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OF SCIENCE & TECHNOLOGY

DESIGN AND IMPLEMENTATION OF A SECURED SMART HOME SWITCHING SYSTEM BASED ON WIRELESS COMMUNICATION AND SELF-ENERGY HARVESTING

BY

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DESIGN AND IMPLEMENTATION OF A SECURED SMART HOME SWITCHING SYSTEM BASED ON WIRELESS COMMUNICATION AND SELF-ENERGY HARVESTING

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A Thesis Submitted to the Faculty of Engineering and Technology in Partial Fulfilment of the Requirements for the Award of the Degree of Master of Engineering in **Computer and Telecommunications** of BIUST

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June 2020

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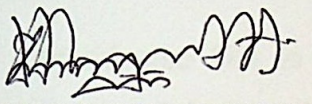
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CERTIFICATION

The undersigned certifies that they have read and hereby recommend for acceptance by the Faculty of Engineering a thesis titled: ***DESIGN AND IMPLEMENTATION OF A SECURED SMART HOME SWITCHING SYSTEM BASED ON WIRELESS COMMUNICATION AND SELF-ENERGY HARVESTING,*** in fulfilment of the requirements for the degree of Master of Engineering in (*Computer and Telecommunications*) of the BIUST.

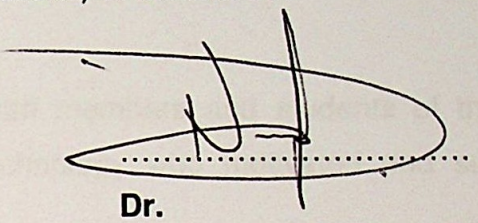


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I would also like to give thanks to the staff members and students of the Botswana International University of Science and Technology who motivated and supported me throughout the research process.

DEDICATION

This thesis is dedicated to God for His provision and sustenance. He has given me all that I could need in both the physical and spiritual aspects of my life.

ABSTRACT

This work presents the design and implementation of a secured smart home switching system based on wireless communications. Traditional Building Switching Systems (TBSS) used in buildings face many problems such as increasing electricity prices, insecure wall sockets, and switches that are vulnerable to misuse. These problems pose inconveniences for the residents of such buildings. As a result, in both private and public buildings, there is a desire to reduce electric usage, automate appliances, and move towards optimizing the electricity usage of buildings. As such, a novel secured smart home switching system is proposed. The proposed secured smart home switching system is intended to integrate physical security (access control) of a building's electricity, renewable energy harvesting, and energy storage for the system's active electronic components. The work gives two contributions to the design of smart home systems. Firstly, practical design and implementation of physical security for a building's power supply which adds a locking feature such that only authorized personnel can alter the power state of the smart sockets and smart switches in a building. Secondly, a model of energy harvesting and storage system for the active electronic components and wireless communication of the system. The results of the research produced an implementation of the system. The secured switching system performed as intended in adding access control to a building's electricity. Installing the secured smart home switching system enables home and building owners to remotely through SMS and locally turn on or off electricity to appliances and lock them to prevent unauthorized use of the buildings' electricity. The renewable energy harvesting system provides renewable energy as intended but consequently has high implementation costs. The energy harvesting system provides an energy harvesting and storage system to remove the operational costs of the smart sockets and switches from a home user electricity bill, but consequently has high implementation costs and is better integrated into an off-grid system.

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LIST OF ABBREVIATIONS

AC:	Alternating current
DC:	Direct current
GPRS:	Global Packet Radio Service
GSM:	Global Systems For Mobile Communication
LCD:	Liquid Crystal Display
MPPT:	Maximum Power Point Tracking
MQTT:	Message Queuing Telemetry Transport
PV:	Photovoltaic
RF:	Radio Frequency
SBC:	Single board computer
SIM:	Subscriber Identity Module
SMS:	Shot Message Service
USB:	Universal Serial Bus
WSHN:	Wireless Sensor Home Network
WSN:	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

Electricity is an important and useful resource with a wide range of applications that play an essential role in the development and functioning of countries and the lives of citizens. Due to its usefulness, its demand has increased over the past years, placing great pressure on its supply and generation. Being a secondary energy source, electricity is generated from converting primary sources of energy such as fossil fuels (coal, natural gas, petroleum), nuclear energy, and renewable sources (solar, wind, hydro, geothermal). Currently, fossil fuels are the largest sources of energy and the primary means of generation. However, the burning of fossil fuels (mostly coal) to release the heat energy used in electricity generation releases greenhouse gases, mainly carbon dioxide, in large quantities, which contribute toward global warming and climate change. Due to the negative impacts caused by a high fossil fuel-based system on the world's environment and climate, the countries and governments of the world are trying to change into clean, greener, and more sustainable renewable energy systems. Such changes demand countries be more conservative by lowering electricity demand and find alternative means of electricity generation. Hence, most countries throughout the world are introducing a range of policies to deliver on reductions and some of the policies extended to the individual (citizens) dwellings and buildings in a positive form such as promotions for buildings with renewable energy sources or opposite method of increase in prices for fossil fuel-based electricity generation through methods such as carbon tax.

Faced with the challenge of high electricity costs on buildings, be it homes, offices, or factories (domestic, government, or businesses), one of the solutions adopted by consumers is the reduction of electricity usage. This requires consumers to be more knowledgeable and conscious of their electricity consumption so that they can take action to adjust their electricity usage habits where possible and incorporate good habits such as switching off electrical appliances that are not in use. However, consumers are not always in the best positions to carry out such tasks effectively, consistently, or conveniently. Aside from the concerns of electricity consumption, consumers with conventional (traditional) buildings also face other problems. Conventional buildings provide electricity to electrical appliances/devices by employing electrical outlets such as sockets and the use of switches. Sockets connect a building's electrical distribution to electrical appliances, and switches control the flow of electricity from a building's electrical distribution to the target appliance. In such conventional switching systems, changing the power state (turning on or off) of appliances is carried out manually by a person onsite physically interacting with the switches and sockets. Working with appliances connected to such switching systems requires the physical presence of a person to monitor and interact with it. This method of control and monitoring is not effective. It is limited since, as humans, tend to, at times, be untimely, forgetful, or unavailable, and this can be an inconvenience and of concern to consumers.

Due to such problems of conventional switching systems, in both private and public buildings, there is a desire to control remotely, monitor, and automize appliances for convenience and to reduce electricity usage. Building automation is one way of overcoming these challenges. Building automation can be described as equipping a building with technologies that enable the control,

monitoring, and management of its appliances, systems, and environment. Examples of a building's systems include lighting, heating, security, ventilation, entertainment, and many more [1], [2]. By extending the range and means of controlling and monitoring appliances using communication networks, sensors, and computing devices, building automation can improve the comfort, energy efficiency, security, and convenience of buildings for people. Homes and buildings with such services are referred to as smart homes and smart buildings.

Smart homes and smart buildings for residents are equipped with building automation services, computing, and communication technology that can control and automate electrical appliances in response to prompt commands and needs of the occupants to promote user comfort, convenience, and security [3], [4]. In the typical establishment of smart homes and buildings, wireless sensor network technology provides a good framework that can be used to easily and inexpensively incorporate smart device technology into existing buildings without the need for dedicated communication and power cables. A Wireless Sensor Network (WSN) is a collection of nodes with sensing, computing, and wireless communication technology that can be deployed in different areas of interest to collect and transfer sensory data to a common point or gateway for forwarding or processing [5], [6]. Some existing solutions (publication based) used in the design of smart homes and smart buildings do so by improving switches and sockets in a building since they are vital to controlling power to electrical appliances [7]–[9]. However, other solutions, especially commercial products, utilise smart appliances, and integrate them into one central system called a hub to create smart homes and intelligent buildings.

By using smart sockets and switches, consumers gain the benefits of home automation or building automation without the cost of replacing every electrical appliance in a home or building with a smart appliance. Instead of purchasing smart appliances and discarding old appliances lacking in the new smart technologies, users can transform already owned appliances into smart ones by plugging them into smart outlets or controlling them with smart switches.

However, as smart home and available smart devices become increasingly popular, most people do tend to require more comfort and home automation devices to upgrade their living spaces to enjoy a high-tech life. This leads to the demand for equipping the houses with different kinds of sensors and actuators for optimal security and ease of appliances control [10]–[12]. By increasing the number of smart sockets, smart switches, and smart appliances installed in our homes for more functionality, energy consumption tends to increase proportionally to the increase in smart appliances. As a result, an operational cost for using existing smart sockets and switches in terms of energy consumption in our homes also increases [12]. The addition of operational costs introduced by the control and automation devices calls for an alternate means for reducing the energy consumption cost due to smart devices.

Even though available smart home and smart building solutions try to solve the challenges of traditional switching systems, the physical security and access control of sockets and switches in buildings remain unchanged. They are vulnerable to misuse or unauthorised use by anyone with physical access to them. Such can result in waste in electricity by unauthorised turning on or off of appliances, disrupting the operation of appliances that should not be turned off or damage to appliances and equipment. Large areas with open movement such as public spaces and buildings

(schools, dorms, hospitals, halls, and many more) are at a higher risk than private buildings (homes, offices, etc.). Still, all can benefit from the added security of which can help create new services and use cases for smart sockets and switches.

This study intends to address these challenges of existing smart sockets and switches used in smart homes and buildings. The study proposes two things. First, practical design and implementation of a secured switching system to introduce security and access control to a building's electricity, hence, allowing only authorized personnel capabilities of altering the power state of sockets and switches in a building. Second, a model of a renewable energy harvesting and storage system to remove the operational costs of the smart socket and switches from a building's electricity bill. Such a system creates a clear distinction of the energy used by appliances in a building, in addition to the one used to control and manage the switching system in place. This enables buildings to remove recurrent energy costs by use of renewable energy, and aids in the scaling of energy supplies used to power smart systems.

1.1. BACKGROUND

1.1.1. Wireless Sensor Networks

Most advances related to building automation, smart homes, and smart buildings can be attributed to improvements in wireless sensor networks. This growth is partly due to advances in wireless communication technologies, improvements in renewable energy harvesting, energy storage devices, and computing devices. All of which are essential building blocks in wireless sensor networks.

In general, wireless sensor networks consist of small-sized computing devices with sensing and wireless communication capabilities. These devices are called nodes. Wireless sensor networks typically have two types of nodes; these are the sensor nodes and sink nodes. Sensor nodes are responsible for collecting information from their environment/sensor field and communicating it to the sink/destination node [13]. The measured data can be any physical phenomenon of interest such as temperature, light intensity, humidity, and many more depending on the application scope and sensing unit attached to the nodes. Depending on the application and size of the WSN, the data collected at the sink node can either be stored and processed locally by the sink node, or it can be forwarded further to a remote place for storing and processing. Fig. 1.1 shows the general layout of a wireless sensor network.

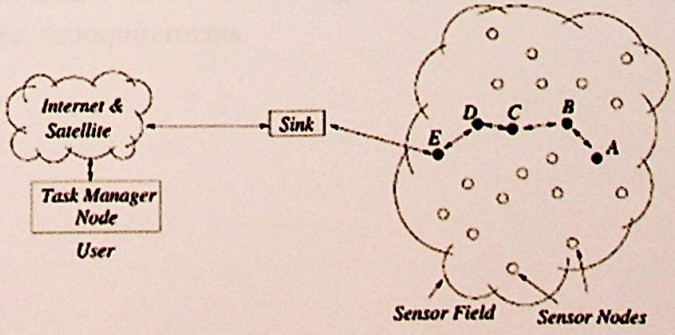


Figure 1. 1: A typical wireless sensor network

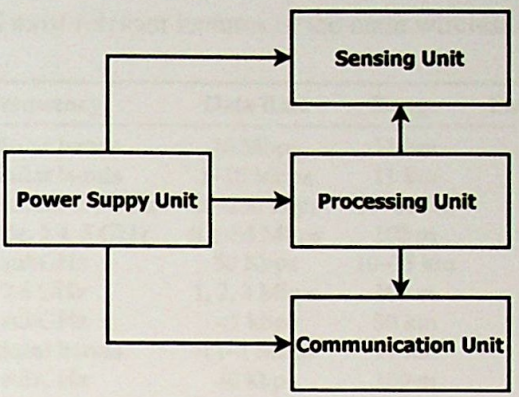


Figure 1. 2: A Structure of a Wireless Sensor Network

As can be seen in the block diagram of Fig. 1.2, the main elements of a WSN node are:

1. **A sensing unit**
   Responsible for collecting environmental data. The type of collected data is dependent on the type of transducer used to build the sensor.
2. **A processor unit**
   The processing unit is used to coordinate the activities of a node. For a sensor node, this includes tasks such as starting the process of collecting sensor data.
3. **A power supply unit**
   It provides the necessary energy to perform the task of a node such as collecting, processing, and transmitting data.
4. **A communication unit**
   To facilitate the communicating of information around the WSN.

Depending on the field of application, additional components can be added to the wireless sensor network node to improve its functionality. The additional components may include units such as actuators to interact with or modify certain aspects of the monitored environment. These can be found in applications such as home automation, smart homes, and smart buildings. Other additions include renewable energy harnessing and storage units to increase the operation time of battery-powered nodes.

Networks used in wireless sensor networks are based on wireless communication standards. Table 1.1 from the review work of [14] shows a comparison of the most relevant features of the main wireless communication standards used in WSN's. Selecting a suitable communication technology depends on the type of application and its requirements.

Table 1. 1. Comparison of most relevant features of the main wireless communication standards

Standard	Frequency	Data Rate	Range	Energy Efficiency	Cost
2G/3G	Cellular bands	10 Mbps	11 km	low	high
LTE Cat 01	Cellular bands	1–10 Mbps	11 km	high	low
6LoWPAN	subGHz and 2.4 GHz	20–250 kbps	10–100 m	medium	low
Low Power Wi-Fi	subGHz, 2.4, 5 GHz	0.1–54 Mbps	100 m	high	low
LoRaWAN	subGHz	50 Kbps	10–15 km	high	medium
Bluetooth/BLE	2.4 GHz	1, 2, 3 Mbps	100 m	high	low
SigFox	subGHz	<1 kbps	50 km	high	medium
NB-IoT	Cellular bands	0.1–1 Mbps	11 km	medium	high
Z-Wave	subGHz	40 kbps	100 m	high	medium
Weightless	subGHz	0.1–24 Mbps	13 km	high	low
802.15.4	subGHz	40, 259 Kbps	15 km	high	low
ZigBee	2.4 GHz	25 Kbps	100 m	high	medium
WirelessHART	2.4 GHz	25 Kbps	100 m	high	low
Thread	2.4 GHz	1, 2 Mbps	10–30 m	high	medium

1.1.2. Renewable energy harvesting and storage

Technological advancements in renewable energy generation and energy storage solutions have vastly improved over the past years and continue to grow as countries around the world intently shift from fossil fuel-based economies to a green energy-based one. Among renewable energy sources, hydroelectric plants are the most popular, followed by the wind and then solar energy. However, solar has gained a lot of interest and is becoming the most preferred in many countries around the world [15]. This is mainly due to the use in photovoltaic systems, especially for off-grid systems and domestic use, despite most solar panels having a typical efficiency below 20%.

