

Development of a Self-Powered Environmental Sensing Platform for Smart City Applications: A Case Study on Weather Stations with LoRaWAN Integration

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Abstract

This paper has proposed the design of a self-powered environmental sensing platform that can be used as part of Smart City solutions, in this case weather stations with LoRaWAN communication technology. The real-time monitoring of the environment has been on the rise as cities are becoming more and more problematic in terms of air pollution, noise, and climate change. Conventional environmental monitoring systems have been associated with high costs of operation and energy use. In order to solve these problems, this study will suggest a system based on solar power, with low-power components and LoRaWAN protocol to send data. Some of these parameters observed on the platform are the temperature, humidity, air pressure, brightness, noise, and air quality. The information is relayed to cloud computing systems such as MyDevice Cayenne where it can be monitored and analyzed in real time. A pilot project was rolled out in the University of Liverpool, with results showing that the system was highly energy efficient, there was stable transmission of data and long-lasting operation on minimum energy consumption. The study will help to further the development of the Smart City infrastructure by offering an affordable and sustainable environmental monitoring method that can find its ways in urban development, air quality control and transportation management optimization.

Keywords: Self-powered, Environmental sensing, Smart City, LoRaWAN, Renewable energy, IoT, Cloud integration, Wireless communication

1. INTRODUCTION

Due to the growth in cities and the influx of people into the cities, the need to have sustainable and efficient infrastructure grows. Smart Cities, which run on IoT technologies, are designed to deal with these issues by incorporating creative solutions that would improve the quality of the living in the urban area as well as promote environmental sustainability. Internet of Things (IoT) is the key to these urban changes since it helps to monitor the environment in real-time, manage resources, and optimize the work of cities in general. Environmental sensing is one of the fundamental uses of IoT in Smart Cities, as it implies the installation of multiple sensors that identify such parameters as air quality, temperature, humidity, noise, and others. Such sensors gather important information so that the city managers can make sound decisions, particularly on matters of public health, urban planning, and environmental protection (Atzori, Iera, and Morabito, 2010). Nonetheless, conventional environmental sensing systems have been characterized by problems of high cost of operation, energy consumption and constraint in infrastructure which has facilitated massive implementation in an urban setting. Self-powered environmental sensing systems, that can autonomously work using renewable energy sources like solar power have become a concept of growing popularity as a solution to such problems. These systems have the ability to reduce the operation costs, minimize carbon footprints and offer sustainability in the long run hence it is best suited in urban settings. Low-power components are employed in such

systems to facilitate efficient operation and with the aid of solar panels and other energy storage systems such as lithium polymer (LiPo) batteries, such systems can operate without an external power source (Kang, Dempster, and O'Hara, 2011). Moreover, the incorporation of low-power communication standards like the LoRaWAN (Long Range Wide Area Network) would make it possible to transmit environmental data wirelessly over a long distance with the minimum amount of energy use (Dohler & Puchinger, 2011). The energy efficient hardware and software combined with renewable energy harvesting and wireless communication technologies can transform how data on the environment are collected and analyzed in Smart Cities.

The need to observe the environmental parameters in the cities could not be overestimated. Cities also have big problems associated with climatic change and air pollution, noise pollution and other environmental risks that directly impact the quality of life and health (Evans, 2014). In addition, air pollution and noise as major causes of air pollution are contributed by urban transportation systems. Cities may minimize their impact on the environment and enhance safety and performance by using smart technologies in transportation systems. This study focuses on the establishment of an autonomously powered environmental sensing system that has the ability to detect various environmental conditions such as temperature, humidity, air pressure, brightness, noise levels and air quality, all of which are important in the complex management of urban environments (Schaffers, Komninos, and Pallot, 2011). The system will be cost effective and energy efficient whereby the solar energy will be used to power the sensors and the LoRaWAN will be used to transfer the data hence it can be deployed long term in a city. Within the framework of smart transportation, environmental monitoring systems would be the source of crucial information that can reduce the adverse impact of transportation infrastructure. According to Lee (2002), economic costs of infrastructural changes related to transport infrastructure such as energy and emissions are high. Real-time data about the conditions of the environment that cities gather allows them to optimize their transportation systems, decrease the congestion, enhance the quality of air in the cities, and make cities safer. The purpose of the proposed environmental sensing platform in this paper is to find a solution to these problems through an affordable, renewable energy-based, the wireless communication platform. Also, it enables real-time monitoring on the platform permitting dynamic modification of the transportation systems and other city management operations (Maibach, 2008).

The utilization of cloud-based systems, including MyDevice Cayenne, is also a crucial part of this study. With the help of cloud computing, real-time environmental data can be captured, processed and stored through various sensor nodes in cities and give them information about the current conditions of the environment. This online integration provides an easy access to the data, assures the municipal decision-makers with the availability of the information needed to make proper decisions. Additionally, analysis of data at advanced stages is possible through cloud computing and can be utilized to forecast the environment, evaluate the efficiency of interventions, and recognize possible means of improvement in urban planning and management (Miller, 1991). This self-powered environmental sensing platform was developed to utilize these technologies in order to establish a strong and scalable system which can be implemented in different urban environments. In order to evaluate the viability and usefulness of this self-powered environmental sensing platform, this study will utilize deployment of a pilot system at the University of Liverpool, which gathers data on important environmental parameters by use of wireless sensor nodes. The pilot project is used to not only prove the capabilities of the proposed system but also to test its energy consumption, accuracy of the data and its overall performance during the real world conditions. The

outcomes of a pilot project will be able to give much information about the practical application of such systems to Smart Cities, the challenges and possible advantages of using renewable energy and low-power communication technologies in urban contexts (Zhao and Zhang, 2018).

This paper will be focused on designing, developing and implementing a cost efficient, self-powered environmental sensing system, incorporating both IoT technologies and renewable energy to be used in Smart City implementation. This study aims to make a contribution in the development of sustainable urban infrastructure by using low-power components, energy harvesting methods, and wireless communication protocols. Results of the presented research will provide a useful insight on future smart city, in particular, those that strive to develop environmentally friendly and energy-efficient cities that will be able to be extended to a larger metropolitan region.

2. METHODS AND MATERIALS

This study is aimed at cost-benefit identification and monetization of Smart City technology and applications, namely Smart Transportation. The paper presents the aspects relating to Smart Transportation. There is also the non-monetary variables that are not easy to quantify in Cost-Benefit Analysis (CBA). The calculations of net present value (NPV) and the benefit-cost ratio (BCR) are done using numerical variables to assist the municipal decision-makers to determine the feasibility of such applications.

2.1 Hardware and Software

2.1.1 Hardware

Environmental sensing platform is made up of multiple hardware components. This system is constructed under the sensor node, which comprises of Power Management Unit (PMU), sensing unit, microcontroller unit (MCU) and communication unit. The sensor node gathers the information of different environmental factors which can include temperature, humidity, air pressure, light intensity and air quality. The MCU interprets the data obtained and transmits it as a payload to the cloud by the help of a LoRaWAN communication module.

The sensor node operates on solar energy that is collected by the use of solar panels, and is stored in Lithium Polymer (LiPo) batteries. Energy consumption is maximized with the use of sleep mode when the sensors and the MCU go into low-power modes between measurements.

Table 2.1: Characteristics of Sensors

Sensor	Parameter	Range	Accuracy
Temperature Sensor	Temperature (°C)	-40 to +85°C	±0.5°C
Humidity Sensor	Humidity (%)	0% to 100%	±3% RH
Air Pressure Sensor	Air Pressure (Pa)	300 to 1100 hPa	±1 hPa
Light Sensor	Brightness (lux)	0 to 65535 lux	±5%

2.1.2 Software

The sensor node is programmed with Arduino IDE; it is combined with the LoRaWAN communication protocol. The software runs in a cycle that activates the MCU and sensors,

gathers environmental data, processes the data and transfers it to the cloud. The sensor node goes into sleep mode when it is not in use in order to conserve energy.

