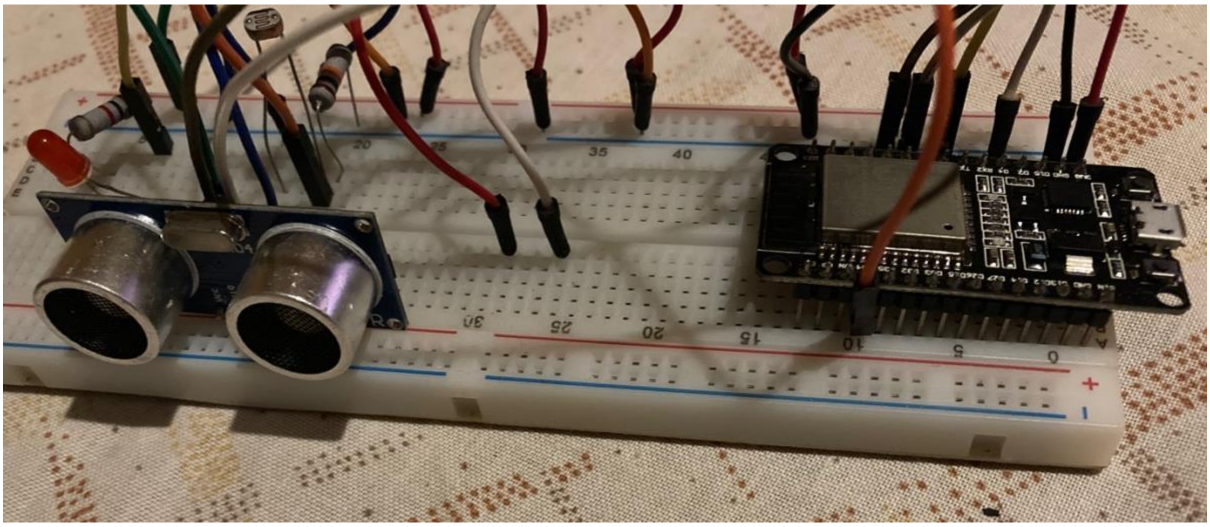

Figure 4.1: Breadboard circuit of smart device prototype

The light source by dimmed by using the Pulse Width Modulation (PWM) method. The PWM signal is generated by one of the PWM pins of the ESP32. PWM reduces the average power used by providing a signal that is high or on for a fraction of a single period. The duty cycle refers to the period or duration of which the signal is high within a total period, as a percentage. Therefore, at a 20% duty cycle, the light source appears to be dimmed. The frequency is maintained at 5 kHz to prevent flickering of the light source.

This hardware prototype design used for the project comprised fewer components and parts primarily because of the inherent features of the ESP32, making the end node device inexpensive and compact.

4.5 Software Implementation

The ESP32 was programmed using the Arduino IDE with some libraries like the ESP32 library, Wi-Fi library, Time library, Mail Client library, and Asynchronous Web Server/TCP libraries.