Photovoltaic (PV) transducers/cells are the most common energy transducers which convert the solar irradiance received on the earth's surface into electrical energy [16], [17]. A solar panel is a transducer made from a combination of parallel and series electrical connections of PV modules, which in turn are made up of connections of PV cells [17]. The efficiency of the cells and hence the panels that are used for solar energy harvesting is dependent on the amount of solar energy or solar irradiance falling on the panel and the ambient temperature at which the panel is operating [15]. Changes in either solar irradiance, load size, or temperature conditions cause fluctuations in the amount of electrical power being harvested. To maximize the amount of power produced by panel systems and help to maintain relatively constant power generation over a day, Maximum Power Point Tracking (MPPT) through the use of DC-DC converters is used.

In general, MPPT techniques maximize the energy harvesting by modulating the duty cycle of a power switches in DC-DC converter to match the impedances of a solar panel and a load to get maximum power from the PV system. Many methods to perform the MPPT have been presented in the literature. Amongst them, the perturb and observe is the most widely used due to its simple design and ease of implementation through digital systems. Amongst the DC-DC converters, the buck and boost converters are the preferred converter to use in MPPT due to their simplicity and effectiveness at the available price, but they have problems in the tracking under various combinations of the load, radiation, and the temperature. The buck-boost converter is the best suited since it overcomes the challenges of both converters [15], [16]. For applications that require AC electricity, inverters are used to convert DC to AC.

Since the sun does not shine at night, and there may be large fluctuations of solar irradiance due to poor weather conditions during the day, PV systems alone cannot provide a consistent flow of electricity. Hence in certain use cases such as off-grid PV systems, where loads are solely powered by solar, the PV system is combined with energy storage systems such as batteries to compensate for changes in solar irradiance or to power loads in the night-time. The most popular battery technology for PV systems is lead-acid batteries [17], but as of recent lithium battery technology, performance and production has improved and is becoming a more economically viable option. The size and battery technology of an energy storage bank significantly impact the overall cost of PV systems. The larger the battery system, the higher the cost and the longer the time of investment return [16]–[18].

PV systems have a higher initial cost of installation than conventional power generator solutions, and they, however, also lower running costs than traditional power generators. Therefore off-grid systems in regions that lack grid electricity and where solar energy is abundant, PV systems offer long term economic benefits and reduced routine cost [19]. Botswana's climate is well suited for solar PV systems; on average, Botswana receives an average of 5.16 KWh/KWp daily of photovoltaic output power. This makes it ideal enough to exploit and generate renewable energy [19], [20].

1.2. MOTIVATION

Advances in technology have significantly improved the performance and size of computing, sensing, energy storage, and wireless communication modules and hence an improvement in wireless sensor networks of which are integral in the implementation of smart homes and smart buildings. This in turn has made smart homes and buildings gain tremendous research interest because of their various applications in both the private and public sectors.

Under the public sector, Botswana could benefit from the proposed system by using it in public or government buildings such as schools, offices, and hospital facilities. These are buildings with high volumes of people and large spaces to monitor. The application of the proposed system in such buildings improves building management. It gives management the ability to control who has access to their building electricity, and it also provides a means of controlling or monitoring multiple appliances from a central location.

On another note, some Batswana are investing in rental houses. Under the private sector, Landlords with multi-tenant offices, buildings, and residences can benefit from such systems by using them to partition their home and building electrical sockets and switches based on tenant's rooms or living spaces. Tenants that do not pay for the electricity, waste electricity, or use unauthorized appliances can have their sockets isolated and locked to prevent them from using them.

Adding security or access control to homes and building sockets and switches adds a new layer of functionality that can be explored through creative software designs. This is to create new services and interesting ways home, and building owners can impose restrictions on how users interact with their home and building power supply.

1.3. PROBLEM STATEMENT

Electricity is an essential resource with growing demand and increasing cost, hence in both the private and public sectors, there is a desire to save and use it wisely so as to save money proactively. Existing smart home and building systems can provide monitoring, automation, and control of electrical appliances in a building. Still, these systems do not have an independent power supply, and they lack security and access control measures for the sockets and switches in the buildings. The absence of security and access control for sockets and switches in a building leaves them vulnerable to misuse by unauthorized users, which can lead to electricity wastage or damage to electrical appliances and property. Powering the smart home and building system control and communication circuits with power from the building adds a cost to the owners. Both missing features from the existing smart home and building system are a problem, especially for large buildings or buildings with shared spaces such as schools, hotels, and flats.

1.4. AIM

The main aim of this research is to design, implement, and test a wireless sensor network-based smart home switching system with two main functions. First, a secured switching system to introduce security and access control to a building's electricity supply and second, a model of energy harvesting and storage system to remove the operational costs of the smart sockets and switches from a homeowner's electricity bill.

1.5. OBJECTIVES

The specific goals of this research work are:

1. To design a security system that controls access to the power supply of a building through a locking mechanism that allows authorized personnel to alter the power state of the smart sockets and switches.
2. To design a model of an energy harvesting and storage system for the active electronic components, the circuitries, and wireless communication for smart switches and sockets.
3. To implement and test the performance of the designed smart home and building system and energy harvesting system.

1.6. CONTRIBUTIONS

The approach adopted by this work contributes to two main things:

1. Practical design and implementation of a security system that controls access to the power supply of a building through a locking mechanism that allows authorized personnel to alter the power state of the smart sockets and smart switches.
2. A model of energy harvesting and storage system for the active electronic components of the circuitries, and wireless communication for smart switches and sockets.

1.7. RESEARCH PUBLICATIONS

The following research outcomes of this study have been published/submitted in international journals and books:

1. **J. Gaboitaolelwe**, A.M. Zungeru, J.M. Chuma, N. Ditshego, T. Semong, "A formal analytical modeling and simulation of wireless sensor home network," in International Journal of Intelligent Engineering and Systems, vol. 13, Issue 3, pp. 56-68, 2020. DOI: https://doi.org/10.22266/ijies2020.0630.06.
2. A.M. Zungeru, **J. Gaboitaolelwe**, B. Diarra, J.M. Chuma, L.-M. Ang, L. Kolobe, M. David, I. Zibani, "A Secured Smart Home Switching System based on Wireless Communications and Self-Energy Harvesting," in IEEE Access, vol. 7, pp. 25063-25085, 2019. DOI: https://doi.org/10.1109/ACCESS.2019.2900305. IF: 4.098

1.8. THESIS OUTLINE

The structure of the thesis is divided into five chapters that are broken into related sub-sections. A summary of the organisation of the thesis is outlined as;

1.8.1. Chapter 2: Literature Review

This chapter presents a study and comparison of smart home and smart building implementations, energy harvesting and storage systems, and wireless sensor networks that have been studied in this research work. Previous work is explored and analysed to get a better understanding of smart home and smart building systems, energy harvesting systems, and wireless sensor networks in general, outlining the factors that are crucial in their design and implementation.

1.8.2. Chapter 3: Research Methodology

This chapter describes the framework that is to be followed in the research study to design and implement and test a secured smart home switching system based on wireless sensor networks. The approach is described in detailed steps to provide a better understanding of the work undertaken.

1.8.3. Chapter 4: Results and Analysis

This chapter discusses the results obtained from the testing of the implemented system design.

1.8.4. Chapter 5: Conclusions and Future Works

This chapter presents an evaluation of the objectives that were presented earlier in the research work. The chapter informs whether the intended objectives have been met through the research methodology that was proposed. The different methods applied are validated under this chapter, and recommendations are made based on the evaluation. Finally, future directions to improve or advance this work are highlighted.

CHAPTER 2

LITERATURE REVIEW

INTRODUCTION

This section discusses some of the existing approaches and designs of smart home systems based on wireless networks. Previous work is explored and analysed to get a better understanding of existing smart home and building systems.

2.1. RELATED WORKS

Smart home appliances can be easily controlled using wireless technologies. Han et al. [21] proposed home automation based on energy management schemes that utilize ZigBee wireless communication to minimize standby energy consumption. In their proposed work, the power cut-off of standby appliances connected to the power outlet, server, and a ZigBee hub are the major constituents of their system. The power outlet of their system using a ZigBee module tends to break the power mains whenever there is a low energy consumption associated with the devices connected to these power outlets. In the system, the central hub collects information and controls the intended power channels using the ZigBee module. In related work, Gill et al. [22] also proposed a ZigBee-based home automation system consisting of a home network unit and a gateway. The main idea of their approach is the incorporation of interoperability of networks of different structures in the home environment, for which there is not much home automation in their design.

Song et al. [23] proposed a home monitoring system based on hybrid sensor networks. Their idea of the combination of different sensors in the home monitoring application is to use roaming sensors to move around various locations in the home environment and participates in the network, most especially when the network is disconnected. Also, in [3], a system integrating WSN with a service robot for the smart home monitoring system is proposed for home automation. In a similar work, [24] recommended the use of a WSN-based intelligent light control system needed for indoor environments applications, which is directed towards home energy management for a reduction in energy consumption. Similarly, Suh and Ko [25] proposed an intelligent home control system that utilizes wireless sensor network/actuator networks with link quality indicator-based routing protocol. The proposed work intends to enhance network reliability using a link quality indicator approach. Their work is like the work reported by Suh and Ko [25], Nguyen et al. [26] that utilizes a rehabilitation-based approach on the optical linear encoder (OLE).

Even with the advancement of home automation [27], additional functionalities are needed to be able to catch up with fast-growing smart systems. In this, Lien et al. [27] have improved upon the earlier work by [27], which developed a system that can be controlled using GSM wireless and Bluetooth technologies. However, authors in [27], [27]-[28] have suggested that home power outlets could better be controlled using the Power Line Communication (PLC) module. The authors developed systems to back-up their claims. The more robust system developed by Bai and Hung [29] using Zigbee technology, is one of the few power outlet systems that adapt wireless sensor networks (WSNs) in home automation. Other likes of approaches are reported in [8] and [30], which uses Zigbee wireless

communication to switch off and on remote outlets, but by using different methods. Similar to work in [31] and [28], Lien et al. [32], Lee et al. [33] proposed the use of PLC interfaces embedded system in the smart home. Their system was able to switch on and off appliances, monitor current consumption, and also add the feature of sensors for monitoring the living conditions and optimization of energy savings in the smart home.

The use of Zigbee technology was also reported in the work of authors in [34], [34]–[36], though, using different approaches. In [37]–[39], wearable devices for monitoring and management of power grid, in addition to musical activities, were introduced and reported to aid in improving home automation. A kind of shift approach using the open alternative of Zigbee alliance that includes internet protocol (IP) communication, using IPv6 over low-power wireless personal area networks (6LoWPAN), is reported in [40] and [41]. An extension to work in [40] and [41], Mattern and Floerkemeier [42] proposed the use of the internet of things (IoT).

Various smart sockets and switches that utilize the Zigbee microcontrollers of frequency 2.4GHz are some of the proposed approaches of authors in [12], [21], [34], [43], [44]. In their work, simultaneous real-time data on power as well as on and off the appliances were both achieved. In [9], [45]–[47], the use of the analog-to-digital converter (ADC), and wireless power consumption and time-of-use (ToU) was introduced to enhance smart home system development. Though the work in [47] does not include the design of a control unit, hence, sockets cannot be controlled automatically. In a similar approach, Singaravelan and Kowsalya [48] developed a system that can bring down the standby power of appliances to zero. However, the work in [48] does not also include real-time power monitoring.

Recently, Rahim et al. [49] proposed an energy management system using a hybrid scheduling technique with the aim of reducing electricity consumption cost, peak to average ratio, and maximization of user comfort. The authors employ a hybrid scheduling technique, an optimization technique involving the Bacteria foraging algorithm, and the Harmony search algorithm. The authors, however, introduce the concept of coordination amongst smart appliances and achieved by the help of the large data generated from the appliances of multiple homes with the joint work of heuristic techniques and Dynamic Programming. The authors evaluated the performance of the proposal, and a comparison was performed with already existing techniques of which the proposal had a significant improvement in energy management. Furthermore, with the simulated results, their proposed method validates the desired objectives while considering consumer comfort.

In a similar work, a demand-side management scheme proposed by Rahim et al. [50], uses elephant herding optimization (EHO) and adaptive cuckoo search (ACS) algorithms to achieve similar objectives. The system's effectiveness regarding electricity utilization cost, peak to average reduction, and consumer comfort maximization were achieved. Authors in [7] also proposed a smart power socket and central control system that utilizes the Zigbee communication protocol to control devices connected to smart power sockets. The system is designed such that smart sockets wirelessly provide the necessary data to a central controller, to reduce energy consumption in a smart building. Experimental results show that the proposed smart socket can correctly read the power consumption of wirelessly connected devices from up to 18m away without loss of data. The central controller can effectively control multiple sockets from a scheduled user program code. The system was implemented and tested for 24 minutes, which shows an improvement in the home energy management system.

In this work, the system comprises of WSN application, Smart House, and Energy harvesting for the support of the secured smart home switching system.

2.2.WIRELESS SENSOR NETWORKS

Wireless Sensor Network (*WSN)* is an area of research that is growing very fast and has recently attracted responsiveness in the worldwide business market, standardization of industries, and academic research. A *WSN* system lends itself to several applications, including monitoring of the battlefield or other environments, detecting and rescuing from disasters, smart agriculture, traffic control, and object tracking, medicine, and health care as well as environment-friendly buildings.

WSN is a collection of small size, relatively inexpensive computational nodes with sensing, computing, and communication devices. These devices are usually powered by batteries and deployed in different areas of interest. They sense conditions in and around their environments and other factors such as temperature, pressure, humidity, vibration, sound, and radiation and forward the measured data to a common point to be processed. The *WSN* node can detect the environment, pass the sensed information to other neighbouring nodes as well as compute the data that it has received. The wireless sensor nodes are responsible for sensing and gathering data from a source point, pre-process it, and transmit through a transceiver back to its intended destination point or sink [13]. Energy is expended during the sensing, processing, and communication stages in a *WSN*.