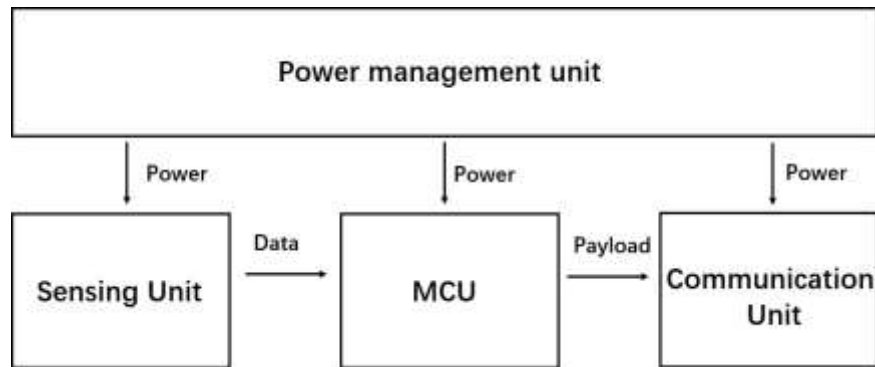


Figure 2.1: The architecture of the weather station.

The weather station architecture has the following parts:

- o Power Management Unit (PMU): Controls the collection of power and charging of the battery.
- o Sensing Unit: It consists of environmental data sensors.
- o Microcontroller Unit (MCU): Processes the data and codes it into a payload to send.
- o LoRaWAN Communication Unit: Sends the information into the cloud.

2.2 Cloud-Based Data Integration

The sensor data is sent to The Things Network (TTN), which is free and global open LoRaWAN network. After receiving the data it is presented and stored on the MyDevice Cayenne platform. Proper data encoding and decoding are achieved by using the Cayenne Low Power Payload (LPP) format.

The microcontroller in the Sodaq Mbili is a Microchip ATmega 1284p, with 128kB ISP flash memory, read-while-write, 16kB SRAM and a real-time counter. When operating in the active mode, the MCU draws 0.4 mA of current when in the power-saving mode, the MCU draws 0.6 A of current when running at 1MHz, 1.8, and 25C, and the sensor node real-time counter can be configured to put the node to sleep or awaken it at specified times, greatly lowering power consumption in the sensor node. Another useful MCU capability is that the sensor data can be read by the MCU and the measured values can be encoded to payloads. Figure 3.2 shows that payloads are delivered to the LoRaWAN gateway via the RN2483 LoRaWAN transceiver. The RN2483 load 43.5 mA of instantaneous transmission current and 3.1 mA of idle transmission current when not transmitting when connected to a 3.6 V power source. The transceiver working frequencies of 863 MHz to 870 MHz allow the transceiver to carry out the LoRaWAN frequency in Europe.



Figure 2.2: RN2483LoRaWAN communication module

The wireless sensor node is enclosed in an IP66 dust- and water-resistant box with a 3D printed foundation as shown below. The box is topped by a transparent polycarbonate (PC) lid and bottomed by a base made of an acrylonitrile butadiene styrene (ABS) base which is opaque (ABS). The sensor box has the black base that is 3D printed and mounted with the sensors, battery and the Sodaq Mbili boards. The sensor box has been sealed to IP66 sealed against rain. Figures 3.3 and 3.4 are the interior and exterior views of the sensor node, respectively.

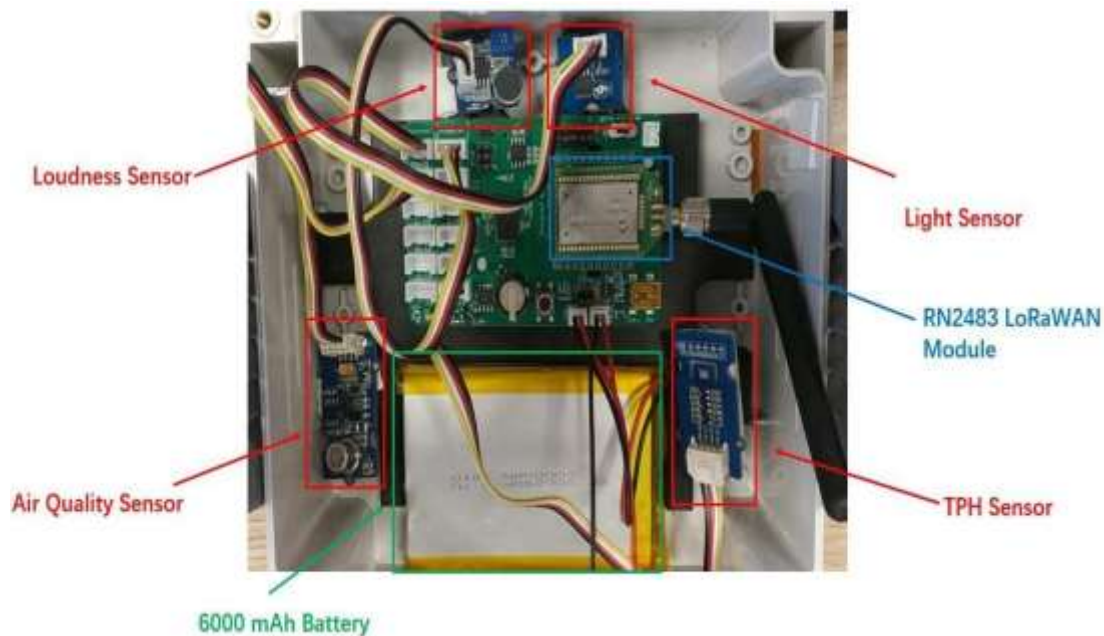


Figure 2.3: The inside look of these nsor node

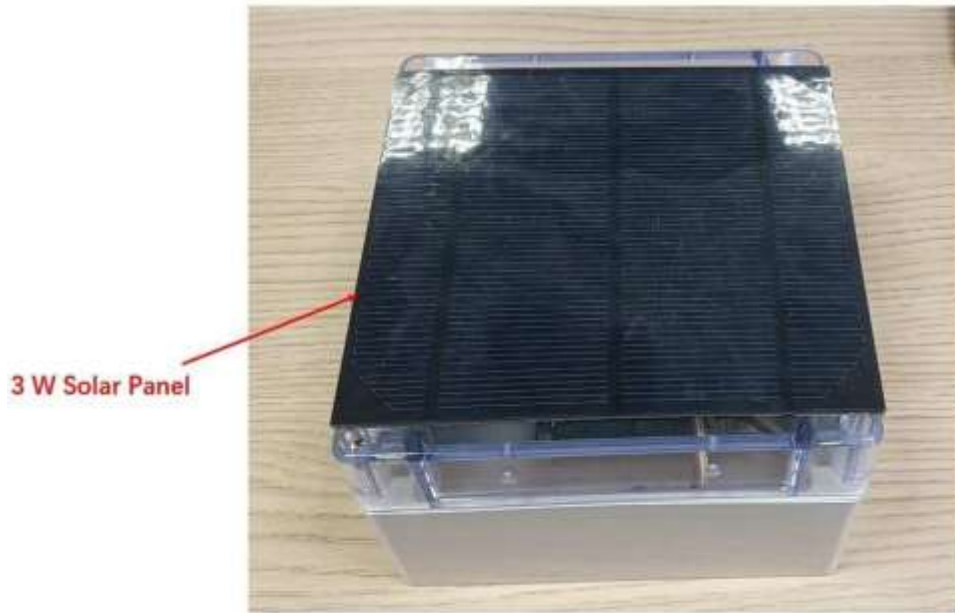


Figure 2.4: The outside look of these nsor node



Figure 2.5: The LoRaWAN gateway

2.3 LoRaWAN Gateway

In order to form a wireless sensor network, the environmental sensing nodes will be connected to the gateway by the LoRaWAN protocol. LoRaWAN coverage is provided to the sensor nodes using an 8-channel LoRaWAN gateway to construct the LoRaWAN-based environmental sensing system. The indoor LoRaWAN gateway is based on the Raspberry Pi 3 and RAK831 concentrator module (see Figure 3.5). The RAK831 has many channels and thus can simultaneously get as many as 8 packets by LoRa with different spreading factors on different channels. It can support LoRa and Frequency Shift Key (FSK) modulation and it operates within the frequency range of 863 MHz to 870 MHz. Raspberry Pi 3 controls the

RAK831 frontend. In order to operate the Raspberry Pi 3 with the RAK831, one has to connect a 5V/2A power source to the machine.