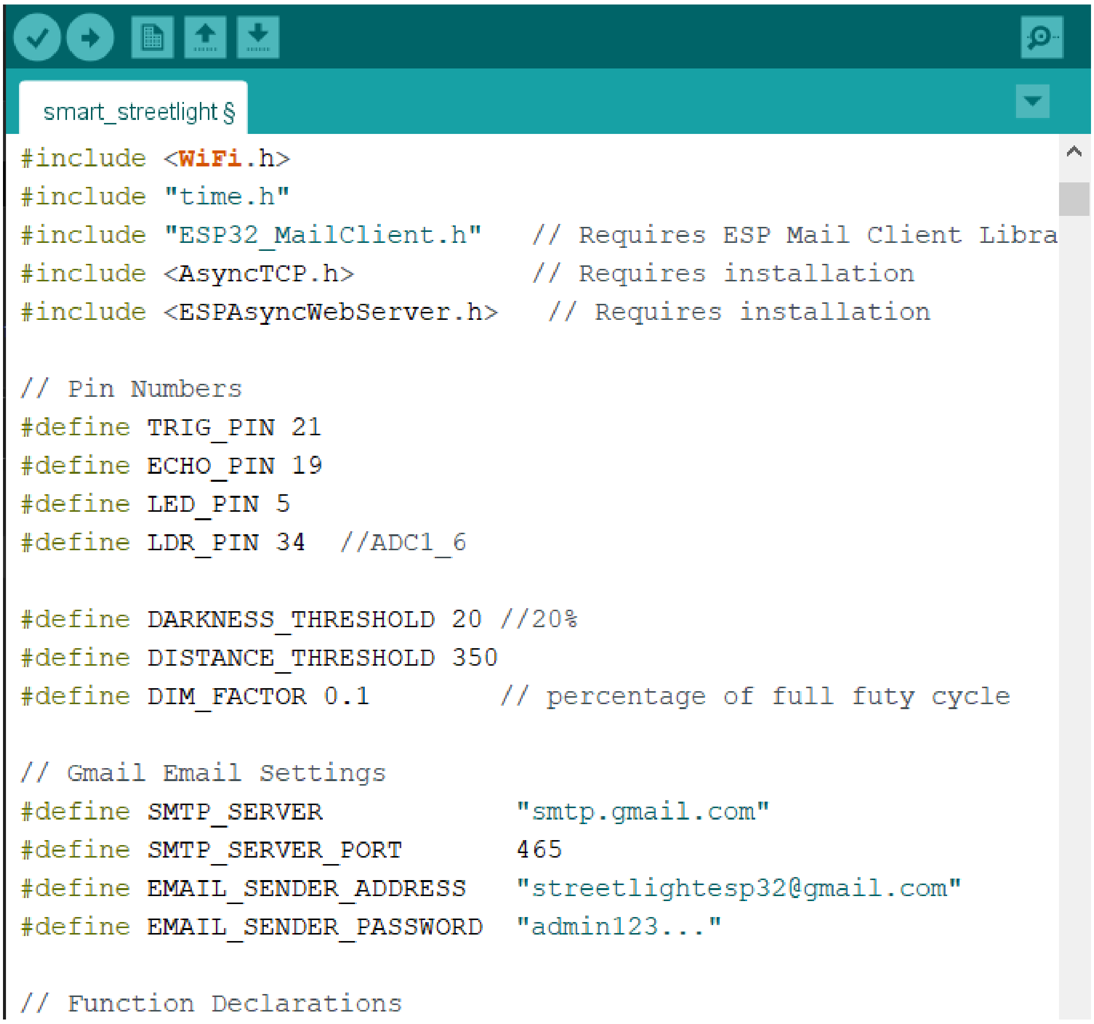

Figure 4.2: Arduino IDE

The Arduino IDE's serial monitor was used to display information and debug the sensors and the code that works on the development board. The Serial monitor prints to the IP address of the ESP32 board, recordings from the sensors, e-mail status, and other relevant information used to implement the code for the smart device.

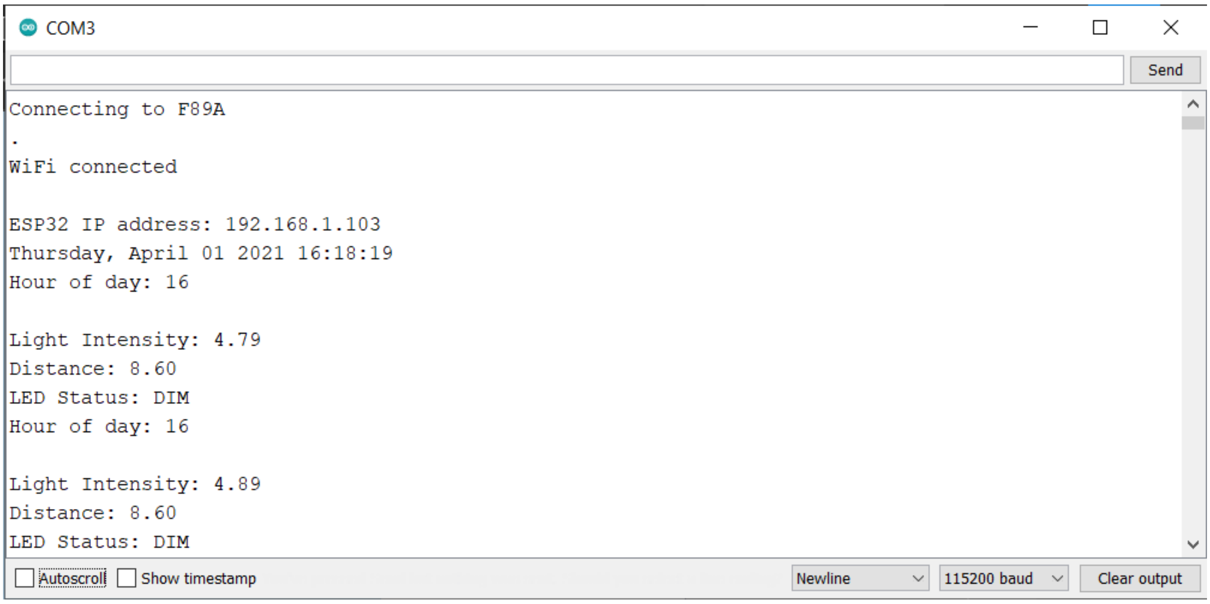

Figure 4.3: Serial monitor of the Arduino IDE

To avoid network congestion and reduce the amount of data transmitted over the network, some processing is carried out by the ESP32 at the node. Additionally, to reduce the amount of data stored, the smart device does not transmit data to the database instantly but periodically. This practice is not problematic because the streetlight data has very little variance over a short period.

4.6 Wi-Fi and Web Server Setup

The Wi-Fi setup requires a network SSID and a password. The command `WiFi.begin(ssid, password)` starts the connection to the specified Wi-Fi network. To allow time for authentication and the connection, the code stays in a while loop until a connection is established to the Wi-Fi network.

The intelligent device was set up as a webserver and a soft access point to allow other authorized devices on the network to access the monitoring interface. `AsyncWebServer server(80)` creates an AsyncWebServer object from the library on port 80 (HTTP). The asynchronous web server was deployed to serve requests asynchronously without interfering with the code in the loop or waiting for requests. This feature makes the ESP32 work as a standalone server to instantly serve requests from an administrator to control a streetlight.

4.7 Web Application

The end node prototype is accompanied by a user interface for remote monitoring and control of the streetlight. The web application for this project was developed using HTML, JavaScript, CSS, PHP, and the Bootstrap framework.

The dashboard web application ensures secure administrator login by requiring an administrator username and password if an intruder connects to the webserver. The secure login is imperative because it grants the administrator access to control the streetlight and access its data.

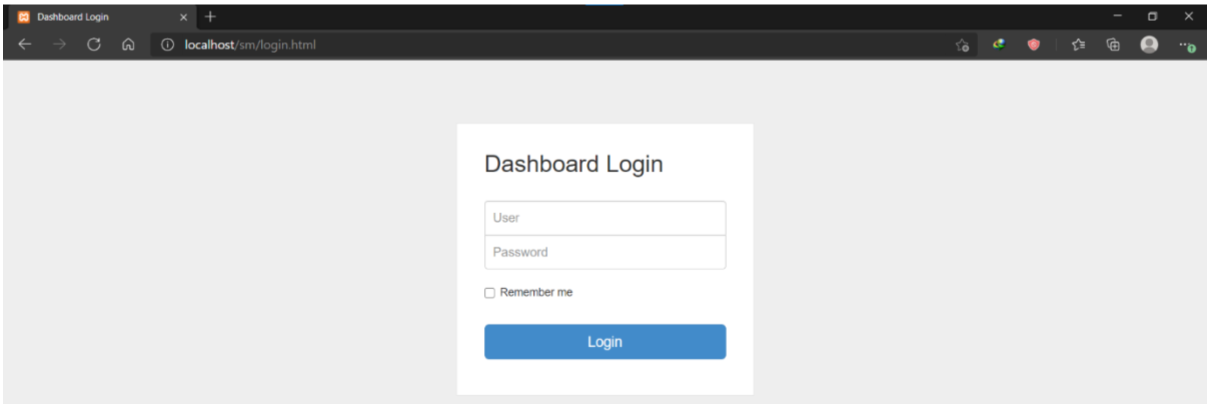

Figure 4.4: Dashboard login page to authenticate the control center administrator