WSNs can dynamically adapt to changes in their environment, a quality that makes them suitable for deployments in conditions where the network topology changes at a fast rate. *WSN* should be capable of deploying a huge number of tiny sensor nodes that can be able to assemble and configure themselves for a common purpose. Most applications of WSNs adopt an ad-hoc deployment of sensor nodes, and these nodes must be capable of independently organizing themselves with no planned or external coordination and form a wireless transmission network. Fig. 2.1 illustrates the different sub-units of a wireless sensor node [13]. The node has the following basic units:

1. A sensing unit
2. A processor unit
3. A power supply unit
4. A communication unit

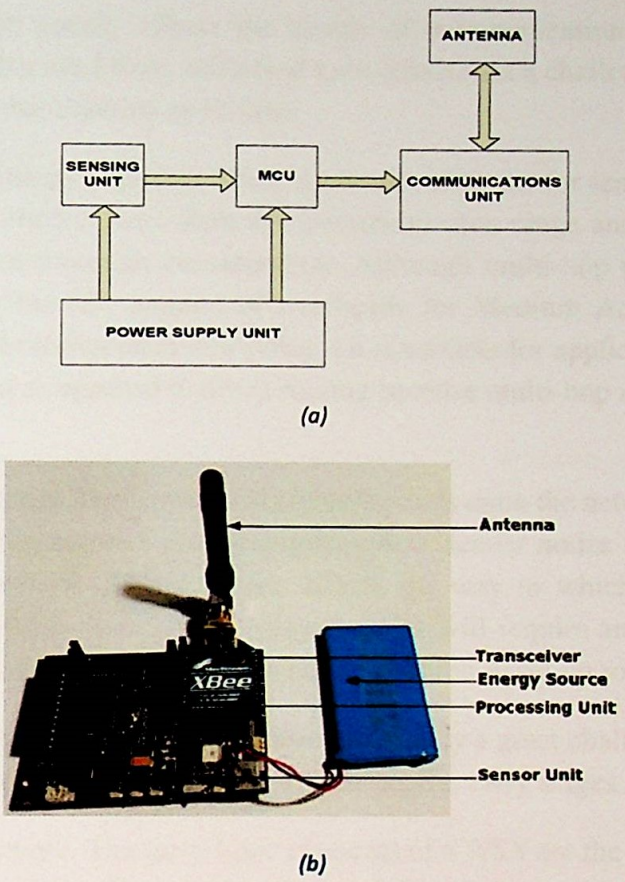


Figure 2. 1: (a) A Structural Blocks of a typical WSN and (b) An example of a standard WSN node and it's associate parts [13]

Additional components can be added to the WSN based on the desired application [51], [52]. This study is focused on designing a wireless home sensor network. The heart of every computer network lies in its communication protocol. The communication protocol discovers paths that are used for information exchange in the network under an existing set of constraints. Some of the factors which need to be considered when designing sensor networks are discussed in sub-section 2.2.1.

2.2.1. Factors to be considered when designing WSNs and communication protocols

Due to the dynamics of the operating environment of *WSNs,* and a huge number of sensor nodes, the architectural design of sensor networks experiences some distinctive challenges. To address some of these challenges, and issues of power dissipation, scalability, responsiveness, and tolerance to a fault, data aggregation, cost of production, and many others, new ideas or systems have to be put in place. The design of a model for the structure

of a network system greatly affects the design of communication protocols. It is also affected by factors that need to be addressed to overcome such challenges. Authors in [13], [53]–[55] identifies these factors as follows:

1. Inadequate Energy Capacity: The main source of power for sensor nodes is batteries, which are limited in their capacity. Communication range and power consumption must be given thorough consideration. Although multi-hop routing schemes may increase a noticeable amount of overheads for Medium Access Control (*MAC*) protocols and management of topology, it is suitable for applications of information dissemination as opposed to direct routing because multi-hop routing consumes less power.

2. Node deployment: Deployment of nodes depends upon the network application. The structure of the network also determines how sensor nodes should be distributed across the network, which in turn affects the way in which the communication protocols perform. Randomly deployed nodes will require an infrastructure where they can organize themselves in an ad-hoc fashion to set up routes efficiently.

3. Sensor Location: Positioning of sensors is usually a great challenge when designing communication protocols, particularly during the early stages of path-finding.

4. Dynamic Network: The three basic elements of a *WSN* are the sensor nodes, events, and the destination. The sensor nodes and destination node can either be fixed or mobile, but in most applications, nodes are fixed and ought to support the movement of the destination nodes in the network. This means careful consideration has to be taken to keep the routing data stable in the network

5. Hardware Resource Constraints: The limited resources of storage capacities and processing abilities pose challenges of low computational capabilities. This, alongside the limited energy, is a threat to the network and software algorithm design for sensor networks, and they need to be taken into consideration.

6. Aggregation and Data Collection: It covers any physical event of the sensor network, which could be instigated by events, queries, or programmed time or a combination of two or more. Data collection systems are very important for sensor network direction-finding. This is because, on the reception of messages, the node has to forward the messages to the end node.

7. Latency: This is the delay from one end of the network to another. It describes the amount of time it takes for a message to be moved from a source node to the destination node and can either be a one way (from source to sink) or two-way trip (from a generator to destination and back from destination to a generator). Latency can be affected by both data aggregation and forwarding of data through multiple hops.

8. Scalability: Network nodes are usually deployed in large numbers. Scalability defines the network routing protocol's ability to tolerate and react to the dynamics of the network.

9. Fault tolerance: The general performance of the network and handling of tasks should not be affected by insufficient or lack of energy source, interference from the environment, or physical damage of any particular sensor node in the network.

10. Traffic pattern structure: This feature differentiates *WSNs* from other network types like wired networks and *MANETs*. It defines the behavioural outline of the network based on the amount of communication and how it reacts to changes in events. The traffic arrangement could be query-driven, where the sink node forwards a request to some network nodes to seek interest for information with an expectation to get a reaction with the information that is sought after. In a pattern of traffic that is instigated by events, traffic usually flows as a result of an event in some parts of the network. In a continuous monitoring traffic pattern, events are forwarded at regular intervals to the destination nodes. The choice of the routing protocol is determined by the pattern chosen in gathering or sensing of information [13].

2.3. ENERGY HARVESTING

Energy harvesting is a process of capturing environmental energy and generate electric energy [10]. There are many types of harvested energies, such as Radio Frequency (RF), sun radiations, vibration, or heat. These sources differ in their ambient densities, type of transducers, and type of electrical current they can harvest (DC or AC). In essence, the DC sources are solar and thermal, and the AC sources are RF and piezoelectric transducers. The circuit in Fig. 2.2 demonstrates the principle of a transducer delivering maximum energy.

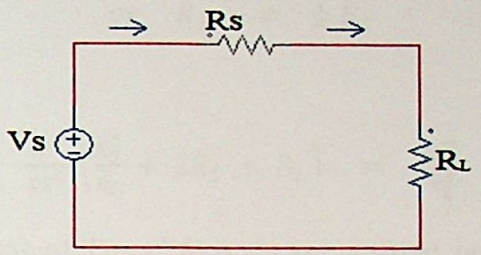


Figure 2. 2: A typical source and load circuit

In Fig. 2.3, the circuit has the following parameters

$$\text{Voltage Source} = V_S$$

$$\text{Source Resource} = R_S$$

$$\text{Load Resistance} = R_L$$

By Ohm's Law

$$\text{Source Current} = I_s$$

$$I_S = \frac{V}{R_L + R_L} \tag{2.1}$$

The power at the load R_L is defined as

$$P_L = I^2 R_L$$

$$= \left(\frac{V}{R_S + R_L}\right)\left(\frac{V}{R_S + R_L}\right)R_L = \frac{V^2}{R_S^2/R_L + 2R_S + R_L} \tag{2.2}$$

$$= \frac{R_S^2}{R_L} + 2R_L + R_L \tag{2.3}$$

Differentiating the Eqn (2.3) with respect to R_L, this gives Eqn. (2.4) as:

$$\frac{d}{dR_L}(R_S^2/R_L + 2R_S + R_L) = -R_S^2/R_L^2 + L \tag{2.4}$$

For upper and lower limits (maximum and minimum), the first derivatives are zero, hence,

$$\frac{R_S^2}{R_L^2} = 1$$

$$or \quad R_S = \pm R_S \tag{2.5}$$

And

$$\frac{d^2}{dR_l^2}\left(\frac{R_S^2}{R_L} + 2R_S + R_L\right) = \frac{2R_S^2}{R_L^3} \tag{2.6}$$

For R_S and R_L, positive values, Eqn (2.6) is always positive, hence

$$R_S = R_L \tag{2.7}$$

Therefore, the two parameters R_S and R_L of Energy Harvesting System (EHS) in Eqn. (2.7) are linearly dependent and maximum power is transferred when the value of impedance load matches that of the source.

2.3.1. Ambient Energy Transducers

Ambient energy harvesting is a promising technique to solve sustainable and long term power supply problems at remote nodes [56] . The ambient energy sources are solar, radio frequency, thermal heat, vibration, and so many more. The approach of integrating more than one energy transducer in a single unit where several ambient energy sources can be captured either simultaneously or separately enables sufficient energy for remote nodes [56]. A photovoltaic transducer is a relatively powerful technology and relatively simple to run [57], but unutilized during the night. On the other hand, thermal heat is permanently available [58]. The deployment of a particular energy transducer must be based on the criteria of such remote nodes.

2.3.1.1. Photovoltaic Transducer

A photovoltaic transducer is typical for the deployment of energy harvesting. It converts ambient irradiance into electrical power, and its energy source is relatively high when it is available during the day. If integrated with other energy transducers, it delivers more reliable and continuous electrical energy [59].

Fig. 2.3 illustrates an equivalent circuit of a photovoltaic transducer consisting of a current source connected in parallel with a forward-biased PN junction diode and a shunt resistance R_{SH} all in series with resistance R_S. While the current and voltage relationship is expressed in Eqn. (2.9). The ambient irradiance and temperature variations influence the performance of a solar cell [60]. Similarly, photovoltaic transducer characteristics such as I_{PV}, I_D, R_S, and R_{SH} in Fig. 2.3 affects it.

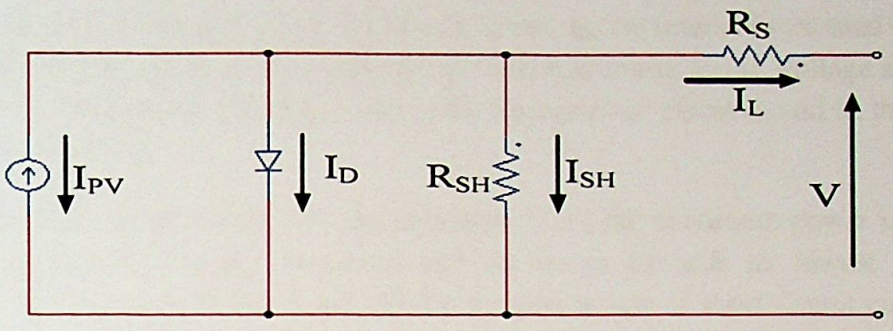


Figure 2. 3: Equivalent Solar Cell Circuit

Where I_{PV} = Current generated from irradiance incident on the solar cell

I_D = Diode Current

R_S = Parasitic Series Resistance

R_{SH} = Parallel Shunt Resistance

V_{OC} = Open Circuit Voltage

A current source I_{PV} feeding the diode, a voltage across the resistances in Fig. 2.3. By Kirchoff's Current Law, the load current, I_L is expressed as [61]:

$$I_L = I_{PV} - I_D - I_P \tag{2.8}$$

$$I_L = I_{PV} - I_s \left\{ \exp\left[\frac{q(V+IR_S)}{KT_CA}\right] - 1 \right\} - \frac{V+IR_S}{R_{SH}} \tag{2.9}$$

$$I_D = I_s \left\{ \exp\left[\frac{V+IR_S}{KT_CA}\right] - 1 \right\} \tag{2.10}$$

$$I_P = \frac{V+IR_S}{R_{SH}} \tag{2.11}$$

Generated Power, P = IV, where

$I = I_L$,

$V = V_{OC}$,

$$P = V\left\{ I_{PV} - I_S \left[exp\left(\frac{q(V+IR_S)}{KT_CA}\right) - 1 \right] - \frac{V+IR_S}{R_{SH}} \right\} \tag{2.12}$$

Where I_{PV} is the generated Current, I_L, Load Current, I_S, the reserved saturated Current of the Diode, I_P, the Current flowing through parallel resistance, V, the Voltage across the Solar Cell, T_C, the operating Temperature, q, the Charge of an electron, and K, the Boltzmann's constant.

In the equivalent circuit of Fig. 2.3, applying Eqn. (2.2), the maximum power is achieved when resistances R_{SH} largely increases, and R_S moves towards its lowest value. To determine the Maximum Power Point (MPP), the constraints of short circuit current (I_{SC}) and open-circuit voltage (V_{OC}) for the energy transducer are utilized. The Short Circuit Current I_{SC} is proportional to the irradiance at 25^0C or below and remains steady when the temperature varies [62]. V_{OC} can be expressed as [63]:

$$V_{OC} = \frac{kT}{Q} \ln\left(\frac{I_{sc}}{G} + 1\right) \tag{2.13}$$

$$\text{Output Current} = I = I_{SC} - G\left(e^{q\frac{V_D}{kT}} - 1\right) \tag{2.14}$$

V_D is the Voltage across the Diode D, G, the Irradiance

If Current $I_L = I_{SC}$, then V= 0 for Open Circuit Voltage (V_{OC}), and it relies on the characteristics of the solar cells. If $I_L = 0$, $V_{OC} = V$.

2.3.2. Energy Bank (Lead Acid Battery)

Conventionally, a battery has a voltage source that depends on the state of charge, internal resistance (R_{batt}), and parallel RC network, as shown in Fig. 2.4 [64]. The circuit describes the relationship between terminal voltage, R_{batt}, and the open-circuit voltage V_{OC} (V_{source}). The R_{batt} determines the energy loss of a battery due to the current flow through which generates internal heat [65], [66]. The value of a terminal voltage determines the self-discharges, which are losses of charges during an idle state of the battery. The self-discharge and internal heat losses are internal phenomena of battery, which cause V_{OC} decays, and as expressed in Eqn. (2.15).

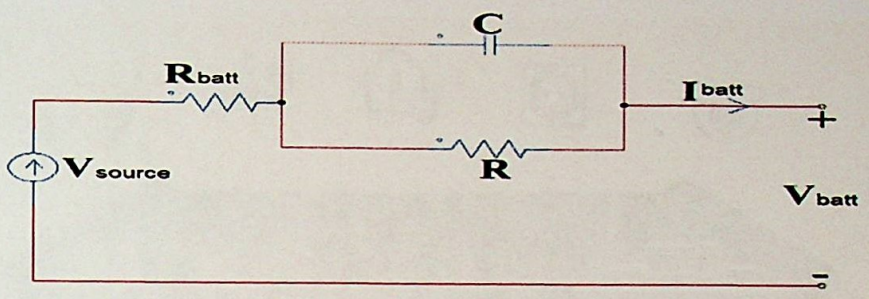


Figure 2. 4: Equivalent Battery Circuit

$$V_{batt} = V_{source} - V_{Rbatt} - V_R, \quad (2.15)$$

2.4. SMART HOME APPLICATIONS

Smart homes, popularly known as home automation, are residential areas using networked devices to enable remote monitoring and management of home appliances. The goal of smart homes is to provide homeowner's security, comfort, and convenience to homeowners at the same time giving them control over their home appliances often through a smart home mobile application on their smart devices [67]–[69]. Smart home controls appliances such as lighting, climate, appliances, entertainment, and security systems such as access controls and alarm in a home. The functional diagram of a smart home is shown in Fig. 2.5. Protocols such as Z-wave and Zig bee enable communication between smart home systems through mesh network technologies over short-range, low power radio signals. A centralized master home automation controller (smart home hub) controls devices in a smart home. The smart home hub is a hardware device that interfaces other smart home devices with the ability to sense, process, and communicate data wirelessly. The smart hub integrates several applications into a single, smart home application for purposes of remote control and management by homeowners. Smart home hubs include Google Home, Samsung Smart Things, Amazon Echo, and many others. Other smart-home systems can be developed from scratch using prototyping boards such as Raspberry Pi or even purchased as bundled smart home kits. Artificial intelligence and machine learning are increasingly applied in smart homes to allow home automation applications to learn about their environment and offer personalized services to homeowners according to their preferences and patterns using applications that use virtual assistants such as voice-activated systems, e.g., google chrome. An example of a smart home scenario is a time-triggered event, for example, lowering blinds at a time every single day, or when the user's smartphone approaches the door, the smart lock will unlock or lock the house.