2.4 Software

The wireless sensor node is made by the Sodaq Mbili that is based on Arduino development board. In this project, we make use of Arduino open-source software to program a sensor node and a LoRaWAN transmitter (IDE). Arduino IDE is written in Java and can be programmed in C and C++. The code is essential in order to maintain that the environmental sensing platform operates. The MCU and sensors should be put in the sleep mode to conserve power when they are not in use and to collect information on the surrounding environment, the real-time clock interrupts will wake them up. Figure 3.6 represents the flow chart of the software. Along with the initiation of the LoRaWAN connection, the code must also initialise the activation mechanism, the activation keys, including NwkSKey to the Network Session (NwkSKey), AppSKey and AppKey (AppKey). To be able to utilize the Cayenne cloud, several environmental conditions such as humidity and noise level should be sent to payloads.

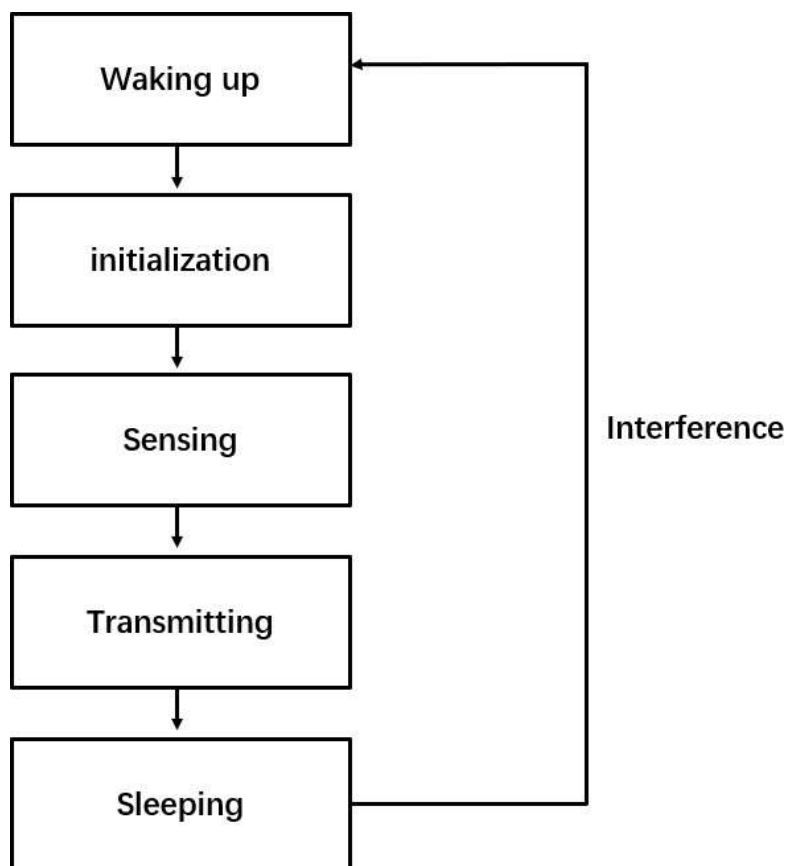


Figure 2.6: Software working diagram

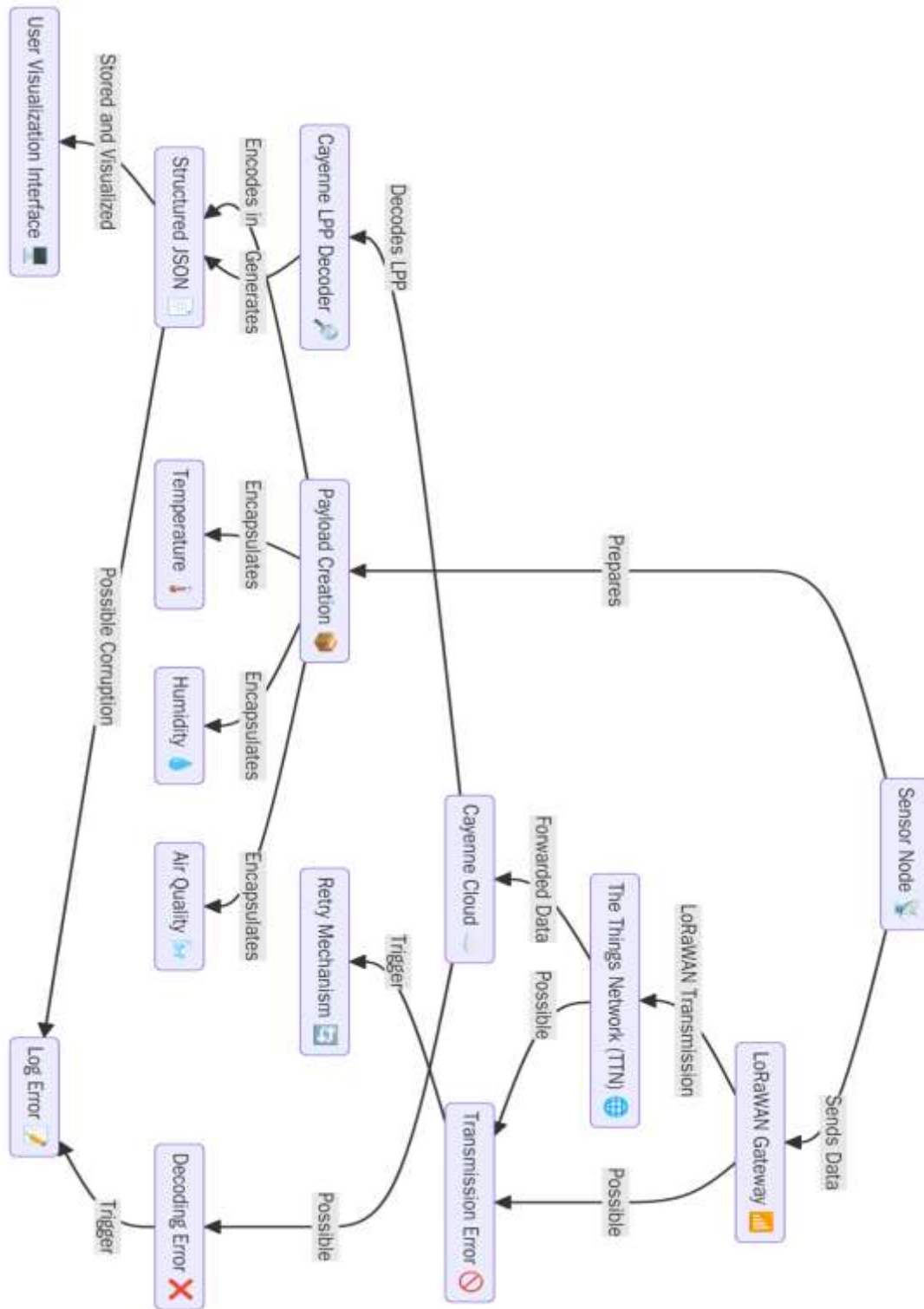


Figure 2.7: Cloud-Based IoT Data Transmission Flow with Error Handling Mechanisms