The streetlights and smart devices are code-named with a unique ID number for identification in the web application. The web application provides the administrator with access to three main features and functionalities:

- *Control center*: The control center provides the interface to monitor the status of streetlights remotely and turn on or off or dim streetlight at a specific street or location. The control center also allows the administrator to detect malfunctioning streetlights with abnormal behaviors.

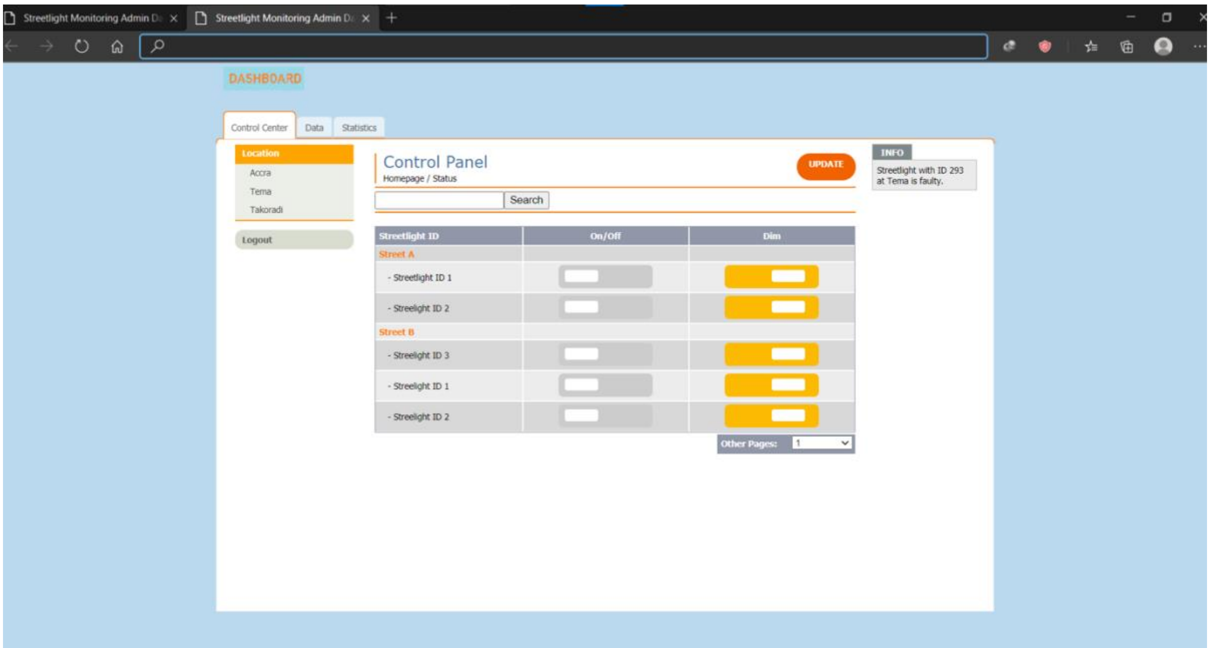

Figure 4.5: Dashboard web application

- *Data Dashboard*: The data page interfaces the database that stores sensor data and the results of back end computations that are done at the node. The page also serves as a data log to track performance, faults and insights from the streetlights. API key strings are used to verify and establish a secure connection between the database and local server to prevent attacks like SQL injections.

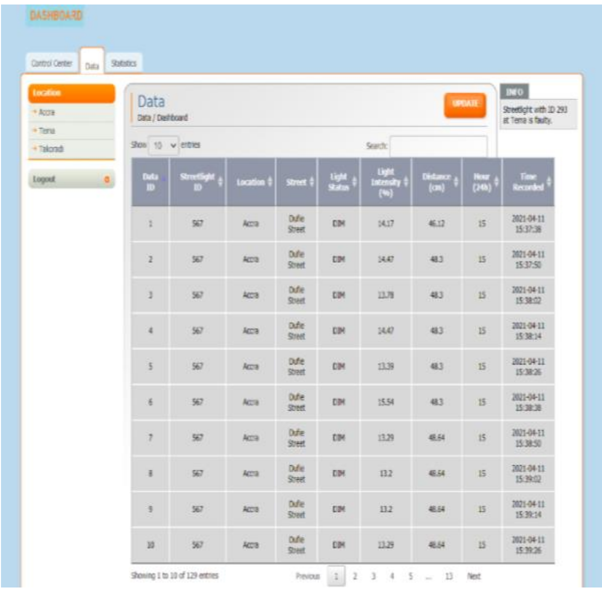

Figure 4.7: Streetlight data stored in the dashboard from smart device

Figure 4.6: Data visualisations of streetlight data in web application

- *Statistics*: The statistics page presents and visualises the data from the database for easy and appealing interpretation. The statistics page also provides results from an analysis made from the gathered data from the end nodes. The data visualisations help to interpret road activity and streetlight data easily.

4.8 Database

The database holds the data gathered from the sensors and other computational results from the smart device node into the cloud for data storage and management.

The database also serves as the source of data for the web application. The database was created in PhpMyAdmin using XAMPP, which ran the Apache and MySQL servers. The data table was made with its respective columns with fields for sensor data, light status, data ID, streetlight ID, location, street name, and recording time. Each record in the database was given an auto-incrementing ID, which identifies every record in the monitoring system. The Streetlight ID is kept constant for this prototype. The time of recording of each record uses the timestamp at the instance of recording.