Figure 2. 5: Smart home

CONCLUSIONS

Concerning true home automation, the references mentioned earlier encounter some drawbacks such as; (1) The security of the mains power supply to prevent unauthorized personnel from switching home and building power supply to the appliances on or off; (2) Each of the control units of the switches and sockets consumed the home main power supply, thereby increasing the cost of running the home automation. Hence, the proposed work intends to solve the mentioned two major challenges by designing a secured smart home switching system based on Wireless Sensor Networks and a self-energy harvesting system for the control electronics in the smart home. Processing

CHAPTER 3

RESEARCH METHODOLOGY

INTRODUCTION

This chapter outlines the methodology to be followed in the research study to design, implement, and test of the secured smart home switching system based on wireless sensor networks prototype. In each section, the methods are described in detailed steps to provide an understanding of the work to be undertaken. Fig. 3.1 depicts the structure of the methodology used to guide the design.

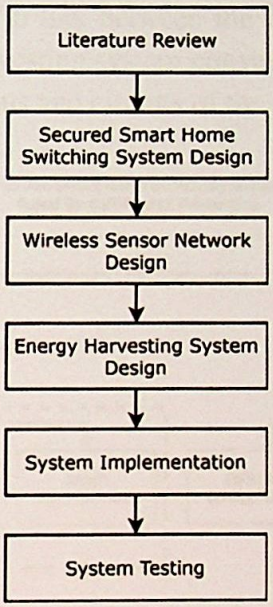


Figure 3. 1: Methodology

3.1. REVIEW OF LITERATURE

The study of journal articles, conference proceedings, and documentation from reputable sources such as Science Direct, Scopus, SpringerLink, IEEE XPLORE, and many others were conducted at the initial stage of this work. Keywords such as smart (home/building/sockets/switches), wireless sensor networks, wireless communication, and internet of things were used to aid in search of relevant documentation to gain a better understanding concerning the problem as well as existing solutions.

3.2. DESIGN OF SECURED SMART HOME SWITCHING SYSTEM

This section further describes the design of the secured smart home switching system. In this section, the design of the system is broken down into three sections showing the different aspects undertaken in the design process. As shown in Fig. 3.2, the structure of the secured smart home switching system consists of three sub-systems. These are secured smart home switching systems, wireless sensor networks, and energy harvesting systems. The secured smart home switching system has two main functions. Firstly, it provides basic smart home functionalities such as centralised local control and remote control over SMS. Secondly, it includes access control security to a building power supply, starting from the switch box up to the sockets and switches. The wireless sensor network is used to create a wireless communication network to link between the devices of the secured smart home switching system. The energy harvesting system converts solar energy to electrical energy to power the electronics components and circuits of the secured switching system.

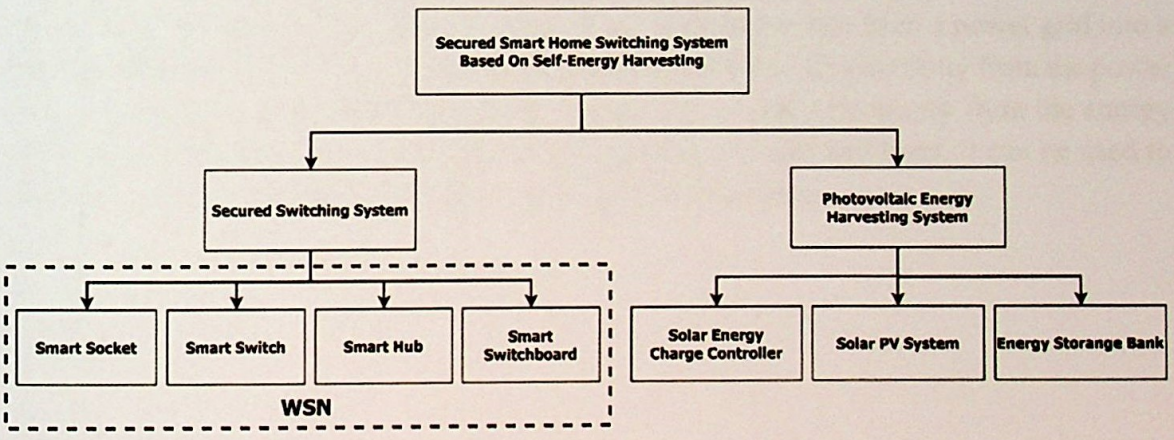


Figure 3. 2: Structure of Secured smart Home Switching System

3.2.1. SECURED SMART HOME SWITCHING SYSTEM

This section describes the design of the secured smart home switching system. The design of the system is divided into four components. Each component is considered a sub-system of the secured smart home switching system. As shown in Fig. 3.2, the secured switching system is divided into four sub-systems: (1) Smart hub; (2) Smart socket; (3) Smart switch; and (4) Smart switchboard.

The smart hub is the centre of the secured smart home switching system. It provides centralized control and monitoring of a building's electricity by creating the system's network and acting as a gateway to bridge the internal wireless sensor network to external cellular networks using a Global System for Mobile (GSM) capable Universal Serial Bus (USB) modem. Through interaction with the smart hub, an authorized user can remotely as well as monitor locally, control, and lock the power states of smart switches, smart sockets, and smart switchboards in a building and hence monitor and control the state of appliances connected to a buildings power supply.

The smart switches, smart sockets, and smart switchboards are both sensors and actuators of the system. They are used to control the flow of AC electricity to appliances in a building based on the commands wirelessly communicated from the smart hub or based on sensed input from a user's physical interaction with the switches present on them.

Fig. 3.3 shows an overview of the entire system. The system has two power sources; one is the energy harvesting system, and the other is the main power line from a power grid into a building. The solid black lines represent Alternating current (AC) electricity from the power grid, and the thick dashed lines depict the Direct current (DC) electricity from the energy harvesting system. By implementing this system in homes and buildings, it can be used to monitor, control, and secure the electricity supply of a building.

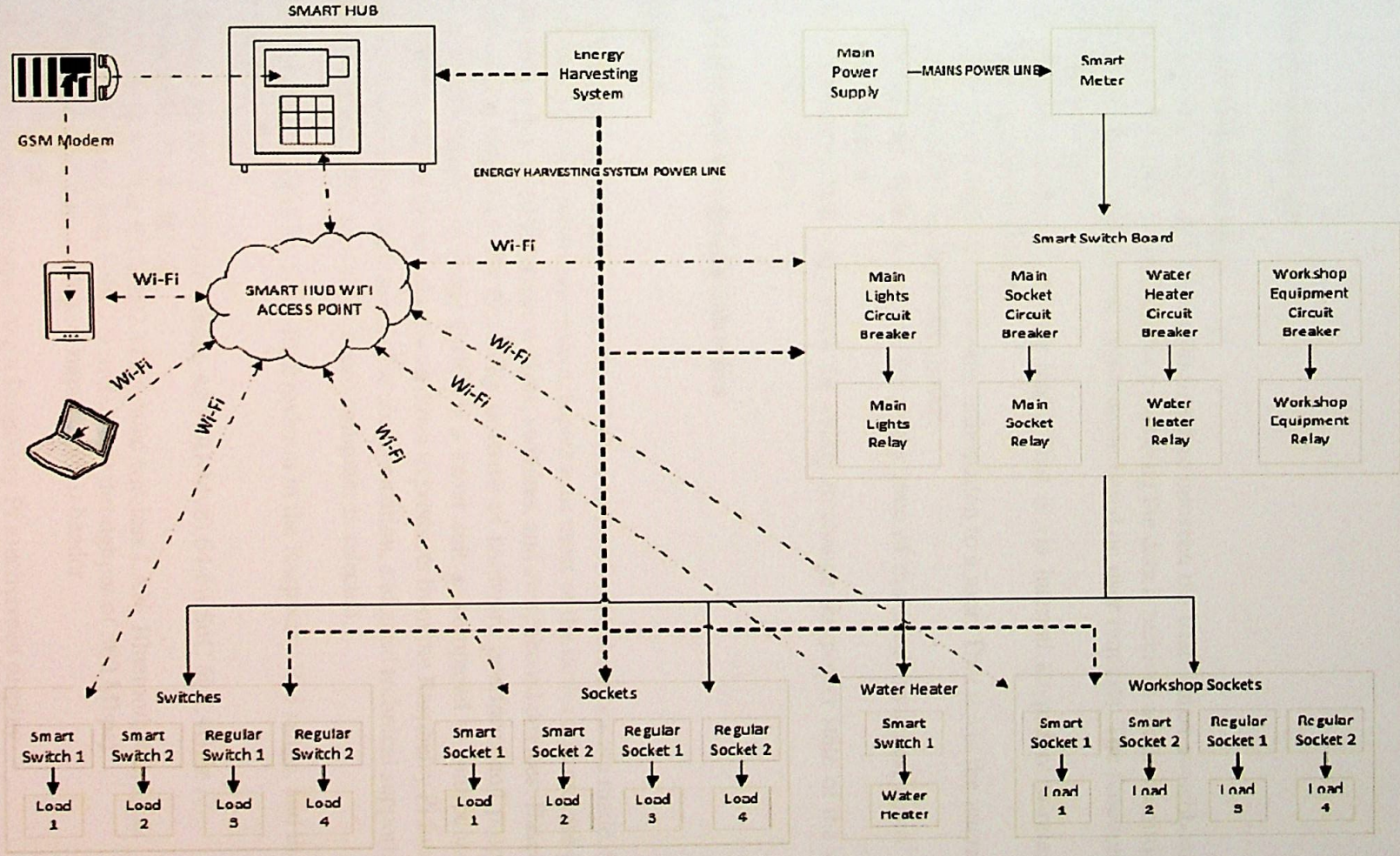


Figure 3. 2: Overview of Secured Smart Home Switching System

3.2.2. Smart Hub Design

3.2.2.1. Smart Hub Functions

The role of the smart hub is to act as an interface between the user, smart switchboard, smart switches, and the smart socket. It is responsible for processing the data it receives and transmitting responses to the end nodes or displaying the relevant information based on user requests. The functional requirements of the smart home hub are:

a) Have two methods of user input. That is via internal keypad or wirelessly through Short Message Service (SMS).
b) Have two methods of relaying information to a user. That is via the internal display monitor or wirelessly through SMS service.
c) Wirelessly turn on and off the power state of the smart switches, smart sockets, and smart switchboard.
d) Wirelessly lock and unlock the ability to change the power state of the smart switches and smart sockets.

3.2.2.2. Smart Hub Hardware Selection

Processing Unit

In selecting the processing unit for the smart hub, a series of considerations are made. Since the smart hub acts as the core of the smart house system, it performs most of the duties that require processing, storing, and transmitting data from the smart sockets, switches, and switchboard devices. Based on the anticipated workload and leaving room for flexibility in terms of hardware interfaces and programming language options, a Single Board Computer (SBC) is a better suit as compared to microcontrollers. Out of the available SBC's, the selection is narrowed down to products from the Raspberry Pi foundation due to their large support community, easily accessible documentation, and good technical support. From the available SBC's the Raspberry Pi 3 Model B+ board computer is selected.

The Raspberry Pi 3 Model B+ is the final revision in the Raspberry Pi 3 range, and these are some of its notable features [70]:

1. Broadcom BCM2837B0, Cortex-A53 (ARMv8) 64-bit SoC @ 1.4GHz
2. 1GB LPDDR2 SDRAM
3. 2.4GHz and 5GHz IEEE 802.11.b/g/n/ac wireless LAN, Bluetooth 4.2, BLE
4. Gigabit Ethernet over USB 2.0 (maximum throughput of 300 Mbps)
5. 40-pin General Purpose Input Output (GPIO) header
6. 4 USB 2.0 ports
7. DSI display port for connecting a Raspberry Pi touchscreen display
8. Micro SD port for loading your operating system and storing data

9. 5V/2.5A DC power input

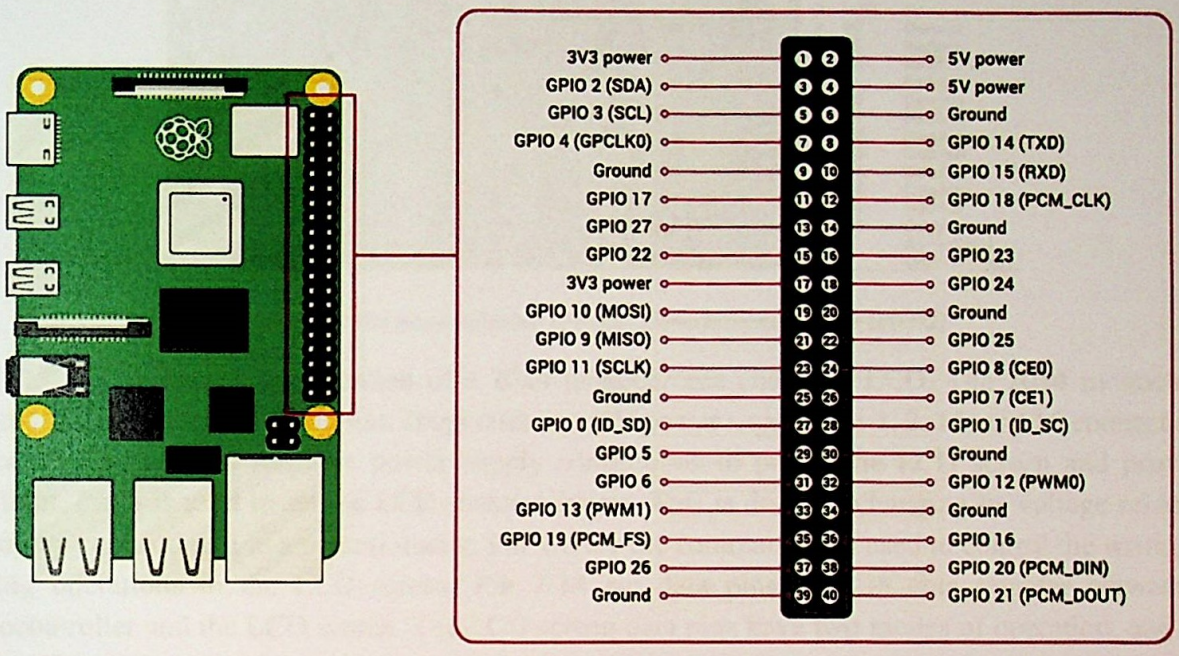


Figure 3. 4: The pin specification of Raspberry Pi 3B+ [71]

Fig. 3.4 shows the pin specification of a Raspberry Pi 3 B+. The Raspberry Pi SBC has a total of 40 pins that can be used to interface with other devices and components. The SBC also provides pins that can be used to supply low power 5V and 3.3V devices. With such a high number of GPIO pins, the Raspberry Pi can be easily interfaced with other devices such as a keypad or LCD screen. The board also has USB ports that can be used to connect devices that support the USB, such as modems and external storage devices.