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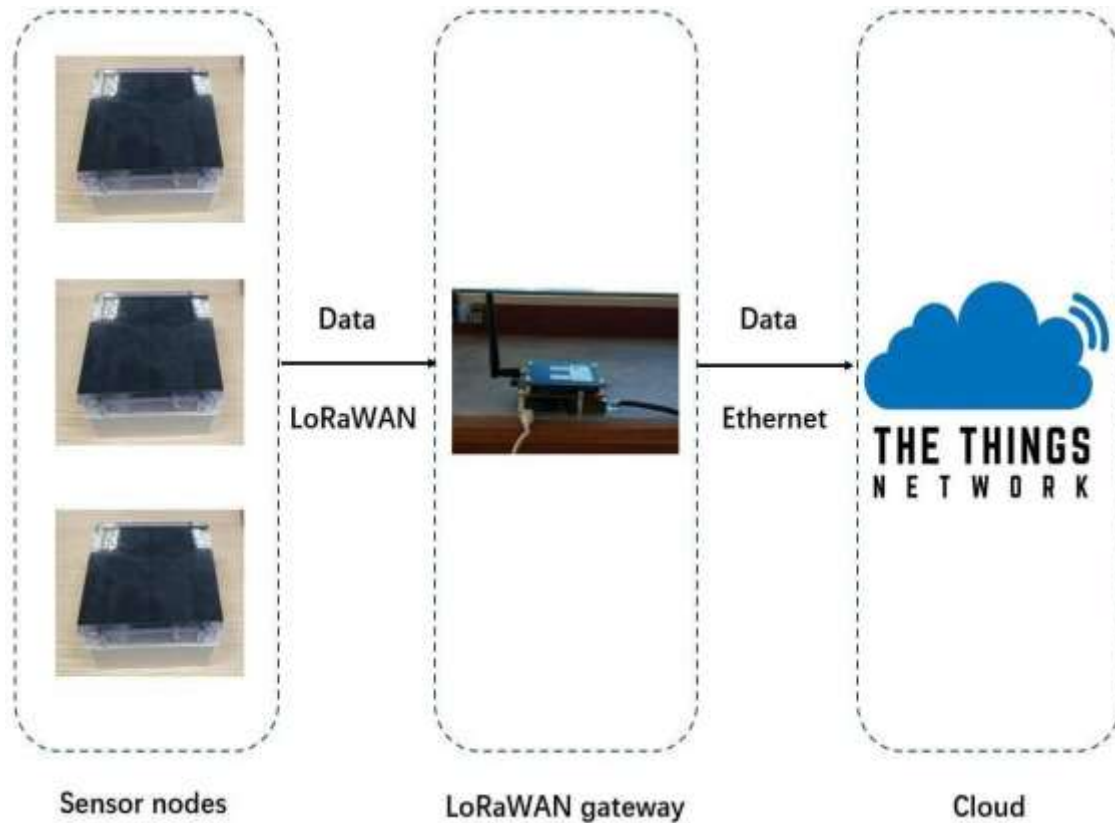


Figure 2.8: The design of the environmental sensor platform

2.5 Variables

2.5.1 Costs

The costs associated with the environmental sensing system include:

- **Capital Cost:** The one-time cost for planning, designing, purchasing equipment, and setting up the system.
- **Maintenance Cost:** The ongoing cost to keep the system operational, including hardware and software maintenance.
- **Operation Cost:** The recurring cost for the day-to-day operation of the system, such as electricity, communication fees, and data storage costs.

Table 2.2: Costs of Smart City Transportation Projects

Cost Type	Description	Amount
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Capital Cost	One-time setup costs, including design and equipment.	\$100,000,000
Maintenance Cost	Yearly cost to maintain systems and infrastructure.	\$800,000
Operation Cost	Yearly cost of operations (advertising, rent, etc.).	\$200,000

2.5.2 Benefits

The benefits of the system include:

- **Travel Time Reduction:** Decreased travel time due to better transportation management.
- **Safety Improvements:** Reduced accidents and fatalities.
- **Reduced Emissions:** Lower air pollution and greenhouse gas emissions due to more efficient transportation.
- **Noise Reduction:** Reduced noise pollution from transportation systems.

Table 2.3: Benefits from Smart Transportation

Benefit	Monetary Value
Travel Time Reduction	\$343.33/year
Safety Improvements	\$116,580,000/year
Reduced Gas Emissions	\$1,292,677,722/year
Reduced Noise Levels	\$1,068,138/year

2.6 Discount Rate

The **discount rate** is used to adjust future costs and benefits to present value. The discount rate used in this study is based on government borrowing rates and is applied to calculate the Net Present Value (NPV) and Benefit-Cost Ratio (BCR).

Table 2.4: Interest Rates of U.S. Treasury Bills

Maturity	3-Year	5-Year	10-Year	30-Year
Interest Rate	0.9%	1.6%	2.2%	2.7%

2.7 Project Lifetime

The lifetime of the project is determined based on the infrastructure involved and the expected durability of the system. The project is assumed to last 30 years.

Table 2.5: Project Lifetime for Infrastructure Sectors

Sector	Project Lifetime (Years)
Energy	25
Water and Environment	30
Roads	25
Ports and Airports	25

2.8 Types of Measures

This study uses the Net Present Value (NPV) and Benefit-Cost Ratio (BCR) methods for evaluating the economic efficiency of the Smart Transportation system.

2.8.1 Net Present Value

The Net Present Value (NPV) is calculated by discounting the future benefits and costs of the project to their present value.

Formula for NPV:

$$NPV = \sum_{n=1}^N \frac{B_n - C_n}{(1+i)^n}$$

Where:

- B_n = Benefit in year n
- C_n = Cost in year n
- i = Discount rate
- N = Project lifetime

2.8.2 Benefit-Cost Ratio

The Benefit-Cost Ratio (BCR) compares the benefits of the project to the costs. If the ratio is greater than 1, the project is considered beneficial.

Formula for BCR:

$$BCR = \frac{\sum_{n=1}^N B_n}{\sum_{n=1}^N C_n}$$

Where:

- B_n = Benefits in year n
- C_n = Costs in year n
- N = Project lifetime

2.9 Predictor System

The **Predictor System** uses machine learning techniques to predict future traffic accidents and suggest the safest and least congested routes. Data from toll plazas, weather forecasts, and past accident data are used to predict accident-prone areas.

3. ANALYSIS AND RESULTS

3.1 Deployment

The pilot project to install three wireless sensor nodes around the University of Liverpool has sensed as many as five environmental variables (air quality, noise level (loudness), temperature and air pressure) in the past three months. Since we would like every sensor node to be an autonomous device powered with solar energy, the unit is mounted close to a window when inside so that it gets enough sunshine exposure. Figure 3.1 depicts that the LoRaWAN gateway is an indoor gateway within a common office environment. The entrance is close to a city center window in order to access as many people as possible.



Figure 3.1: The deployment of sensor nodes and the LoRaWAN gateway. (a) Sensor node in indoor condition; (b) Sensor node in indoor condition (alternative angle); (c) Sensor nodes in outdoor condition; (d) LoRaWAN gateway in indoor condition.