4.9 Fault Reporting and Notification System

This prototype also seeks to resolve the issue where the administrator or the maintenance team is unaware of a faulty or malfunctioning streetlight on the streets. This is problematic, and not addressing it would lead to energy wastage, incur costs, and leave streets unsafe.

The alert sent could be a critical, major or minor alert depending on the severity of the issue and the responsiveness required. For this prototype, the monitoring system automatically sends an alert to the administrator's e-mail when the LED is on during the day or off during the night. When abnormal behavior is detected, the message alert sent is sent as a critical notification with high priority.

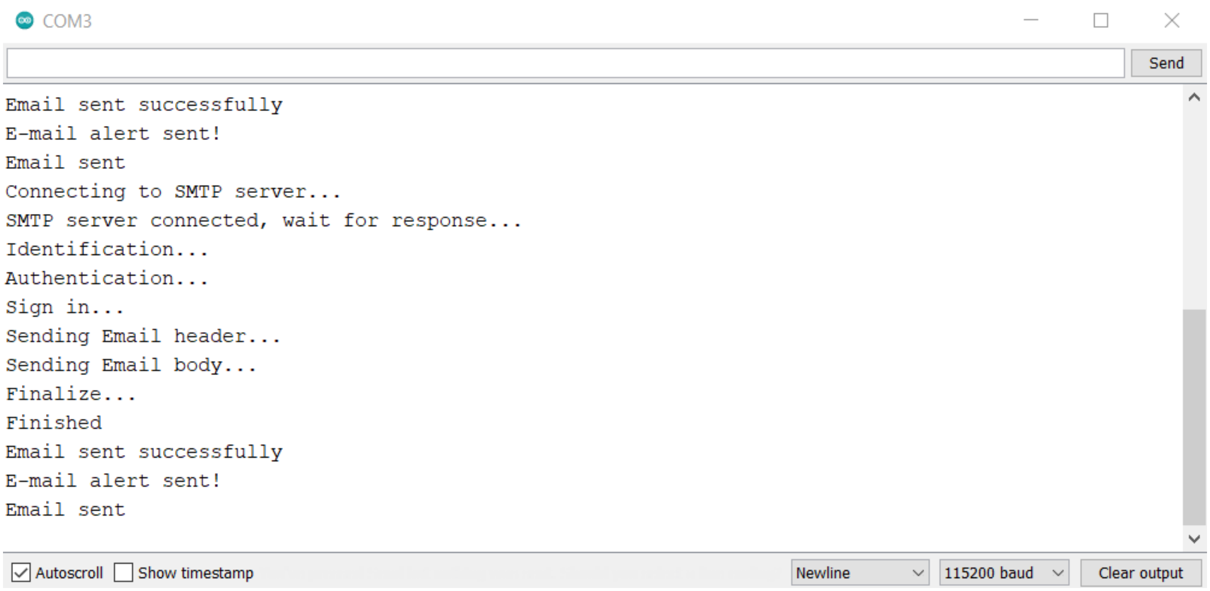

Figure 4.8: E-mail automatically sent from the smart device upon fault detection

The notification message also tells the particular faulty streetlight by ID, its location and street. The time at which the fault was detected is also reported in the alert. The ESP Mail Client library was used to achieve this feature

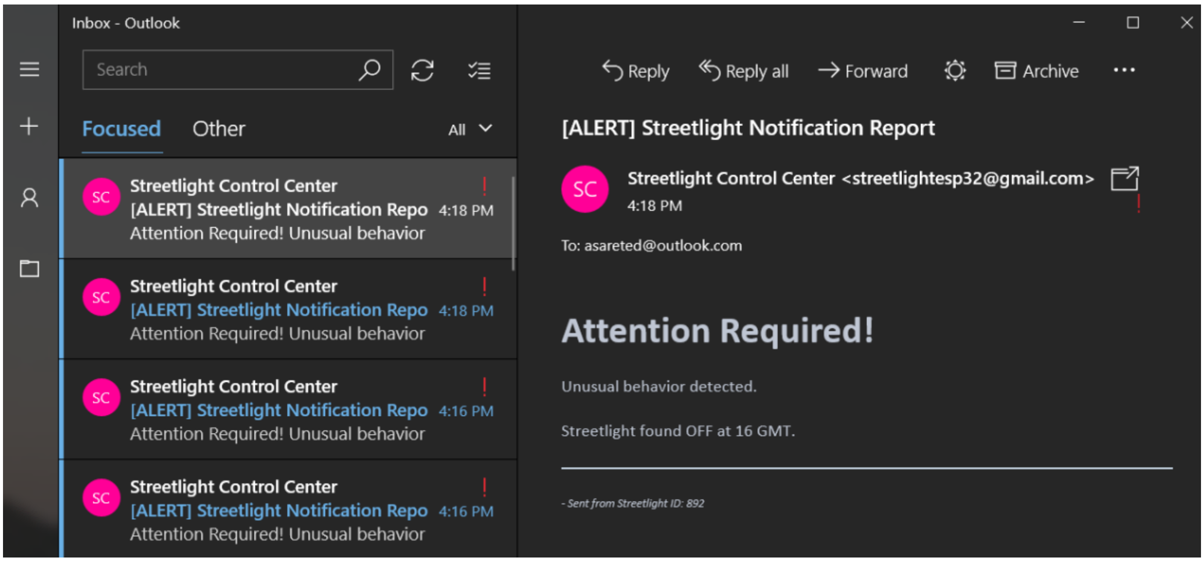

Figure 4.9: Received e-mail message in mailbox administrator

The GSM module was considered for sending high priority alerts directly to the administrator's mobile device. However, the feature was not incorporated in the prototype because of issues with the SIM800L GSM module and the high power it consumes. Moreover, this feature was not implemented in the prototype because of the data plan cost of sending bulk SMS messages.