Display Unit

One of the very important features of a display is to provide users with a good visual interface that is readable and understandable. The bigger the display, the easier it is to interact with a system and the smaller the display is, the harder and longer it is to retrieve visual information. The price of a display is influenced by the technology used in its design and its size. Generally, big displays with new technology cost more. Touch screen displays act as both input and output devices. Their main disadvantage is their high cost compared to regular displays. The 20x4 monochrome character LCD is selected to be the balance between screen size and readability. It is big enough to not strain the user's eyes when reading but also not too costly as compared to touch screens.

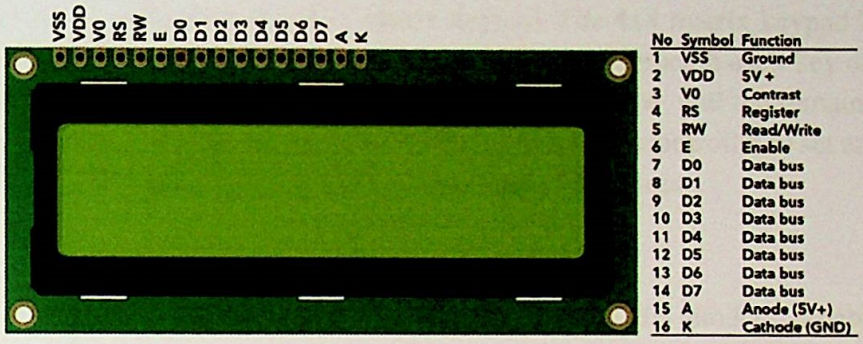


Figure 3. 3: The pin specification of a 20x4 monochrome character LCD [72]

Fig. 3.5 shows the pin specification of a 20x4 monochrome character LCD. The 20x4 monochrome character LCD has a total of 16 pins. It operates on a 5V power supply. Pin 1, 2, 15, and 16 connect to the respective positive and negative power supply connections to power the LCD screen and provide a backlight. Pin 3 is used to set the LCD screen contrast. This is done by changing its voltage relative to ground by connecting it to a potentiometer. Pin 4-6 are the command pins used to control the writing and reading operations to the LCD screen. Pin 7-14 are data pins used in data transfer between the microcontroller and the LCD screen. The LCD screen data pins have two modes of operation, and these are parallel mode and serial mode. In parallel mode, all 8 of the data pins are used to transfer data while in serial mode, only the last 4 pins (11-14) are used.

Input Method

A 4x4 matrix membrane is chosen as the input device for the smart hub. The keypad has both numerical and alphabetic characters, and hence through a thoughtful user interface design, a membrane keypad can be used to navigate through the different options and features provided by the smart hub. These options include actions such as entering pin codes for access control or interacting with the alphabet keys to perform some special tasks such as selecting options and navigating through menus in the smart hub.

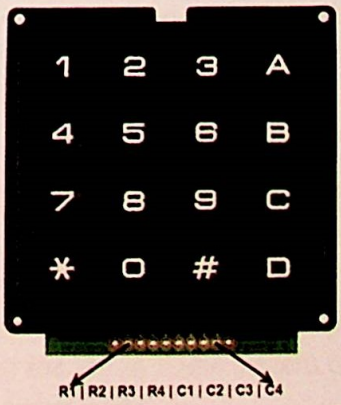


Figure 3. 4: The Pin specification of 4x4 matrix keypad [73]

Fig. 3.6 shows the pin specification of a 4x4 matrix keypad. The 4x4 matrix keypad has 16 keys and 8 interfacing pins in total. Each pin is connected to traces that run underneath each key on the keypad PCB board. Pins R1 to R4 are for traces that connect keys in the same row, and the remaining pins C1 to C4 are for the keys in the same columns. By using 8 GPIO pins of a microcontroller to set and read the voltage state of the keypad pins, it is possible to detect and determine a keypress.

GSM Module

To add SMS functionality to the smart hub, the Huawei E 303 USB modem capable of GSM/GPRS communication is used to create a link between a user's GSM/GPRS enabled phone and the smart hub processing unit. GSM is an architecture used for mobile communication in most countries. GPRS is a packet-oriented mobile data service that is an enhancement of GSM systems that enables a higher data transmission rate and connection to the internet. A GSM/GPRS module is a chip or circuit that is used to establish communication between devices and a GSM or GPRS system. GSM/GPRS modems consist of GSM/GPRS modules assembled with a power supply circuit and communication interfaces (UART, RS 232, USB, and others).



Figure 3. 5: The photo of a USB GSM modem [74]

Fig. 3.7 shows a photo of a USB GSM modem for the local mobile carrier service provider "Mascom." With the modem installed on a compatible computing device such as the Raspberry Pi, the device can be used to transmit and receive SMS over the mobile carrier service provider network. To use the SMS capabilities of the modem, a registered Subscriber Identity Module (SIM) card is first inserted into the modem, and the modem is interfaced with a computing device through a USB port.

3.2.2.3. Smart Hub Block Diagram

Fig. 3.8 shows the block diagram of the smart hub. The smart hub block compromises of a Raspberry Pi single-board computer, a USB dongle GSM modem, a 4x4 membrane keypad, and a 20x4 monochrome LCD screen. The GSM modem creates a link between the Smart Hub and a user's cell phone. The LCD screen provides visual data for the user interface. The keypad is an input device for the system's user interface. The Raspberry Pi acts as both the Smart home system control and network access point for the smart switchboard, smart sockets, and smart switches.

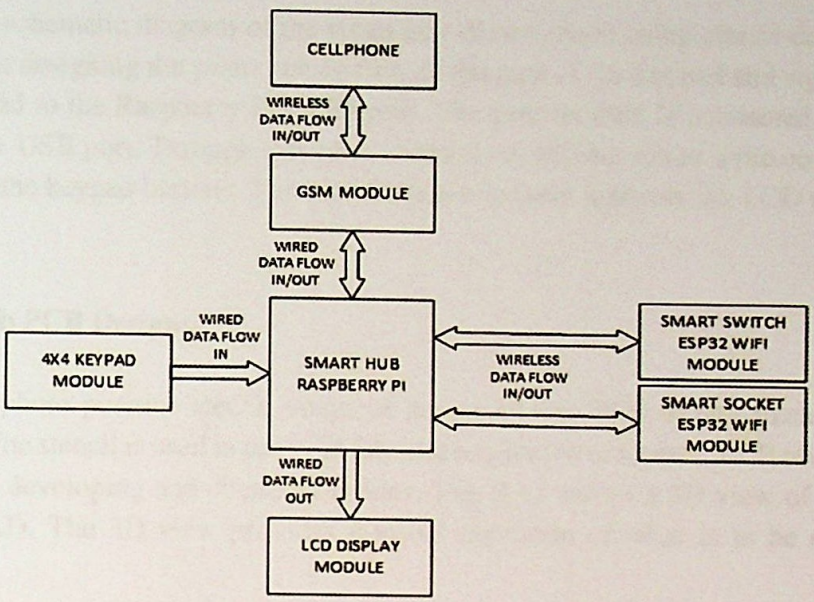


Figure 3. 6: Data flow between smart hub components

3.2.2.4. Smart Hub Circuit Schematic Design

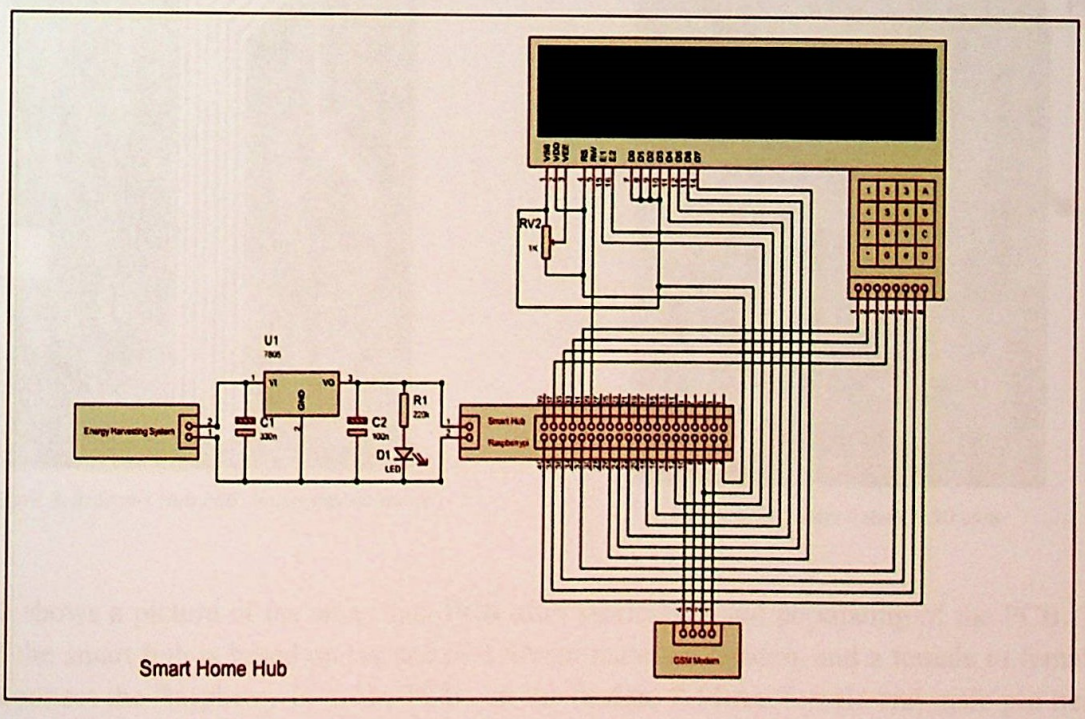


Figure 3. 7: Smart Hub Circuit Diagram

Fig. 3.9 shows the schematic diagram of the smart hub device made using circuit design and simulation software Proteus. In designing the smart hub circuit, all the pins of the keypad and signal pins of the LCD screen are connected to the Raspberry Pi GPIO pins. The gsm module is connected to the Raspberry Pi through the built-in USB port. Through software, instructions will be sent to write on the LCD screen and to read the state of the keypad buttons. The use of a potentiometer controls the LCD screen contrast.

3.2.2.5. **Smart Hub PCB Designs**

Fig. 3.10 shows a photo positive stencil image of the smart hub PCB design made using PCB design software KiCAD. The stencil is used in the PCB fabrication process to transfer PCB traces onto Photoresist coated PCB before developing and chemical etching. Fig. 3.11 shows a 3D view of the smart hub PCB generated in KICAD. The 3D view provides a visual depiction of what is to be expected after PCB fabrication.

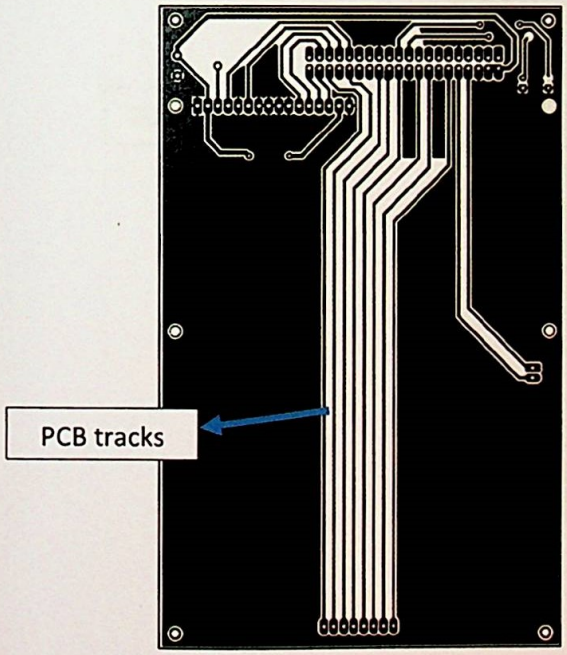


Figure 3. 8: Smart Hub PCB design stencil image

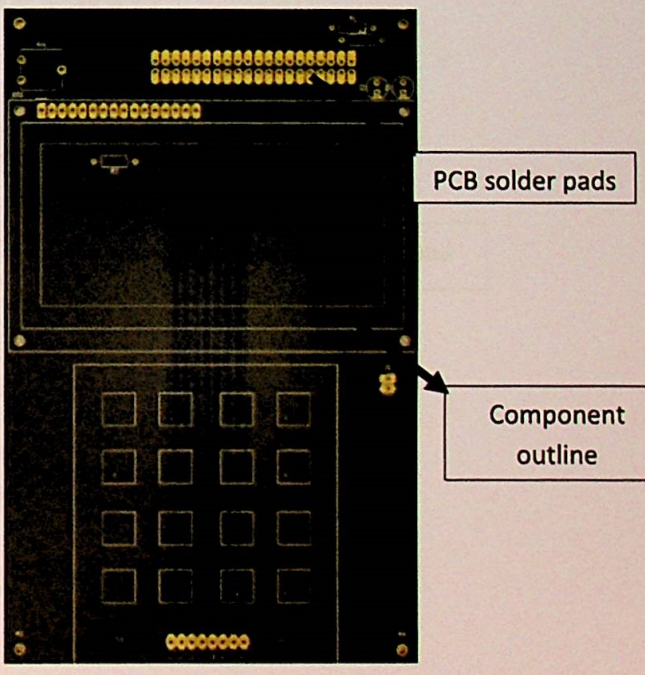


Figure 3. 9: Smart hub PCB 3D view

Fig. 3.12 shows a picture of the smart hub PCB after fabrication and populating of the PCB. The PCB design of the smart hub is based on the use of 2.54mm male pin headers and a female to female ribbon cable to connect the Raspberry Pi to the PCB. In the design, 2.54mm female and male pin headers are used in connecting the LCD screen and the keypad to the PCB.