3.2 Measurement Results

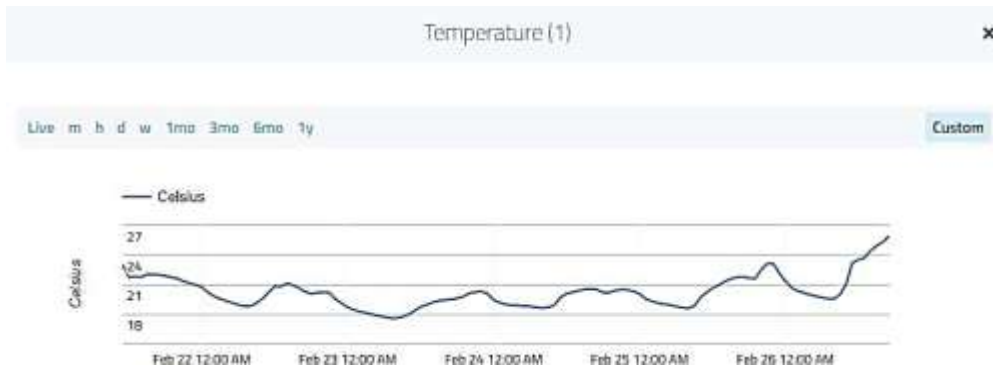


Figure 3.2: The measured temperature over 5 days



Figure 3.3: The measured air pressure over 5 days

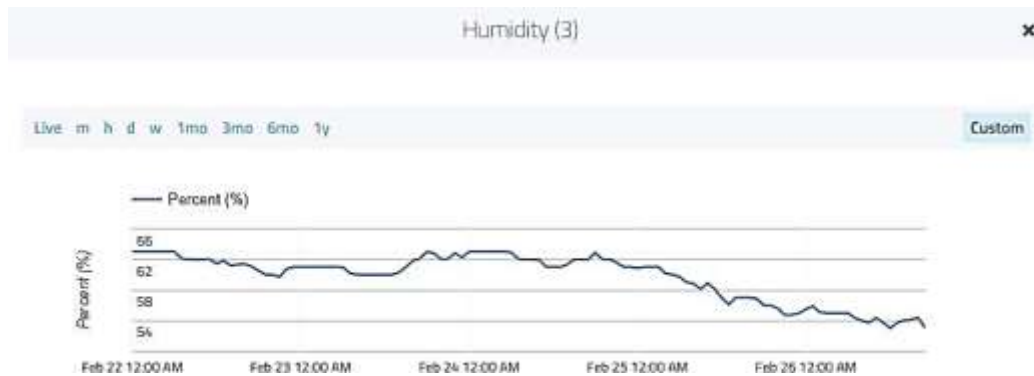


Figure 3.4: The measured humidity over 5 days

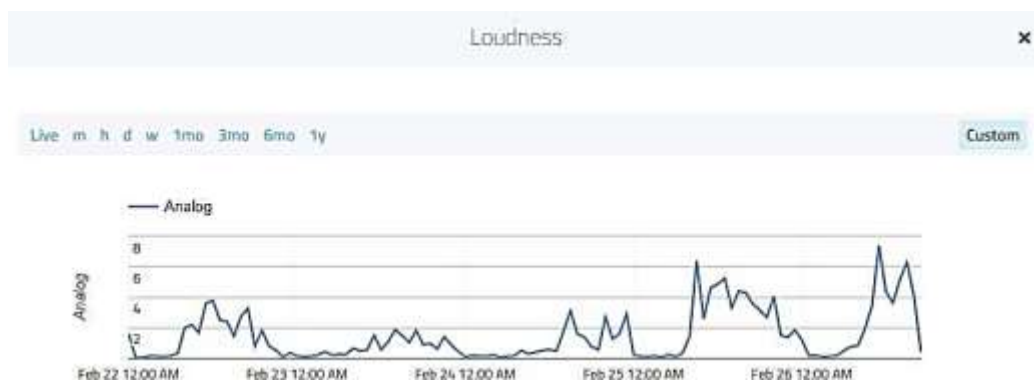


Figure 3.5: The measured loudness over 5 days.

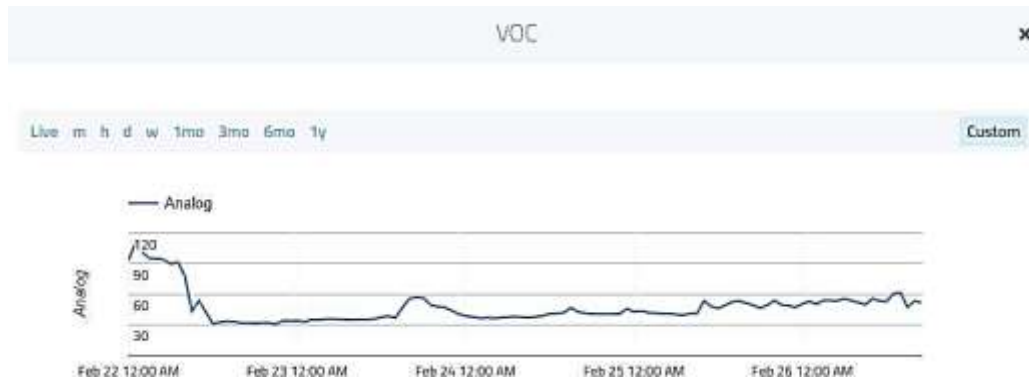


Figure 3.6: The measured air quality over 5 days.

All of the collected environmental data will be stored and viewed in the myDevice Cayenne cloud. The figures 3.2 to 3.6 represent the outcome of a 5-days environmental monitoring experiment in which a single unit was used to detect the five environmental factors. Figure 3.2 shows a plot of temperature variation during five days and it cannot be difficult to notice that the high and low temperature happen every day in the daytime and in the night respectively. It is not out of step with what most people already know regarding the degree to which the temperature varies throughout the day. Figure 3.3 and Figure 3.4 depict the air pressure and humidity, and only a small fraction of change is observed basing on the measurements. Figure 3.5 presents the same tendency in the degree of loudness to temperature changes. This is because there will be increased activities during the day, and the activities might also cause noise. And the noise level varies quickly, and this is the inconsistent nature of noise created by different activities. level The content of volatile organic compounds (VOC) in the air is quantified and could be used to describe the air quality. With volatile organic compounds (VOCs) the difference in the day and night is a minute variation.

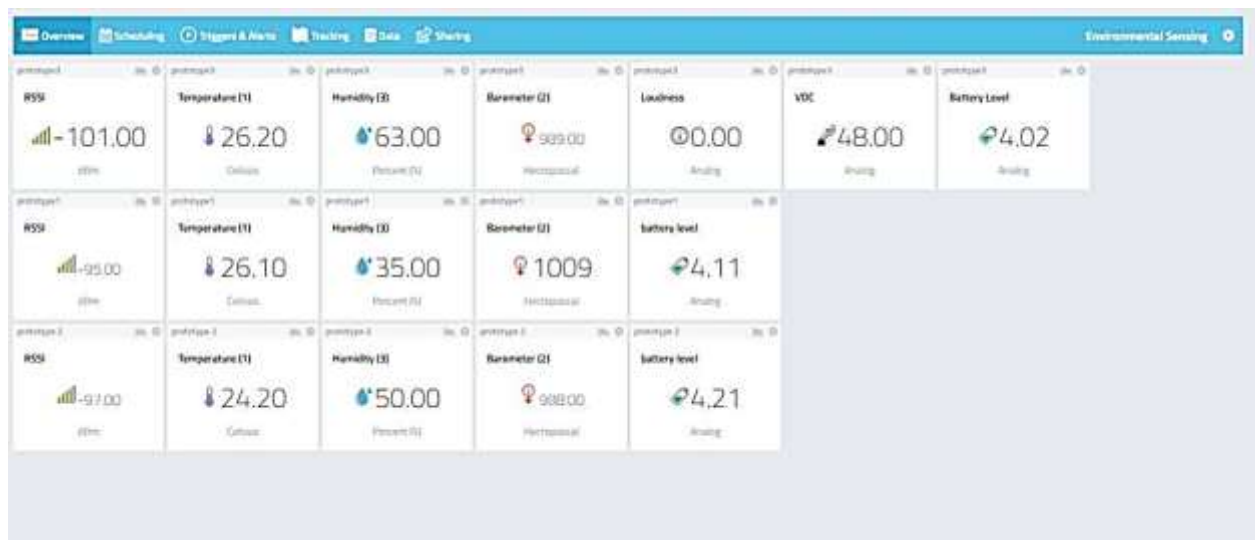


Figure 3.7: The measured results of three sensor nodes.

Three sensor nodes have been used to deploy wireless sensors in order to monitor the ambient environment. Figure 3.7 shows an overview of environmental data obtained with three wireless sensor nodes. All these variables are collected and presented in real time. The

intensity of the signal received by each sensor node can be derived based on the RSSI value and that guarantees a stable connection. A battery level indicates the amount of voltage remaining in the power supply battery and could be used to monitor how much battery life remains. When the sensor node is not functioning properly, this is a significant measure that should be observed. The sensor nodes can be located anywhere as the LoRaWAN gateway has a large range. The users can get all of the measured data of the three sensors positioned in different locations to monitor and control the related activities.

3.3 Coverage Analysis



Figure 3.8: LoRaWAN's test of coverage

A coverage test was conducted at the gateway, and may be viewed at the first level of the Electrical Engineering building in orange. LoRaWAN signal is possible to obtain the reception at the point marked by the green symbol, and impossible at the point marked by the red icon. The signal is being blocked in these two places by the towering structures. LoRaWAN has greater line-of-sight according to the test results, but the signal may be disrupted by obstructions. This implies that a gateway must be installed in a high and unobstructed place whereby it will enjoy optimum coverage upon installation.