Chapter 5: Testing and Results

This chapter discusses the experiments and tests conducted to demonstrate and analyze the performance and significance of the capstone project. The results discussed in this chapter also show how the project and tests meet the problem requirements and the design specifications discussed in the early chapters of the project.

5.1 Experimentation and Testing

5.1.1 Description of Tests

For an effective and efficient monitoring system, the smart device, the IoT network and the user interface and the various use cases must function well. The smart device must gather and transmit the right data to the control center to prevent malfunctions. The web application and database must be secure to prevent unauthorized access and network attacks like man-in-the-middle attacks. The user interface should quickly report critical alerts rapidly for quick actions to resolve the problem. For instance, when all the streetlights on the street are off when there is power. A request to the webserver to control the streetlights must also be fast enough to make the system work well.

The experiments and tests would measure the extent to which the problem satisfies the problem and the design specifications. The tests would focus on the different systems and components that make up the monitoring system. Data and statistical analysis were conducted to make sense out of the data. Finally, the data from the experiments were interpreted.

5.1.2 Smart Device Testing

One of the project's objectives is to reduce energy wastage of malfunctioning streetlights and ensure lower power consumption of the streetlights. One experiment was to determine how much energy is saved when the light is dimmed compared to when the

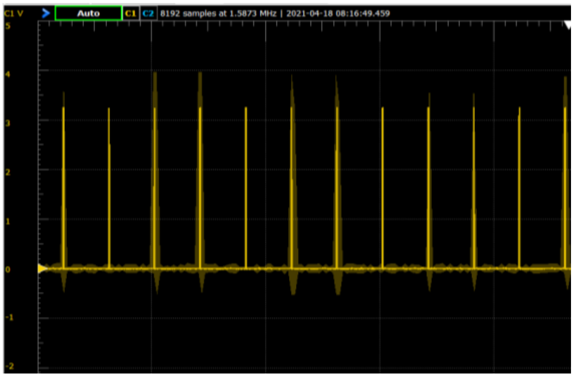

Figure 5.2: Pulse Width Modulation (PWM) signal with 5% duty cycle

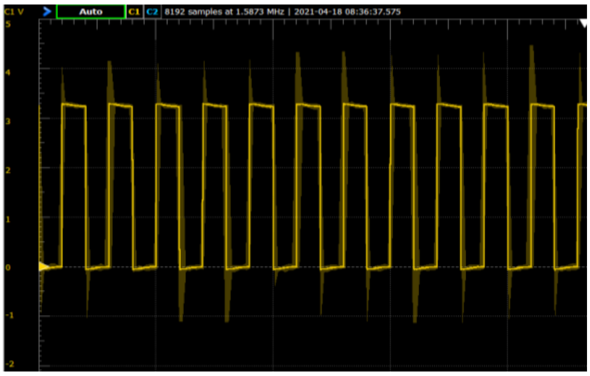

Figure 5.1: PWM Signal with 50% duty cycle

light source uses full power. The smart device generated a PWM signal from its PWM pins to dim the light source at a constant frequency.

The experiment was carried out using the Analog Discovery 2 and the Waveforms software. The Analog Discovery 2 device was used as a voltmeter to measure voltages when the light is dimmed and when it is not dimmed at different duty cycles of the PWM signal. The software showed the measurements from the voltmeter. The electrical signal was also scoped to display how the movement changes over time.

The experiment was conducted by writing a sketch, see Appendix, for the microcontroller to generate a PWM signal at an incrementing duty cycle every second. The resolution of the PWM signal determines the number of levels that can be achieved from zero to full power or brightness. The resolution used was an 8-bit resolution, which provides $2^8 = 256$ levels. The data was recorded in Waveforms by measuring the voltage from 0 to 100% duty cycle for 256 seconds.

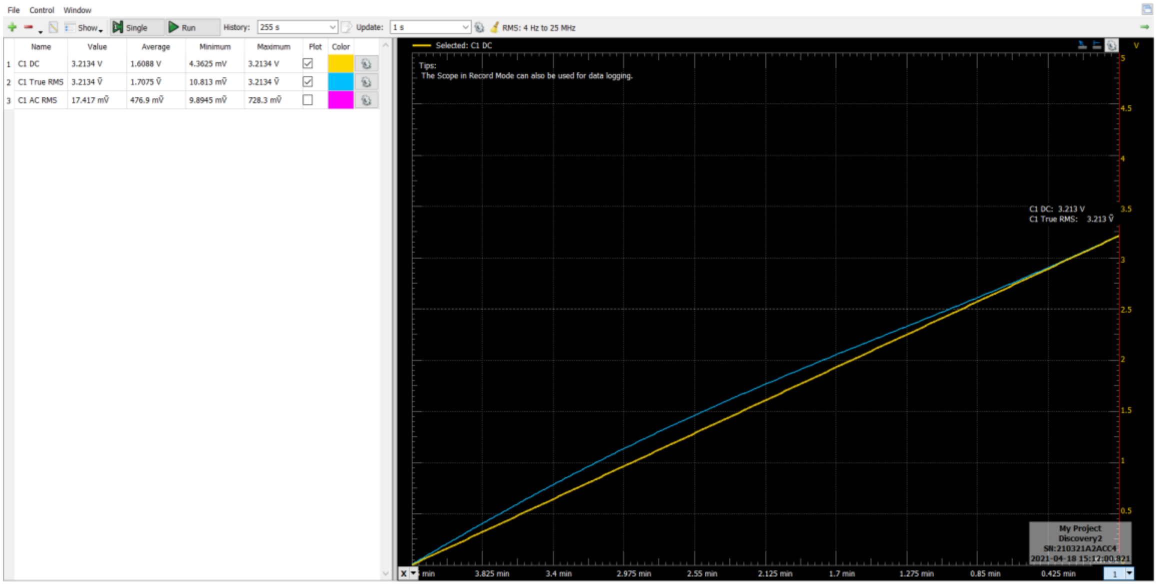

Figure 5.3: Data logger graph with a summary of recorded for DC and RMS voltages

The data was exported to MATLAB as a CSV file. A MATLAB script, see Appendix, was written to plot the data showing the DC voltages per every level of brightness as a percentage.