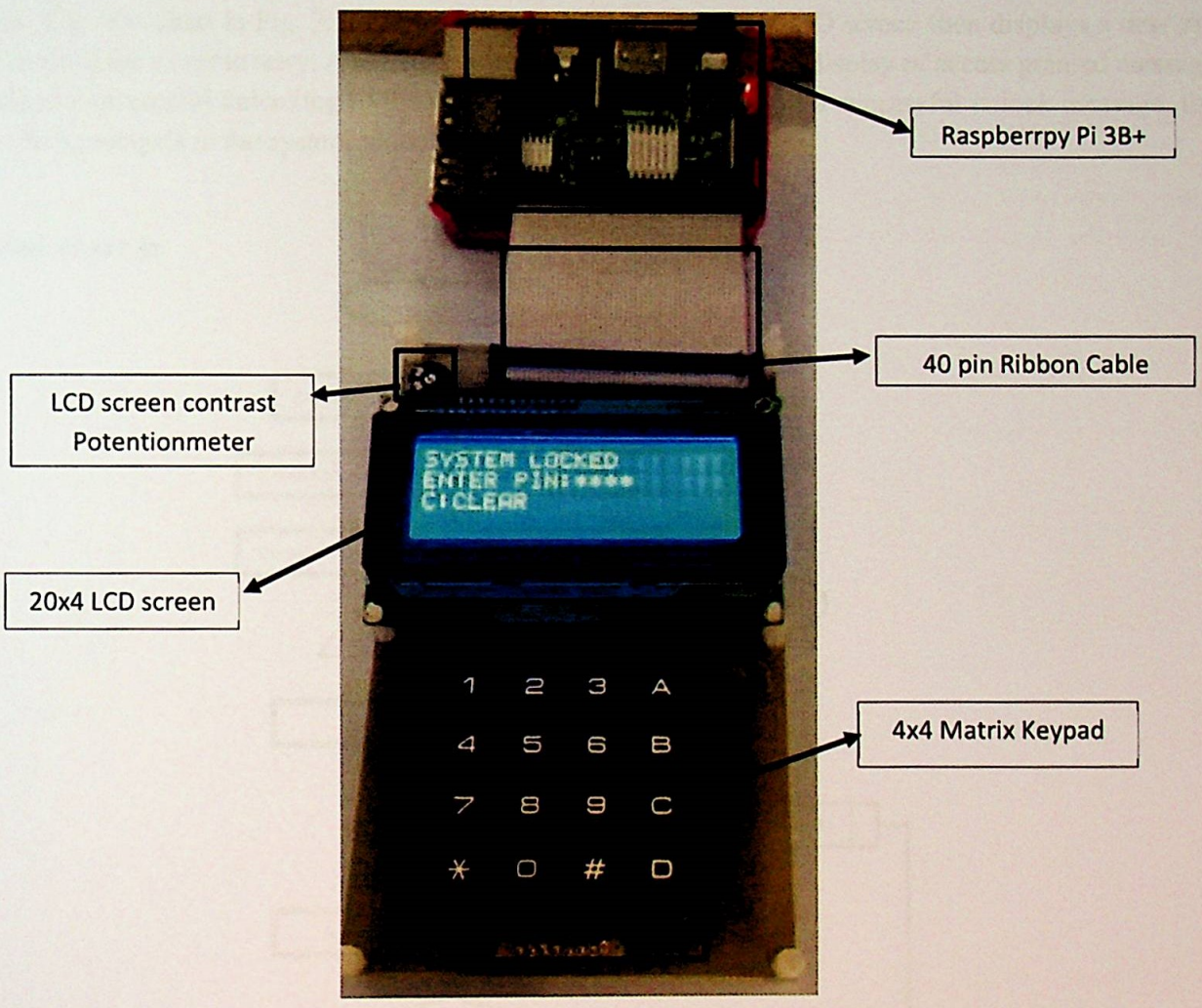


Figure 3. 10: Populated smart hub PCB

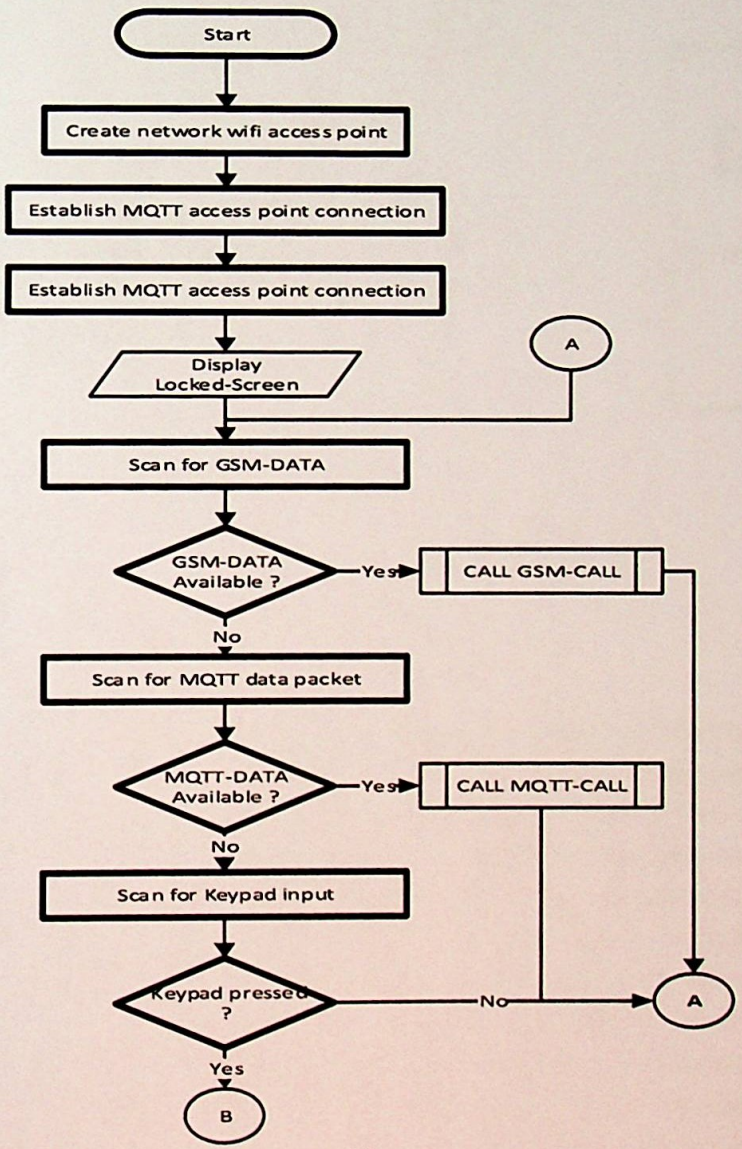
3.2.2.6. Smart Hub Software Design

Procedures and flow charts 1 – 5 describe and show the operations used in the smart hub software design. The corresponding pseudocodes are in Appendix A. The software implementation for the smart hub is written in a python script language.

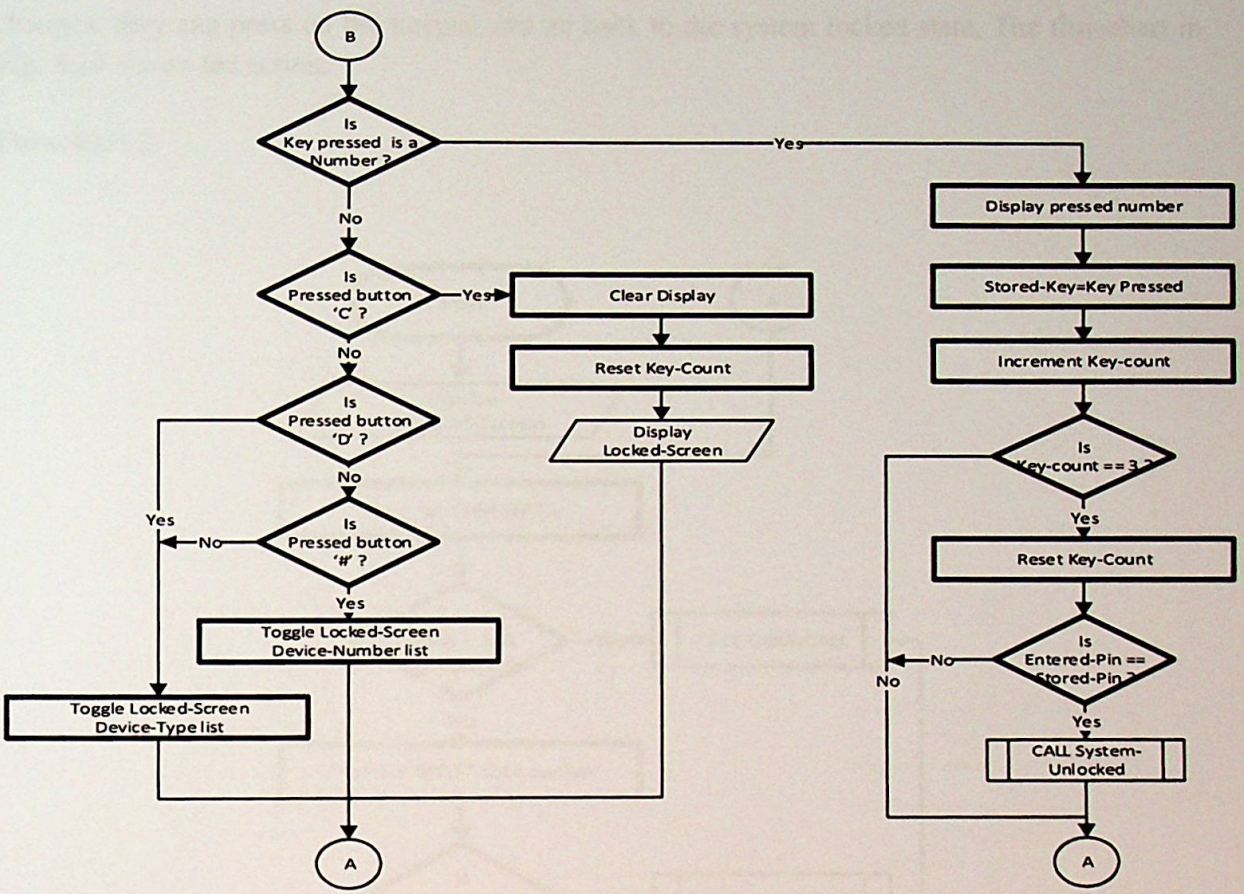
Procedure 1: System-Locked

Description: When the system is locked, a pin code request is displayed on the Smart Hub LCD screens. A user must enter the correct pin code using the built-in keypad to be granted access to the system. Entering a wrong pin code by a user leads to an error message to be displayed on the smart hub LCD screen. The flowchart in Fig. 3.13 shows the action. The smart hub LCD screen then displays a new pin code request for a user to retry. A correctly entered pin code leads to the display of access granted message to indicate successful unlocking of the smart hub. After the display of a successful unlock message, the smart hub proceeds to the system-unlocked procedure.

Flowchart 1:



(a)



(b)

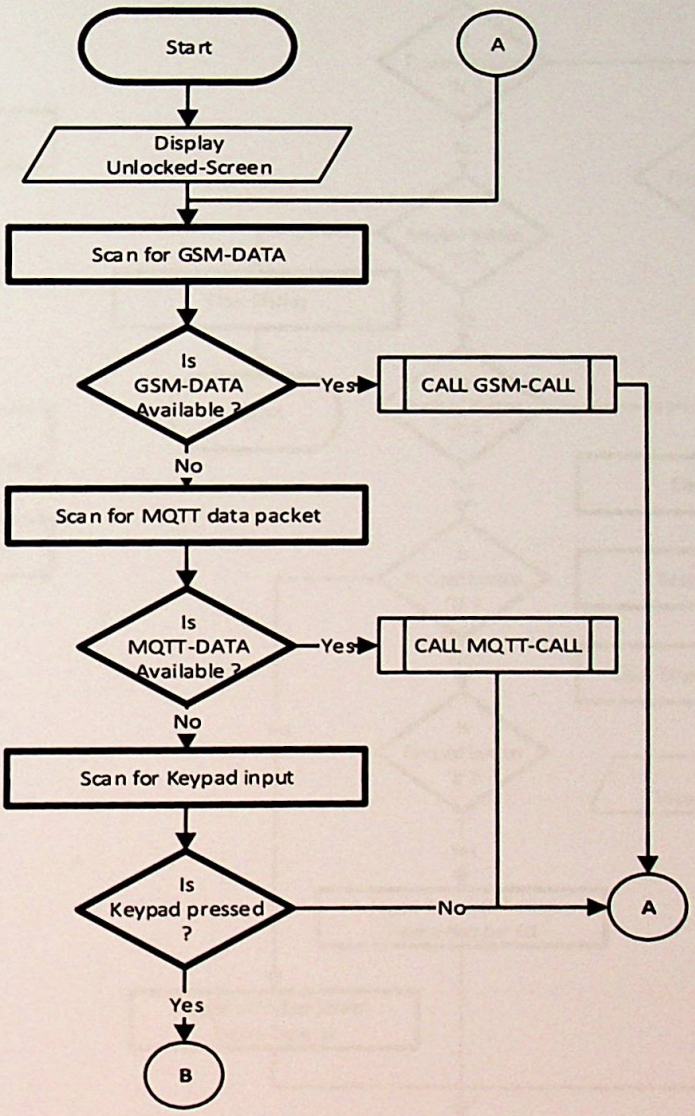
Figure 3. 11: (a) and (b) System locked flowchart

Procedure 2: System-Unlocked

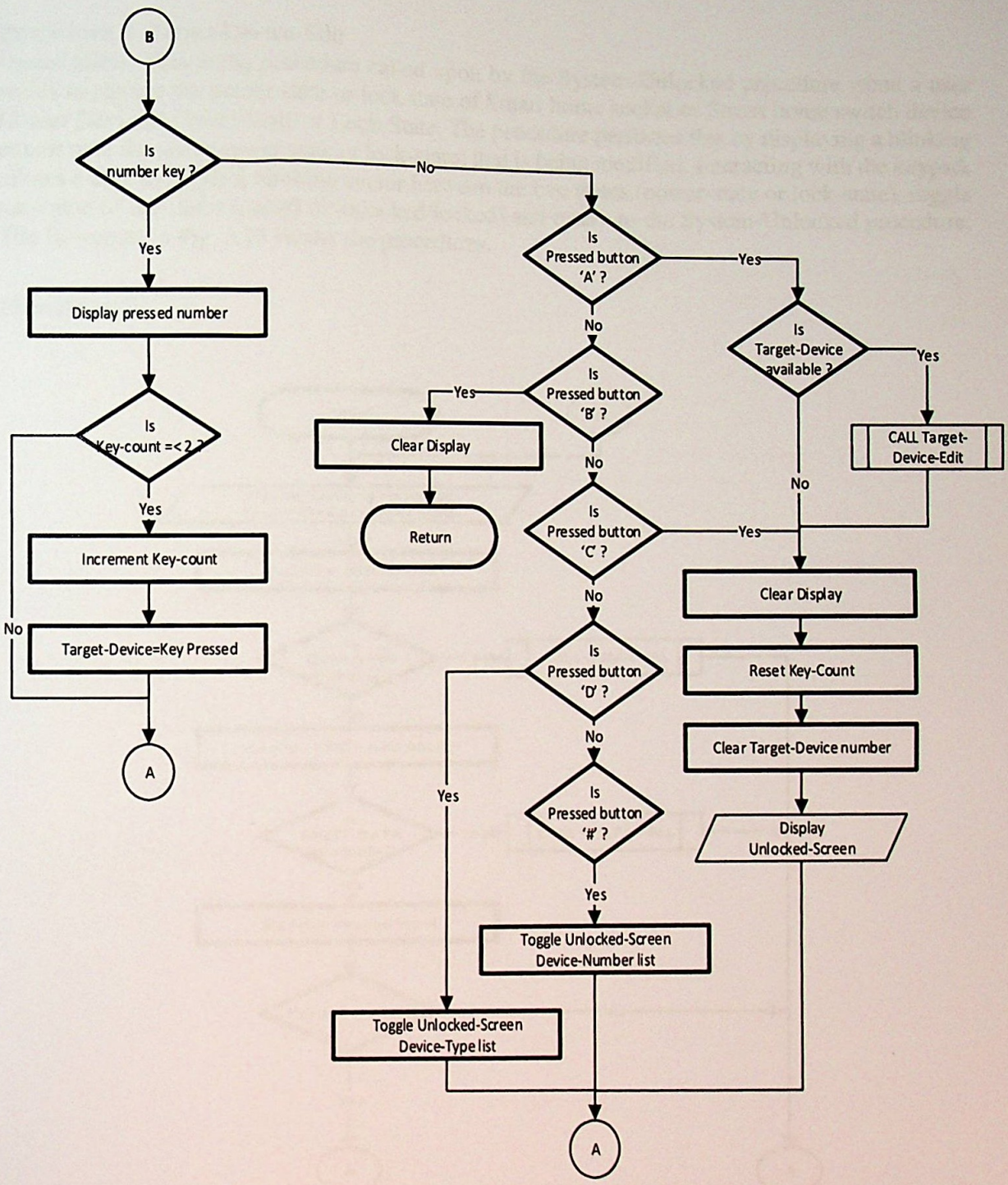
Description: When the system is unlocked, a user is granted permission to look at the status of the available smart sockets and smart switches. Whenever there is any change caused by the manual switching (off or on) of an unlocked smart socket/switch in the network, the system refreshes the LCD screen and reflects the real-life state of the smart sockets and smart switches. If there is an SMS sent by a user to the smart hub, the system processes the message and sends commands to the affected smart sockets/switches and then updates the LCD screen only if the SMS command is valid. Apart from looking at the states of the smart switches and smart sockets, a user can also modify their states. This is accomplished by selecting an available smart switch or smart socket through entering the number associated with the device. Having selected the device, the Target-Device-Edit procedure is called, and the user can then modify the power state or lock state of the selected device. If the user is satisfied with the changes made and does not desire to make further