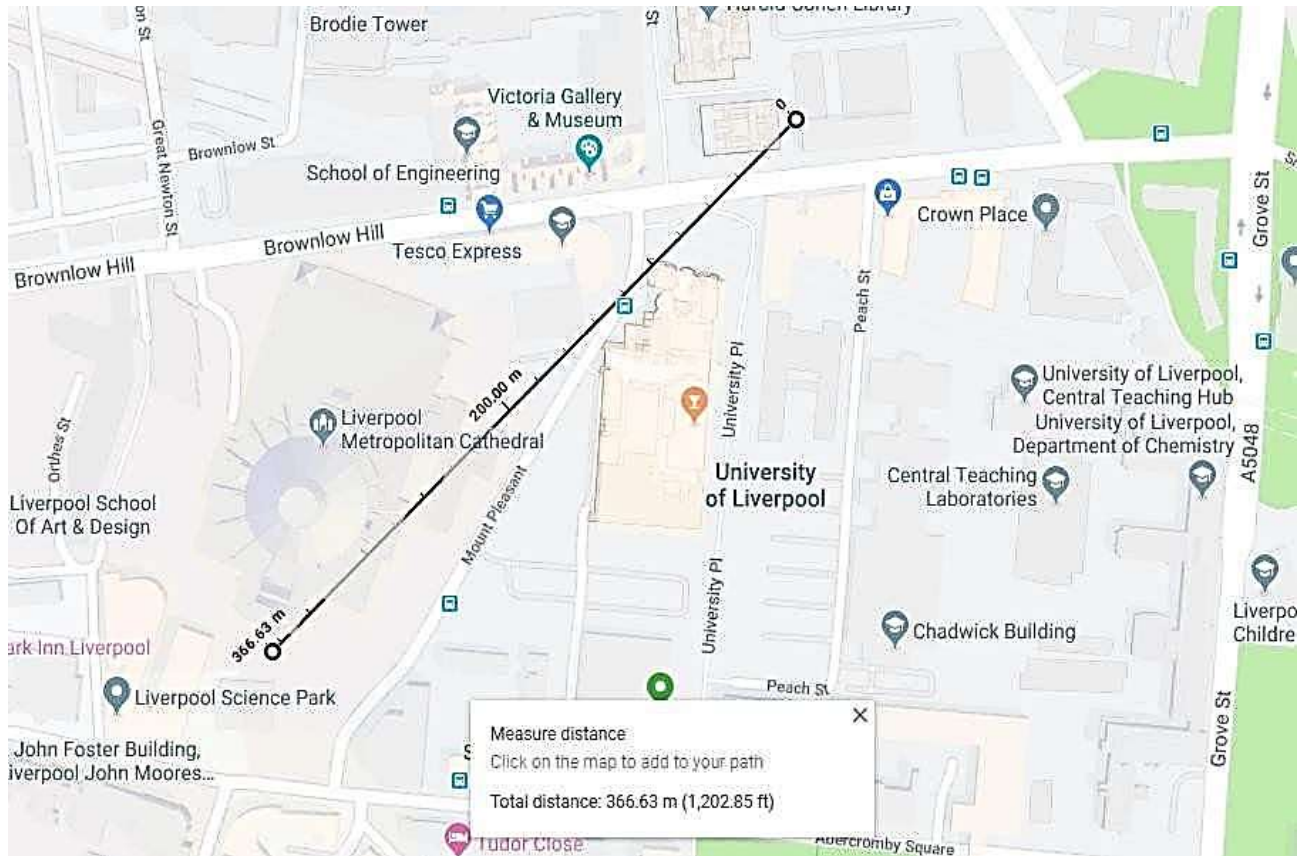


Figure 3.9: The coverage distance of the LoRaWAN gateway

The last test had an approximate coverage of 366.63 m (see Figure 3.9), which is lower than the distance mentioned in the LoRaWAN datasheet. The findings were a perfect match to those of trials of other researchers. Junqing measured 500 meters and Erbati measured 300 meters by using an outside entrance. The LoRaWAN gateway has a low range, and this could be explained by a variety of factors. The transmission power is not very high since it is an inside gateway compared to an outside gateway. Since it is indoors, the walls in the building will absorb the signal lowering the range. There is a 20 dBm loss of penetration in indoor devices. Also, the gateway is placed on the first level, whilst a higher elevation of the gateway would offer more coverage. The entrance is in an urban area and this adds to limited coverage. Tall buildings and other giant street furniture will increase the multipath effect and LoS propagation leading to smaller coverage zones.

Determine the fading margin by the Okumura Hata model to determine whether it is acceptable to the real figure to determine whether it is statistically significant to examine the coverage distance proposed LoRaWAN environmental sensing system. Okumura Hata model estimates a loss of 108 dBm of the route. The maximum power of the transmitting module of the RN2483 LoRaWAN is 10.4 dBm. The location of the gateway internally should increase the loss by the 20 dBm of the route loss on top of that, the lowest sensitivity of LoRaWAN SF 7 is -118.6 dBm, therefore, the received signal intensity was calculated as such. It may be demonstrated that the found results and theoretical values are consistent.

3.4 Energy Performance Analysis

There are sensor ones that need very little power, such as the 13.32 W TPH sensor. Nevertheless, the air quality sensor uses 300 mW of power when active and this would rapidly drain the battery. To reduce total energy consumption, we included a sleeping mode to the MCU. The entire device will be put into a low power sleep so as to conserve energy. Once environmental features are sensed and transferred, the device will reenter sleep in a short period. The MCU or high energy consumption sensors will have no effect on the overall energy performance of the device as they will tend to be in the sleep mode.

Figure 3.10 demonstrates the outcomes of the current consumption measurement of the sensor node in time to obtain numerical values of the energy consumption by the device. A single peak is associated with the board startup and the remaining four are associated with sensor startup, transmission, and two reception windows. The overall wake-up time of the sensor node is 3.5 s. The LoRaWAN transmission also has the highest power requirement of 52 mA when operating at peak. Nevertheless, the transmission time of each transmission is 0.067 s and the energy consumed is 12.395 mJ of energy. The sensor node will consume 3.7 mA when it enters sleep mode and, as such, the power consumption of the sensor node will be 13.69 mW at the end of two receiving windows.