5.1.3 Software Testing

The software aspect was tested by running a network performance test in a browser to determine how fast the requests were served and how quickly the LEDs in the prototype responded to the control from the web application.

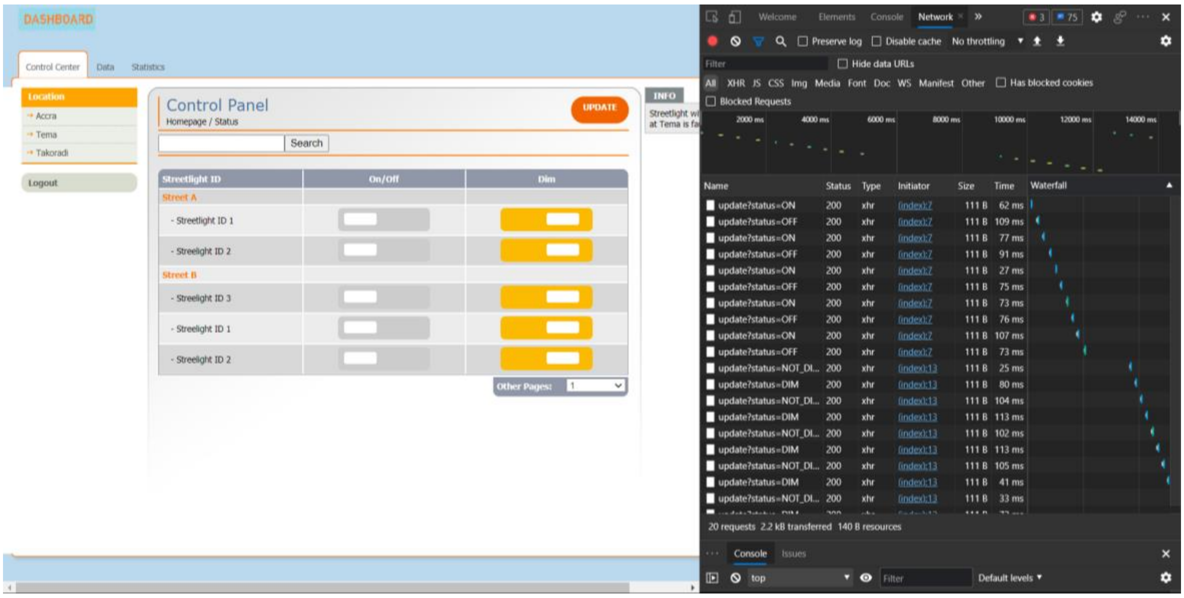

Figure 5.4.a: Microsoft Edge Devtools measuring request performance

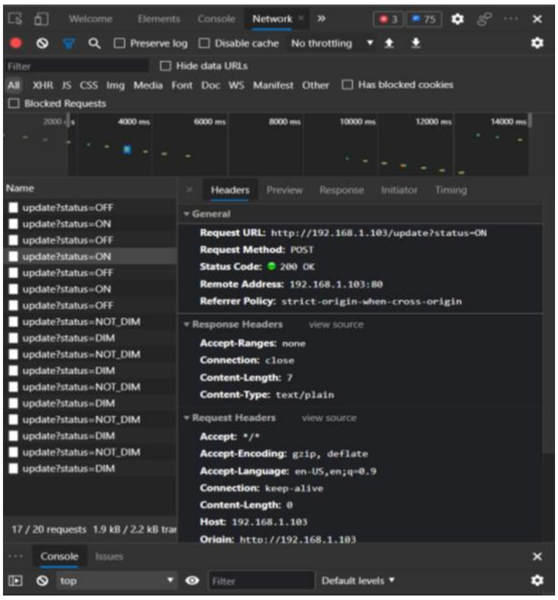

Figure 5.4.b: Header information of requests sent from the control center of web application

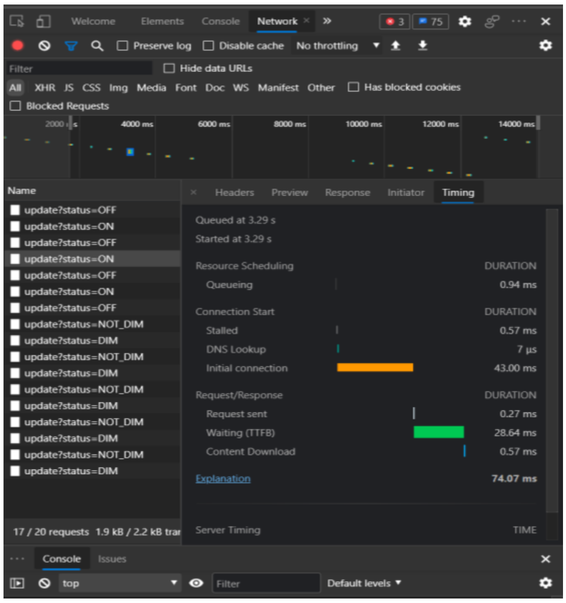

Figure5.4.c: Timing of request breakdown

The tests were done using Microsoft Edge's DevTools to measure the performance of 20 requests using the XMLHTTPRequest API. The requests were made to control the status and dimming of the streetlight prototype.

Another test performed measured how much time it took for the monitoring time to detect and report faults at the streetlight. The abnormal behavior was purposefully created by turning off the light source when it was supposed to be on or otherwise and recording how much time detection and alerting took.

5.2 Results

5.2.1 Smart Device Testing Results

According to the tests, the intelligent device's use Pulse Width Modulation (PWM) to dim the brightness of the light source. This effectively reduced the power consumption as compared to the light source working at full brightness.