changes, they can press on the keypad and go back to the system locked state. The flowchart in Fig. 3.14 shows the action.

Flowchart 2:



(a)



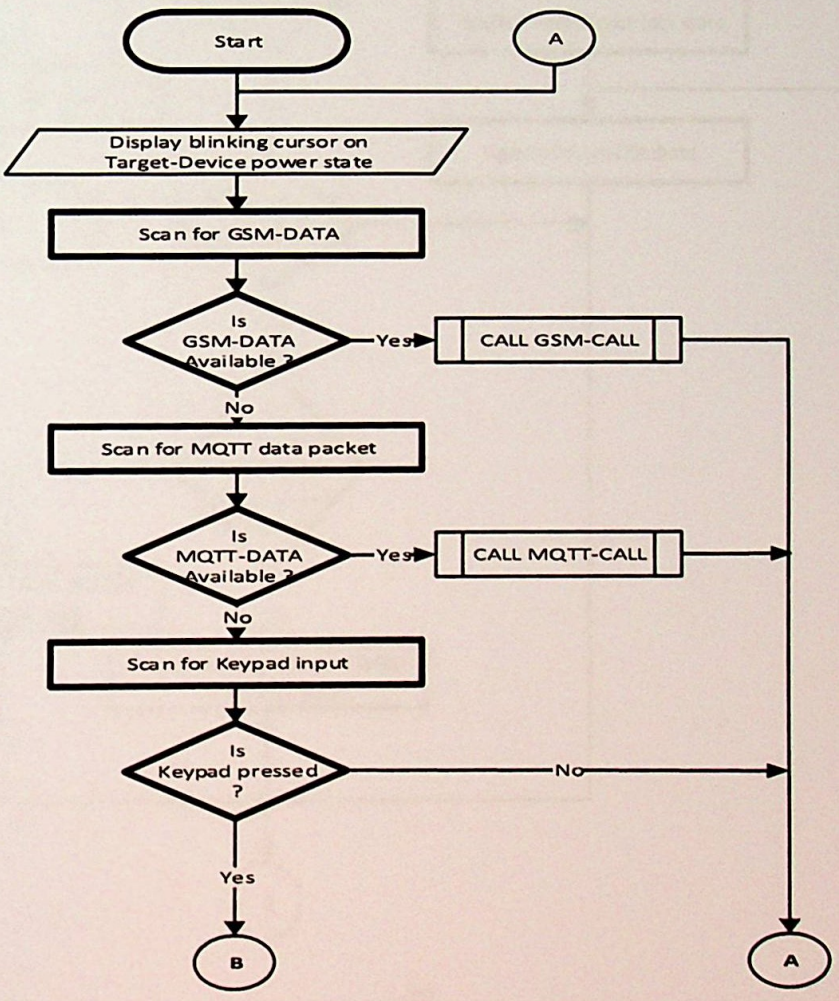
(b)

Figure 3. 12: (a) and (b) System Unlocked flowchart

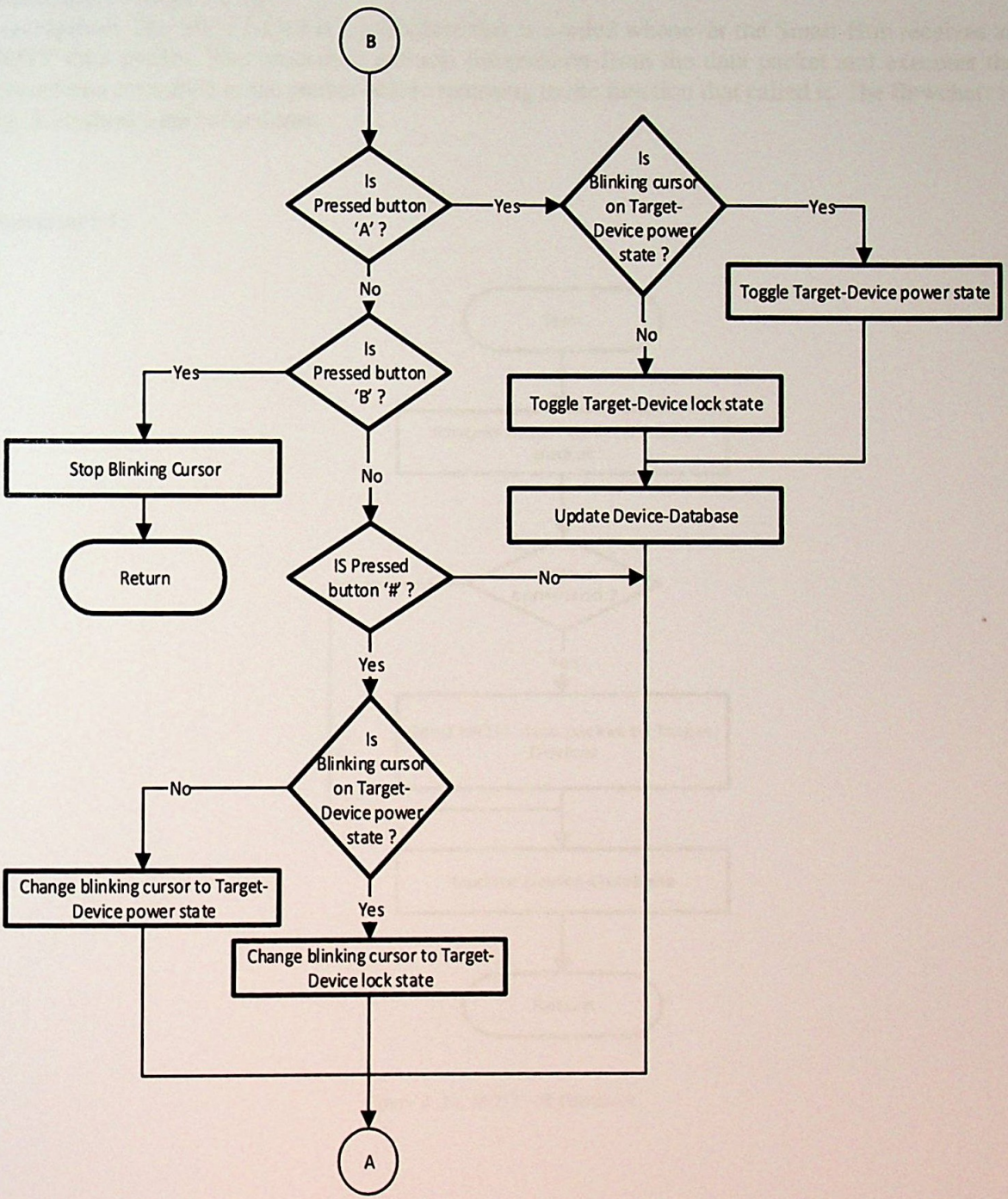
Procedure 3: Target-Device-Edit

Description: This is the procedure called upon by the System-Unlocked procedure when a user wants to change the power state or lock state of Smart home socket or Smart home switch device (Smart Devices) Power-State or Lock-State. The procedure performs this by displaying a blinking cursor over the state (power state or lock-state) that is being modified. Interacting with the keypad, allows a user to toggle a blinking cursor between the two states (power-state or lock-state), toggle the value of the states (on/off or unlocked/locked) and return to the System-Unlocked procedure. The flowchart in Fig. 3.15 shows the procedures.

Flowchart 3:



(a)



(b)

Figure 3. 13: (a) and (b) Target device edit flowchart

Procedure 4: MQTT-Call

Description: The MQTT-Call is a procedure that is needed whenever the Smart-Hub receives an MQTT data packet. The procedure extracts information from the data packet and executes the instructions contained in the packet before returning to the function that called it. The flowchart in Fig. 3.16 shows the procedures.

Flowchart 4:

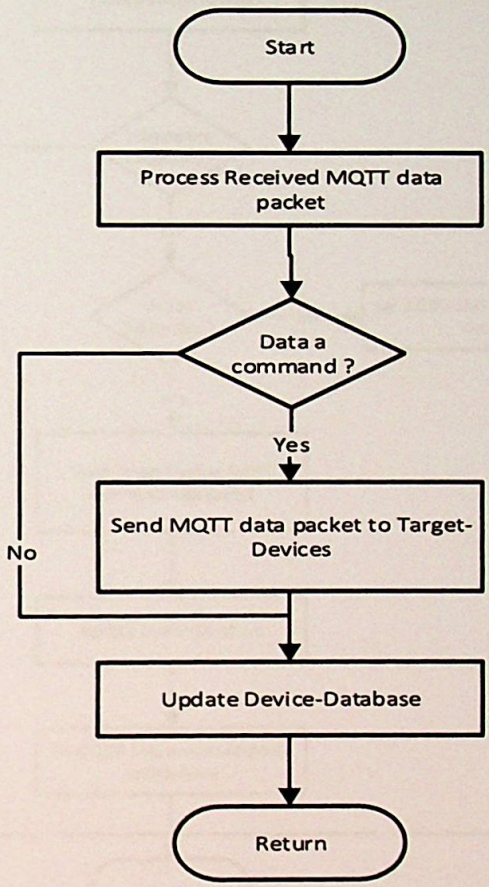


Figure 3. 14: MQTT call flowchart

Procedure 5: GSM-Call

Description: The GSM-Call is a procedure that is called whenever the GSM module receives an SMS data packet. The procedure extracts information from the SMS and executes the instructions contained in the packet before returning to the function that called it. The flowchart in Fig. 3.17 shows the procedures.

Flowchart 5:

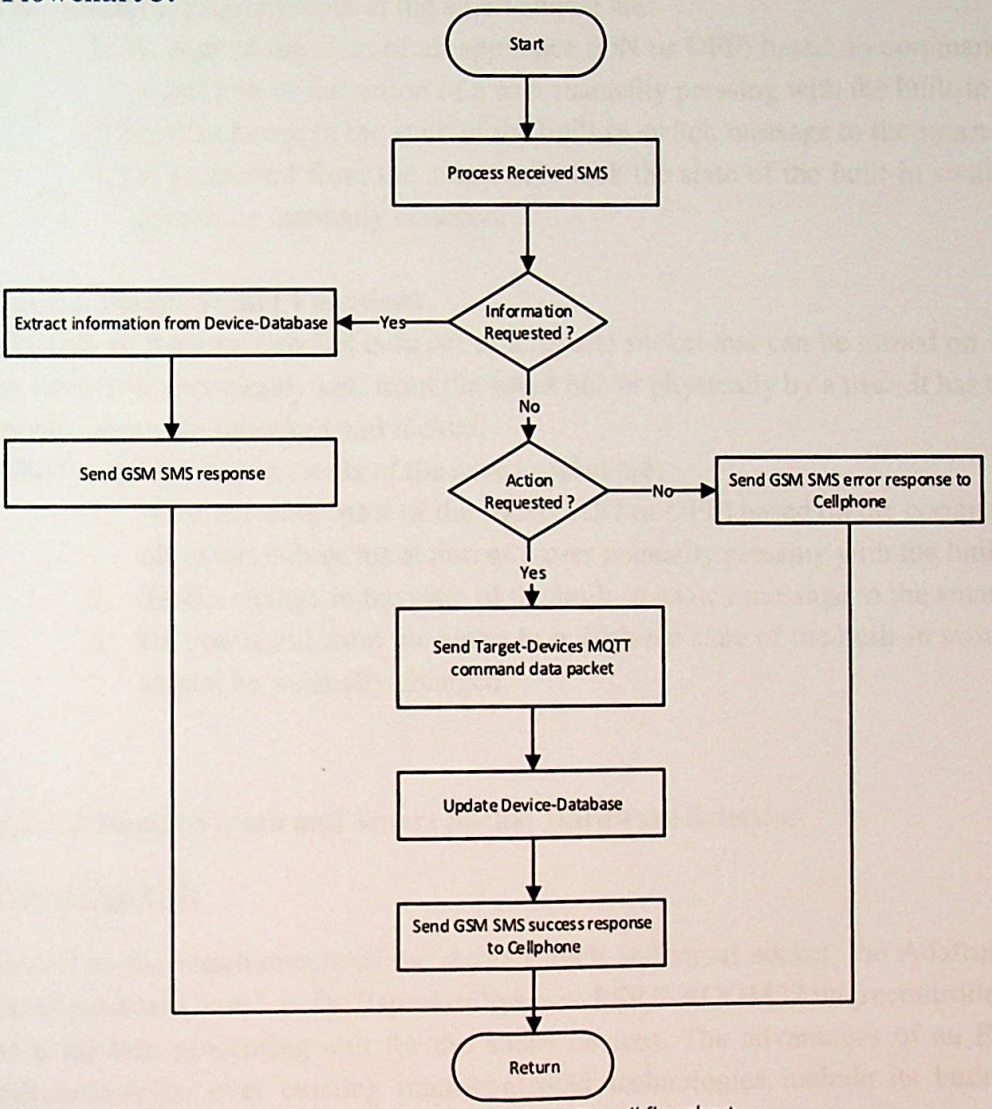


Figure 3. 15: GSM call flowchart

3.2.3. Smart Switch and Smart Socket Design

3.2.3.1. Smart Switch Functions

The role of the smart switch is to act as a remote switch that can be turned on or off either by commands wirelessly sent from the smart hub or physically by a user. It has two modes of security; these are unlocked and locked.