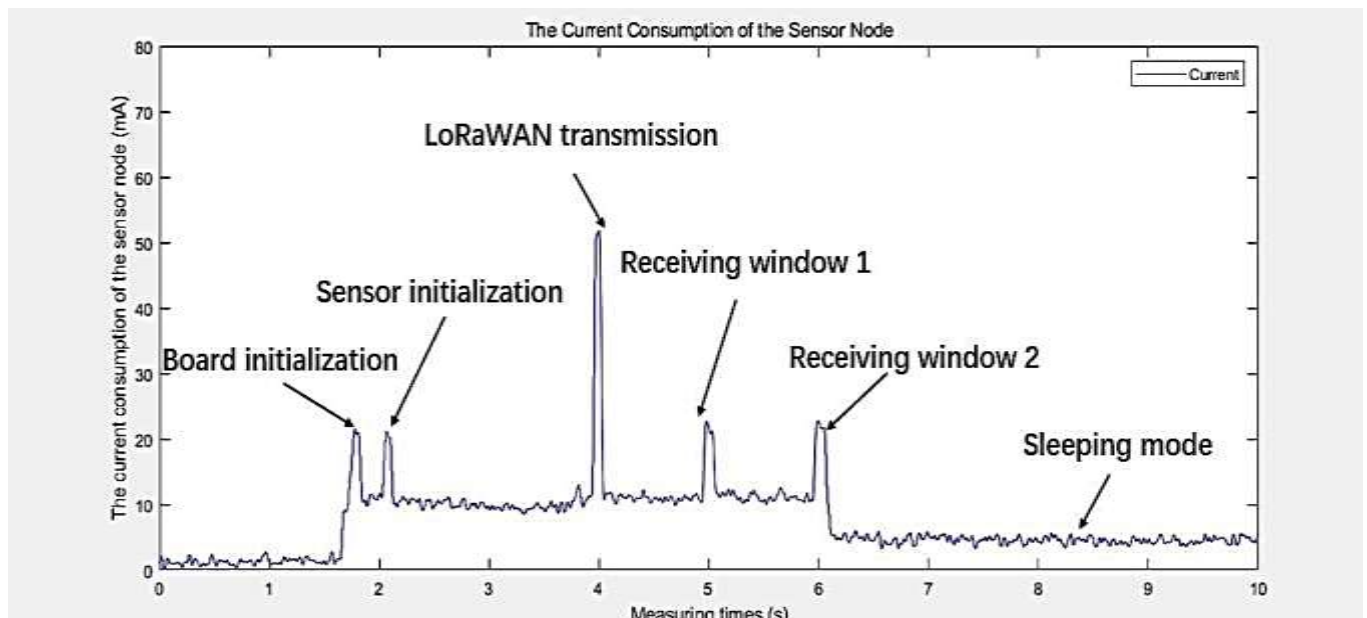


Figure 3.10: The sensor node's power consumption

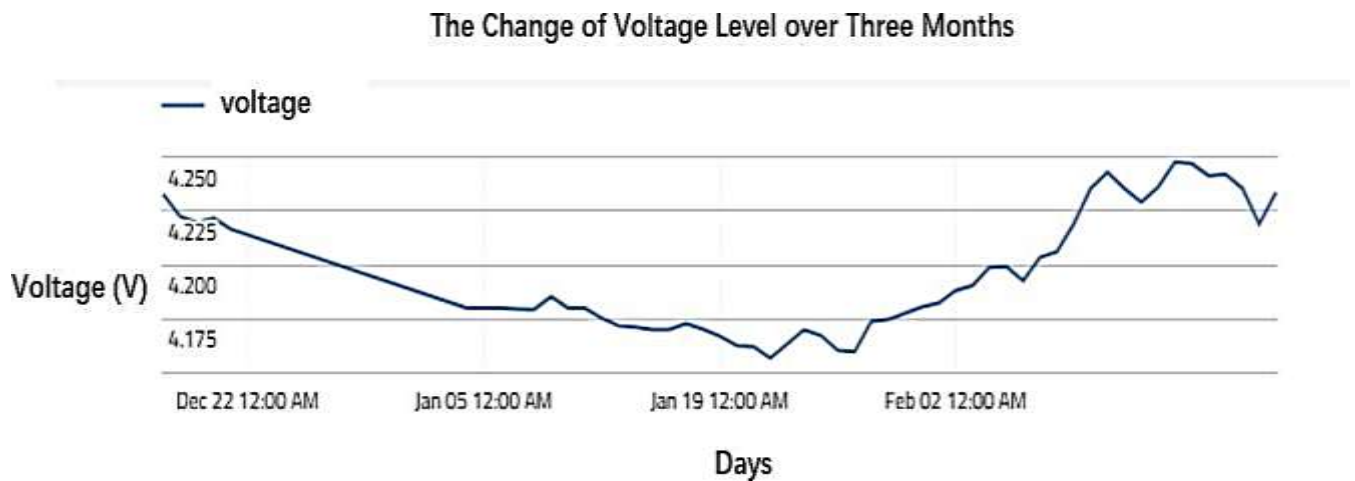


Figure 3.11: In three months, the voltage level went up and down.

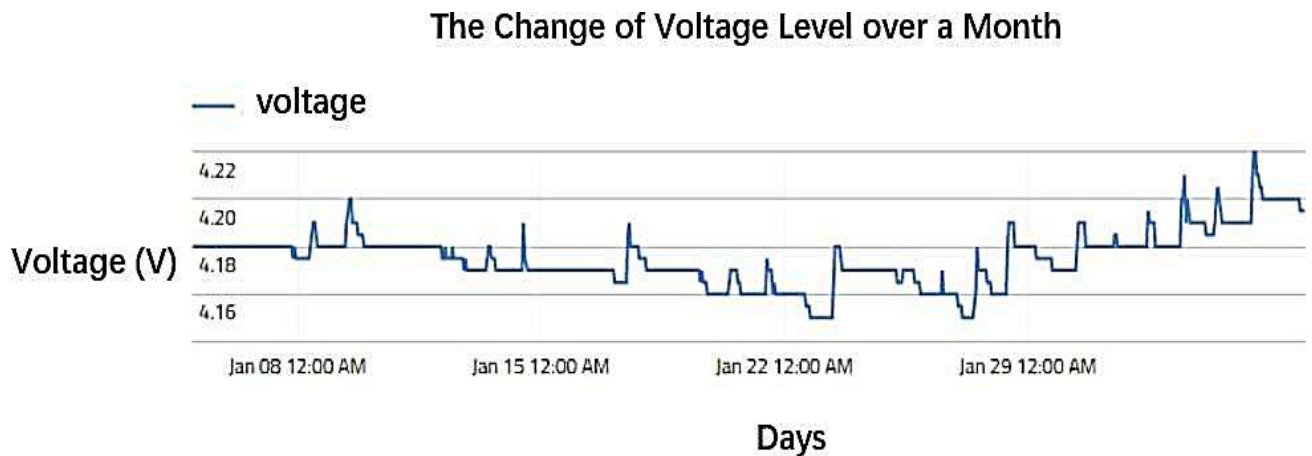


Figure 3.12: In a month, the voltage level went up and down.

On December 17th, 2023, we started the three-month-long monitoring of the quantity of the energy available in the battery of the weather station. In order to determine the amount of energy remaining in the battery, we will use the level of its output voltage. Figure 3.11 depicts three months of battery voltage. Beginning on January 5th, 2024, Figure 3.12 illustrates the shift in a 30-day voltage level in more details. Figure 3.11 reveals that voltage varies through the day. The solar panels do not produce power required, the sensor node consumes the remaining energy in the battery. The weather largely determines solar panel harvesting efficiency. Due to the bad weather between the 17th of December, 2023 and January 22nd, 2024, the voltage level has been decreasing steadily. Even under overcast, solar panels can still be used to charge batteries, and after 10 days, the voltage grows to 3.20 V compared to 3.18 V (see Figure 3.12), which means that the sensor node is getting more energy than it consumes. Here, it is indicated that the sensor node is self-powered because the energy required by the sensor node is less than what the solar panels gather.

The KC 906090P battery of the sensor node is charged and discharged more than 1000 times. A solar panel is used to charge the battery and the battery can be charged very quickly over a comparatively short time. Such a charge method could be aptly termed as shallow discharge. Unlike deep discharge, shallow discharge is favorable to batteries, they can be used longer in

the presence of a solar panel. Theoretically the sensor node could last almost 166 years with a battery provided that it was charged and recharged every two months.

Table 5.1: Comparison of the proposed weather station with other designs

Year	Platform	Environmental Parameters	Energy Consumption	Cloud	Energy Harvesting	Cost
2015	Robin Z530L	Temperature, humidity, air pressure, wind speed	59.75 mW	Yes	No	GBP 100
2017	STM32F103VETb	Temperature, humidity, wind speed, wind direction	68.75 mW	No	Solar panels and wind	GBP 150
2017	(Not given)	Temperature, humidity, wind speed, rain, solar radiation	70 mW	Yes	Solar panel	GBP 140
2017	Raspberry PI and Arduino	Temperature, humidity, air pressure, wind speed, wind direction	1 W	Yes	No	GBP 127.5
2018	Raspberry PI	Temperature, humidity, air pressure, wind speed, wind direction	2.775 W	Yes	Solar panels	GBP 231.81
2019	Arduino	Temperature, humidity, air pressure	50 mW	No	Solar panel	GBP 120
2018	Arduino	Temperature, humidity, air pressure, rain detection	100 mW	Yes	No	GBP 115

2024	Arduino work)	(This	Temperature, humidity, pressure, brightness, loudness, quality	air air	13.69 mW	Yes	Solar panel	GBP 112.59
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The table above gives a comparison of data of multiple weather stations in details. Consequently, every weather station can measure some basic environmental properties such as temperature, humidity and air pressure. Yet, some more advanced functions, including cloud connectivity and energy harvesting, cannot be found in all models of weather stations currently in the market. One of the seven weather stations tested had cloud connectivity and energy harvesting. The second problem is that very little research has examined the amount of power used by these weather stations. Climate station and power harvesting use 2.775 watts of electricity, a lot of power in an electrical device, and they might not be able to be run entirely on batteries. An energy-saving weather station with only 13.69 mW of power consumption can be included in the TTN or Cayenne clouds to allow users to receive real-time data about the measured values. We have demonstrated that with the assistance of solar panels, the weather station can be fully powered by renewable energy.