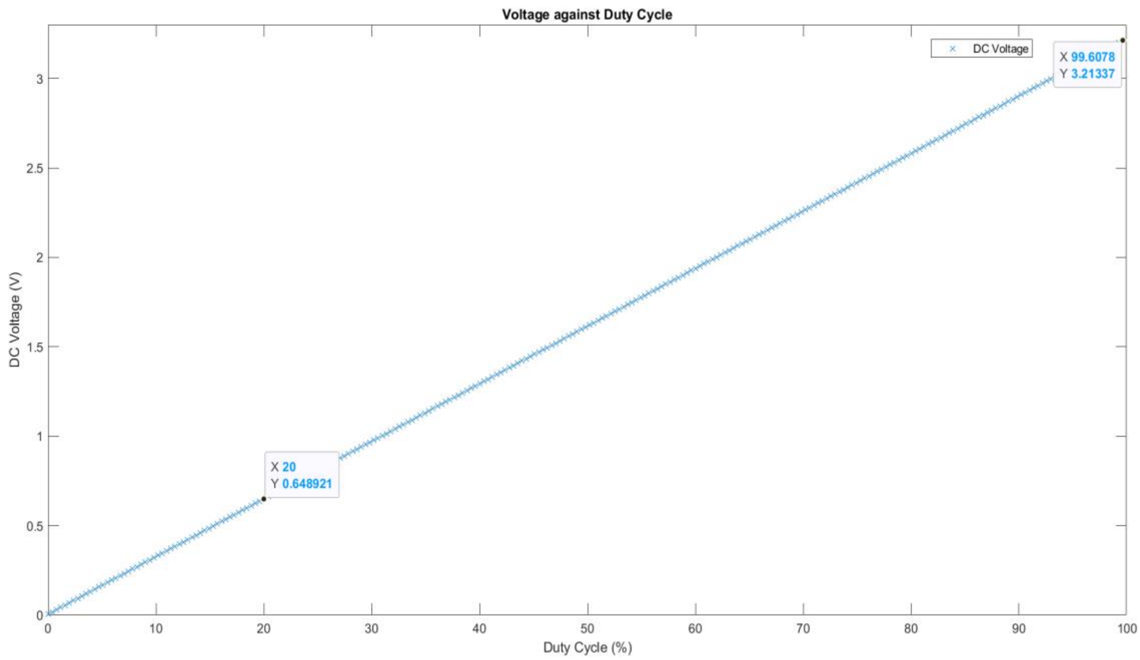

Figure 5.5: MATLAB plot showing DC voltage against duty cycle

Visually, the graph depicts a correlation between the variables. A regression analysis was performed to estimate and predict the relationship between the two variables. The simple linear regression equation that s used to model the relationship can be written as:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

where,

$Y \; = \; dependent\ variable\ or\ output\ (Voltage)$

$X = independent\ variable\ (Duty\ Cycle)$

$\beta_0\ and\ \beta_1\ =\ unkown\ constants\ that\ determine\ the\ intercept\ and\ slope$

$\epsilon\ =\ the\ error\ term\ (from\ noise\ in\ the\ measurements)$

The data was exported to Microdost Excel to make use of the statistical analysis tool. A null hypothesis was set that the model's coefficients are equal to zero, and hence there exists no correlation. The confidence interval was 95%; therefore, the null hypothesis can be rejected with a p-value (≤ 0.05). The p-value to be calculated would tell if the relationship between the two variables is statistically significant and if the observed correlation is inferrable. The results from the statistical analysis are shown in Table 5.1 and Table 5.2.

Table 5.1: Summary table of simple linear regression. Multiple R is the correlation coefficient. R square is the coefficient of determination. The standard error is the estimate of the standard deviation of error.

Regression Statistics	
Multiple R	0.986455535
R Square	0.986455535
Standard Error	0.00044481
Observations	255

Table 5.2: Summary table of statistical analysis. P-value gives the p-value to test the hypothesis to prove the correlation between the variables. Coefficients are the constants for the model. Lower and upper 95% shows the lower and upper boundary for the confi

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.004774156	5.55E-05	85.94854893	3.09E-189	0.004664763	0.004883549
X Variable 1	0.012630489	3.78E-07	33378.14843	0	0.012629744	0.012631235

Therefore, the equation for the relationship can be modelled as:

$$Y = 0.004774 + 0.02363X + 0.000445$$

The equation shows that the was noise in the experiment was almost insignificant, and as such, the data points were well fitted to the regression line. The r-squared statistic of 0.98 indicates that the model above strongly fits the data. The plots shown in Figure 5.3 confirm unbiased estimates. Additionally, the p-value, which is less than (≤ 0.05), indicates that the data provide enough evidence to reject the null hypothesis. Hence, the indication the correlation between the voltage and duty cycle is statistically significant and inferable.

The positive slope of the data shows that an increase in the independent variable increases the mean of the dependent variable, too, as seen in the graph. Therefore, a high duty cycle or a higher brightness infers that more voltage is required by the light source for any data sample. As such, the brighter the light source, the more energy is used. To demonstrate that the prototype meets the energy-efficient requirements of the project, the energy efficiency is calculated at 20% versus at full power or 100% duty cycle. The voltage is used because of its proportionality to power (V=P/I) and energy.

$$Energy\ Efficieny = \frac{Voltage\ at\ Full\ Duty\ Cycle - Voltage\ at\ 20\%\ Duty\ Cycle}{Voltage\ at\ Full\ Duty\ Cycle} * 100\%$$

$$Energy\ Efficieny = \frac{3.213374 - 0.636679}{3.213374} * 100\% = 80.187\%$$

Therefore, the prototype is 80.2% energy efficient when the light source is dimmed after midnight or during periods of inactivity on roads.

5.2.2 Software Testing Results

The results of the network performance and smart device response experiment and analysis are displayed in Table 5.2.