They were able to combine three weather stations and two clouds to form an environmental sensing platform. One of the potential uses of LoRaWAN is to relocate the characteristics of different weather stations to the cloud and the read data sets can be presented and stored in easily accessible formats. All sensor nodes on this sensing platform are small and self-powered hence the sensor nodes can be placed flexibly. The sensor platform can collect multiple environmental indicators in diverse applications to monitor and administer them.

4. DISCUSSIONS

This paper embarked on development of an environmental sensing platform, which is autonomous, that will be implemented to the applications of Smart City, specifically, weather stations that have LoRaWAN communication system. The integration of the IoT infrastructure, renewable energy, and wireless communication standards can reshape the way in which the urban environments are inspected and monitored. This section describes the results of the study in detail and it is possible to mention that the developed platform is efficient, its potential may be extended to further use in the Smart City applications, and contributions to environmental monitoring.

The defined platform was designed to be self-reliant and operate on renewable energy, in this case, solar energy that allows the self-sufficiency of the system and excludes the need of power supplementation. The point was to develop the system that could monitor any type of environmental parameters, e.g., temperature, humidity, air pressure, brightness, noise level, and air quality and at the same time, be energy efficient and inexpensive. Pilot testing of the sensor nodes in the environment around the University of Liverpool produced the following results which indicated that, in fact, the system was being utilized as intended where the sensor nodes could gather data at long periods without a significant decrease in power. Taking into account the energy performance analysis, the system consumed an average power of 13.69 mW, which is relatively highly energy-efficient in comparison with the existing weather stations that use a lot of energy (Lee, 2002). In one example, the weather station

model where it used a Raspberry Pi consumed as much as 2.775 W which cannot be sustained without the presence of external power source (Kang, Dempster, and O'Hara, 2011). The latter demonstrates the immense advantage of self-powered environmental sensing platform because, not only does it ensure its long-term sustainability, but it also minimizes operational costs to the lowest permissible level since it employs renewable energy sources as the power source fully.

Using IoT, the sensor nodes were connected to LoRaWAN to the cloud platforms, which allowed the realization of the remote monitoring of environmental data. This sensor node information was posted to The Things Network (TTN) and was displayed on the MyDevice Cayenne. This is critical integration in real time monitoring and data accessibility, which is a requirement in Smart City applications (Schaffers, Komninos, and Pallot, 2011). The data collected using the sensors deployed provided real-time information of various environmental factors including temperature, air pressure, and degree of noise that can help the urban planners and policymakers to make effective decisions when it comes to the allocation of resources and management of the environment. Furthermore, the cloud platform allowed storing, retrieving, and analyzing large datasets obtained with the help of the environmental sensing system with ease. This aspect in particular is highly useful to the applications where it is required to detect the air quality and apply traffic regulation where quality and timely information must be delivered to assess the situation and take remedial measures (Evans, 2014). Using the Cayenne Low Power Payload (LPP) format, data was coded so as to reduce the data loss and transmission errors in wireless sensor networks (Dohler and Puchinger, 2011).

Findings of this study were contrasted with some other weather stations already available in the market. The proposed weather station became also very energy efficient compared to the other designs as shown in Table 5.1. The Raspberry Pi-based weather stations has a consumption rate of 2.775 W, which is much higher than that of the developed platform of 13.69 mW. Besides, the potential to be interconnected with the cloud and extract energy that are the key features of the invented system was not a feature of most weather stations. The present comparative analysis points to the usefulness of the suggested design which relies on cloud based connectivity and incorporation of renewable energy collecting. Besides that, the fact that the platform can monitor numerous environmental parameters, including brightness and air quality, makes it a more adaptable solution compared with the other ones that could monitor only such basic parameters as temperature and humidity. Using Raspberry Pi and Arduino weather stations of 2017 as an example, they only measured the temperature, humidity, and speed of wind but did not propose the ability to connect to the clouds and use energy (Steinberg and Cheshire, 2005). It means that the proposed environmental sensing platform due to its multi-sensing capability and inclusion of renewable energy is a superior way of monitoring the environment in urban areas on a more comprehensive basis.

One of the greatest problems with systems of environmental monitoring especially those installed in populous cities is how information gathered by remote sensor nodes can be dependably communicated to a central system. The use of the LoRaWAN communication in the present study was an efficient measure because sensor nodes can transmit information accurately over a considerable range and consume low power. The coverage test outcomes showed that the LoRaWAN network had a range of 366.63 meters within an indoor setup, which was anticipated of the LoRaWAN communication protocol within the cities (Zhao and Zhang, 2018). The fact that LoRaWAN can be combined with linking large numbers of sensors and transmitting information over considerable distances with the use of very small

quantities of energy at the same time is also crucial to the scale-up of the environmental sensors implementation in the cities. This particular aspect is particularly important in the cities where large geographical areas are to be covered, and long-term operation demands energy-saving communication systems (Van Aartsengel, 2013). Moreover, the LoRaWAN network might be linked to cloud computing applications such as the TTN to broadcast and track real-time information, i.e., the environmental data would be punctual and transparent at a long distance.

One of the most important results of the specified research is that the self-powered environmental sensing platform can operate continuously on the basis of the solar energy. The analysis of energy performance showed that the system could be used with a minimum amount of energy expenditures due to the efficient design of the sensor nodes and their integration with solar panels. The three months voltage checking tests showed that the system could collect solar power that could restore life to its battery even during cloudy weather. This observation applies more specifically to the use in the urban environment where there is little energy and environmental sustainability is among the priorities (Maibach, 2008). It is self-charging, meaning that it would be in a position to operate without any supervision during a prolonged period without being dependent on maintenance and regular battery replacement. This is far superior to the previous weather station that the station normally requires to replace its battery very frequently or even utilize power supply; therefore raising the cost of operation and the consumption of power (Miller, 1991). The sensor nodes also have a lesser carbon footprint due to renewable energy thereby ensuring that the system is aligned with the idea of creating sustainable and eco-friendly Smart Cities (Schaffer, Komninos, and Pallot, 2011).

This study revealed that a self-powered environmental sensing platform may be possible and practical in the implementation of Smart City. This platform had the capability to integrate the forces of renewable energy collection, wireless communication and cloud-based data storage to generate an effective and sustainable environmental monitoring platform. The findings of the current work reveal the importance of the energy-efficient design, cloud integration, and the usage of the low-power communication protocol during the creation of smart infrastructure. The pilot deployment within the University of Liverpool is the initial step to the actualization of the mass application of the same to urban areas in the future that contributes towards the construction of a more sustainable and data-driven Smart Cities.

5. CONCLUSION

This study proves that it is practical and effective to have a self-powered environmental sensing platform specific to Smart City applications. The system that combines renewable energy sources such as solar energy and wireless communication networks such as LoRaWAN provides a solution that is sustainable to environmental monitoring in urban areas. The low energy consumption of the platform and its ability to monitor important environmental parameters will guarantee the sustainability of the devices in terms of their operation. The pilot project implemented at the University of Liverpool is successful, which demonstrates the opportunities of this platform to be expanded to larger urban scales as part of the development of smart infrastructure. Besides, the cloud-based integration offers real-time monitoring, storing data and advanced analysis, which is a valuable product to urban planners and policymakers. The results of the current work provide valuable information regarding the combination of IoT technologies with renewable energy and wireless communication into the environmental monitoring systems, implying a promising future of Smart City projects. The platform has a great potential in changing the way cities respond to

environmental challenges and address their operations by lowering operational expenses and lessening the negative impact on the environment. The next step in work could be further optimization of energy usage, expansion of the sensor network and improvement of the platform scale to serve bigger cities.

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