Table 5.3: Summary table of geometric mean, median, minimum and maximum time values of requests from the control center to control streetlight prototype

	On/Off Requests	Dimming Requests
Mean	72.75483	64.62226
Median	91	91
Low	27	25
High	109	113

The time recorded for each request was affected by the resource queuing, latency, connection time, DNS lookup, proxy negotiation, and others, as shown in Figure 5.c. For all the requests from the web application, the light source went on or off or dimmed accordingly. The median time for changing the status and dimming of the LED was 91 ms out of 20 requests. The results in the table show that the delays in controlling the streetlight from the web interface are inappreciable.

For the notification performance test, the mean time of receiving an e-mail message was 7.2 seconds. The maximum time it to took to receive a notification e-mail was 13 seconds. The recorded time for sending and receiving a the alert after a fault was affected by the connection, authentication, and delivery of the message by the SMTP server of the e-mail service provider. The shortest time it took to alert the administrator was 5.8 seconds. This time to report the fault generally decreased because less time was required to authenticate and connect to the server after the first few alerts were delivered. The results meet the design requirements of reporting faulty streetlights in the streets to an administrator or technician.

5.2.3 Security

The importance of security in such a project cannot be overstated. It is essential to secure the system to prevent any security vulnerabilities that could allow an attacker to manipulate the streetlights or access data if the attacker can connect to the IoT network.

In testing the prototype, certain security flaws were determined with regards to the GET method. The database and the webserver of the control center used the GET method to send data. This could an attack to change database values or control the streetlights by setting a parameter in the URL without requiring any logging into the system. However, the source code was updated to use the POST method to make the system more secure. Any attempt to control the streetlights or edit the database denies the request and redirects the user to an error 404 page.

The future deployment of this project aims to tighten the security and patch any other flaws in the monitoring system to ensure that the system works as it should.

Chapter 6: Conclusion

This project seeks to retrofit intelligence to streetlights to gather insightful data, monitor and control streetlights, reduce streetlight energy consumption in communities, and provide data required for remote monitoring and control of streetlights. The project's solution takes a step in advancing and using the Internet of Things (IoT) devices and data to solve problems in communities with little or no human-to-human or human-to-device interaction. From the results of the tested prototype, the system proves to consume less energy when lights are dimmed. The results also meet the design requirements of providing a system that controls and alerts the administrator when a streetlight malfunctions.

The focus of this chapter will be to discuss what was accomplished in this project, the limitations and challenges that influenced the scope, and suggested improvements for future versions of the project.

6.1 Discussion

The project report explored the design of the proposed solution and provided analysis for alternative designs that could be considered for the system. The prototype implemented some of the discussed alternative design decisions while meeting the design requirements of the project.

This project successfully designed a network of streetlights uniquely identified by an ID number, location, and street. This feature may help a technician or system administrator track and quickly identify a particular streetlight in a vast network. The addressing of the streetlight nodes also forms a structure to store data from the streetlights into a database.

The project report discussed the circuit design for high power streetlight loads that allow the intelligent unit to draw power from the same power feed as the streetlight. This circuit includes a transformer, rectifier, switchover circuit, and a backup battery charged when the primary power source is available.

The project also explored the design of the IoT network to facilitate the streetlight monitoring system. The ideal network design adopts the LoRa technology to implement a LoRaWAN network for long-rage, low-power communication to a central control center. The network design includes a gateway that allows the data to be sent over IP to a database. In the prototype implemented, the system was built using Wi-Fi and ESP32 board to control the light source and send data to the user. The dashboard web application was developed to provide the user with streetlight information and control of the streetlight. The back end implements user authentication and API keys to secure the system.

6.2 Limitations and Challenges

In developing the system, certain challenges and limitations were encountered, which affected some of the decisions made concerning the project. These limitations and challenges include:

- The LoRa module and gateway could not be acquired due to the budget of the project. This challenge led to the use of Wi-Fi for the prototype network design.
- One limitation was the inability to deploy the smart device on an actual streetlight unit or a higher power output.

6.3 Next Steps and Future Works

Despite the features and achievements of the project, other improvements can be implemented in future versions of this project to make it better and efficient. Below are improvements that can be explored:

- Despite the security measures put in place, the system's deployment would further secure the web application interface. The initial step to improve the security would be to secure the connection with SSL certificates.
- Another consideration is the use of a higher power output light source for the prototype to ascertain the high-power with backup battery design for deployment on a streetlight.
- The use of sleep modes of the microcontroller could be implemented to further save power during the day or when the smart device may not be needed to save power.
- Wi-Fi is not the most efficient access technology because of its shorter range and high power usage. This could be improved by using LoRa technology for long-range and low-power communication for the monitoring system.
- Additionally, a data learning model can be implemented to predict the occurrence of faults in streetlights. These models could also provide richer data analytics.
- Finally, an anti-theft system using camera modules and alarm systems connected to the web application can be implemented to prevent theft of streetlight components.

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Appendix

Sketch for Generating the Test PWM Signal

```
const int ledPin = 5;  // 16 corresponds to GPIO16

// setting PWM properties
const int freq = 5000;
const int ledChannel = 0;
const int resolution = 8;

void setup(){
    Serial.begin(115200);
  delay(1000); // give me time to bring up serial monitor
  Serial.println("ESP32 Analog IN/OUT Test");
  // configure LED PWM functionalitites
  ledcSetup(ledChannel, freq, resolution);

  // attach the channel to the GPIO to be controlled
  ledcAttachPin(ledPin, ledChannel);
}

void loop(){
  // increase the LED brightness
  for(int dutyCycle = 0; dutyCycle <= 255; dutyCycle++){
    // changing the LED brightness with PWM
    Serial.print(dutyCycle); Serial.print(" =
");Serial.print((float)dutyCycle/(float)255*100);Serial.println("%
");
    ledcWrite(ledChannel, dutyCycle);
    delay(1000);
  }
```