The functional requirements of the smart switch are:

1. To control the state of an appliance (ON or OFF) based on commands from the smart hub or the action of a user manually pressing with the built-in switch.
2. Send a change in the state of the built-in switch message to the smart home hub.
3. On command from the smart hub, lock the state of the built-in switch so that it cannot be manually changed.

3.2.3.2. Smart Socket Functions

The role of the smart socket is to act as a remote socket that can be turned on or off either by commands wirelessly sent from the smart hub or physically by a user. It has two security modes; these are unlocked and locked.

The functional requirements of the smart socket are:

1. To control the state of the socket (ON or OFF) based on the commands from the smart hub or the action of a user manually pressing with the built-in switch.
2. Send a change in the state of the built-in switch message to the smart hub.
3. On command from the smart hub, lock the state of the built-in switch so that it cannot be manually changed.

3.2.3.3. Smart Switch and Smart Socket Hardware Selection

Processing Unit

Based on the requirements of the smart switch and smart socket, the Adafruit Huzzah32 breakout board based on the Espressif Systems ESP WROOM32 microcontroller is selected as a suitable processing unit for the smart devices. The advantages of an ESP32 based microcontroller over existing microcontroller technologies include its built-in wireless

communication module capable of both Wi-Fi and Bluetooth standards of communication, a wide range of peripheral interfaces, and relatively fast CPU core that is useful for tasks such as data encryption.

Here are some of the notable features of the ESP 32 microcontroller as contained in [75]:

- Two independently controlled CPU cores with adjustable clock frequency, ranging from 80 MHz to 240 MHz;
- +19.5 dBm output at the antenna ensures a good physical range;
- Classic Bluetooth for legacy connections.
- Support for Bluetooth Low Energy (Bluetooth LE) profiles.
- Bluetooth Low Energy (Bluetooth LE) connects to smartphones, broadcasting low-energy beacons for easy detection;
- Integrates 4 MB flash;
- Peripherals include capacitive touch sensors, Hall sensor, low-noise sense amplifiers, SD card interface, Ethernet, high-speed SPI, UART, I2S, and I2C;
- Fully certified with integrated antenna and software stacks.

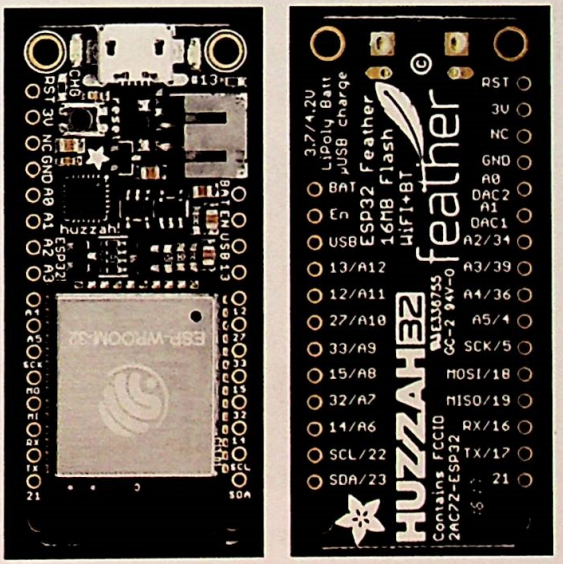


Figure 3. 16: Frontside and backside of an Adafruit Huzzah32 breakout board [76]

Fig. 3.18 shows the front and backside of an Adafruit Huzzah32 breakout board. The advantage of using a breakout board is that breakout boards simplify the handling of complex and sensitive components such as surface mount components. This can be done by making the pins readily accessible or by providing support circuitry such as power regulation, static charge protection, easy programming interface and many more to simplify prototyping. The Adafruit Huzzah32 provides easily accessible pins, 5V to 3.3V power regulation and a USB port for easy programming.

Switching Unit

The design of the switching unit is based on an electromagnetic relay and a transistor switch circuit. The selected electromagnetic relay is an NT72-2C-S10. It operates on 5V DC, has a coil resistance of 60 ohms and the high side contacts are rated for 250V AC at 10A. The relay is used to connect and disconnect the high voltage power from a building to an electrical appliance. Fig. 3.19 shows a picture of an NT72-2C-S10 electromagnetic relay.

The Adafruit Huzzah32 microcontroller GPIO pins cannot source the current required to turn the relay on, hence, a transistor switch circuit is used to turn the relay on or off based on the control signals from the microcontroller. The transistor switch circuit comprises of an NPN BC547 transistor, current limiting resistor and flyback diode. Fig. 3.20 show the transistor switch circuit used to control the relay.



Figure 3. 17 NT72-2C-S10 Relay

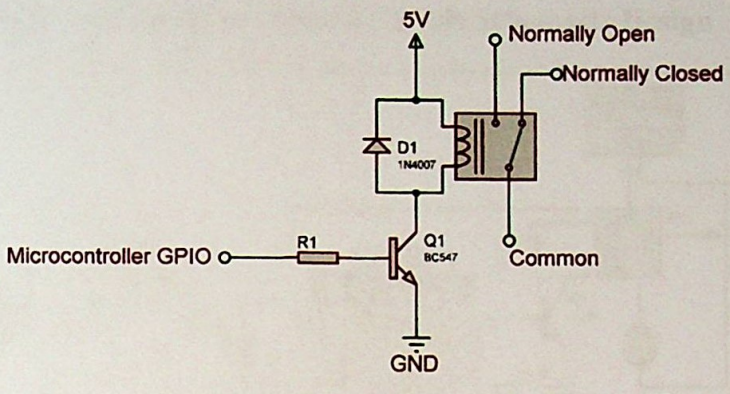


Figure 3. 18: Transistor switch circuit

3.2.3.4. Smart Switch and Smart Socket Block Diagram

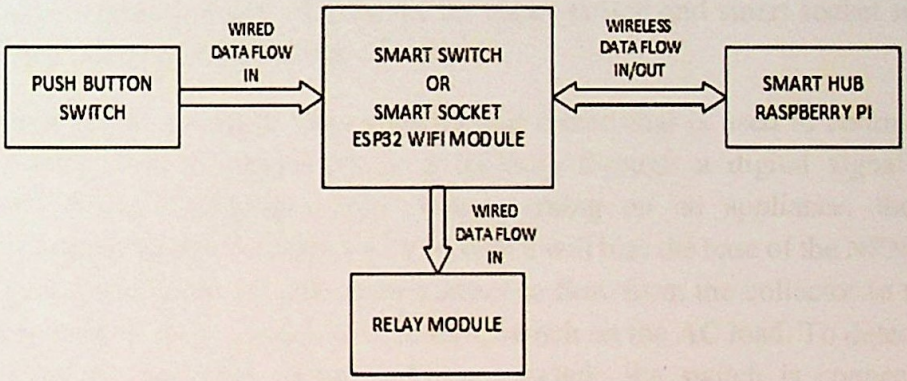


Figure 3. 19: Data flow between the smart switch and smart socket components

Fig. 3.21 shows the block diagram of the smart switch and smart socket. The smart switch and smart socket both have a wireless point to point connection with the smart hub through the selected microcontroller's built-in Wi-Fi module. The smart switch and smart socket connect to an external switch through which a user can use to turn the smart socket or smart switch on or off. A relay module enables the control of ac mains electricity based on signals from the microcontroller.

3.2.3.5. Smart Switch and Smart Socket Circuit Schematic Design

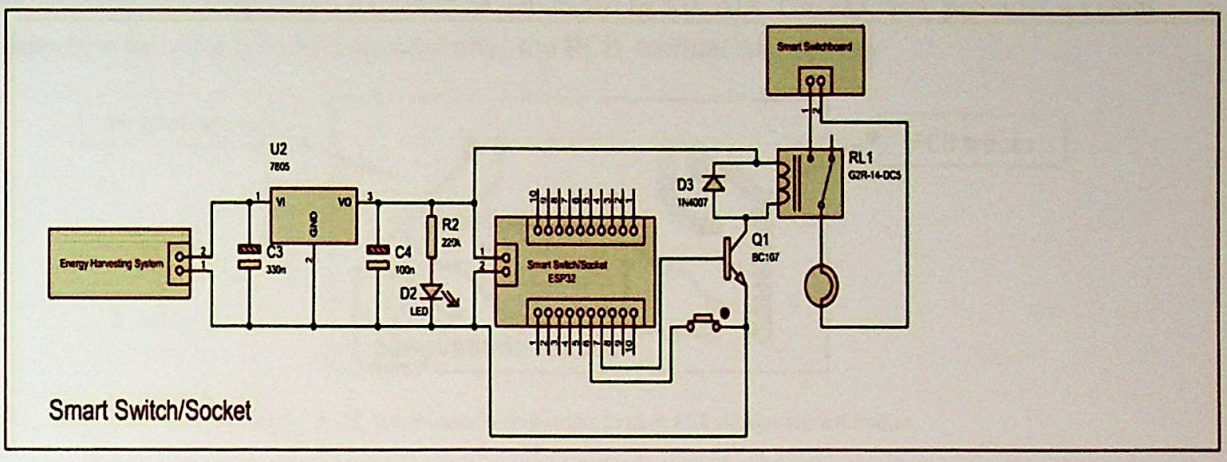


Figure 3. 20: Smart Switch and Socket Circuit Diagram

Fig. 3.22 shows the schematic diagram of the smart switch and smart socket made using circuit design and simulation software Proteus.

The main part of the circuit is the switching unit circuit that is used to control high AC voltage (230V) used by appliances in a building through a digital signal from the microcontroller's general-purpose pin. When turning on an appliance, the Adafruit Huzzah32 breakout board will output 3.3V of which will bias the base of the NPN transistor. When activated, the transistor will allow current to flow from the collector to the emitter and hence turn on the relay, which will, in turn, switch on the AC load. To detect the press of the built-in of the smart socket and smart switch, the switch is connected to the microcontroller general-purpose pin and ground. The powering of the switch is carried out through the microcontroller's internal pull-up resistor. Switch debouncing is carried out in the software.

3.2.3.6. Smart Switch and Smart Socket PCB Designs

Fig. 3.23 shows a photo positive stencil image of the smart switch and smart socket PCB design made using PCB design software KiCAD. In designing the PCB board, wide PCB tracks are used for the tracks between the relay module, AC live wire terminal, and appliance line terminal. To improve safety, sufficient spacing (clearance) above 2mm is left between

the AC copper tracks and the microcontroller signal tracks. Fig. 3.24 shows a 3D view of the smart switch and smart socket PCB generated in KiCAD. The 3D view provides a visual depiction of what is to be expected after the PCB fabrication process.

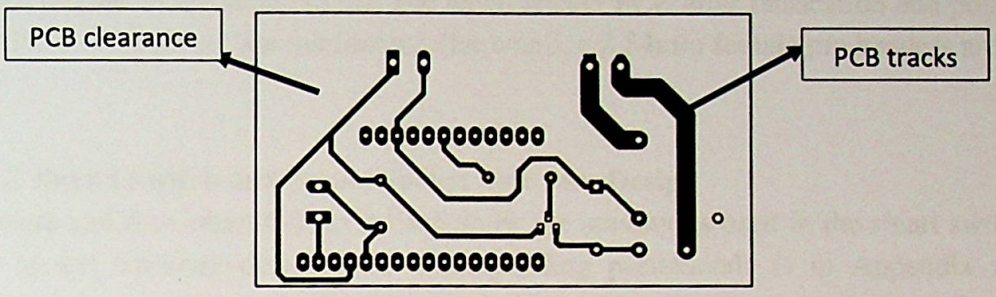


Figure 3. 21: Smart switch and smart socket PCB design *stencil image*

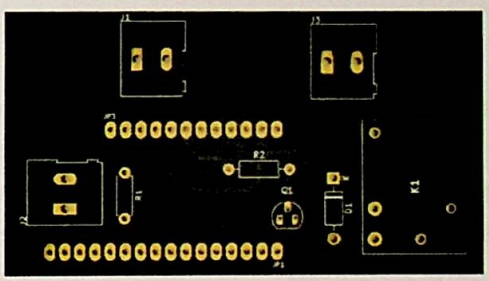


Figure 3. 22: 3D View of smart switch and smart socket PCB design

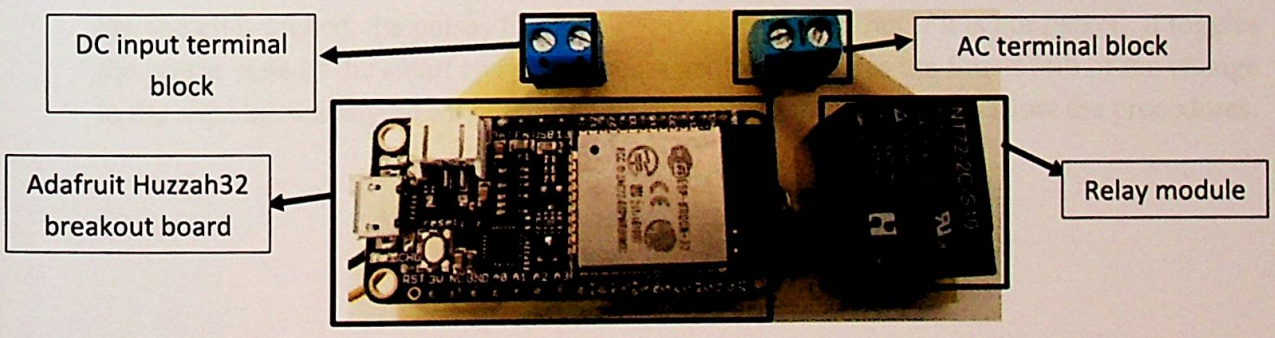


Figure 3. 23: Populated smart switch and smart socket PCB

The PCB design of the smart switch and smart socket is based on the use of 2.54mm male and female pin headers to connect the Adafruit Huzzah32 breakout board to the PCB. Two-pin terminal blocks are used for both the DC and AC connections to the PCB. Fig. 3.25 shows a picture of the smart switch and smart socket PCB after fabrication and populating of the PCB. To connect the microcontroller board, a 2.54mm female pin headers are used.

3.2.3.7. Smart Switch and Smart Socket Software Design

Procedure and flow chart 6 describe and show the operations used in the smart switch and smart socket software design. The corresponding pseudocode is in Appendix A. The software implementation for the smart switch and smart socket is written in C++ script language.

Procedure 6: Smart Socket/Switch-Main-Loop

Description: This is a procedure that is used by the smart sockets and smart switches when they receive an MQTT data packet command from the smart hub or when a user has pressed the local switch on the socket or switch. When a command is received, it is processed to check whether it affects its power state or the lock state of the device. If the command is to change the lock state, it then deactivates any commands from the local switch until the switch is unlocked. If the command is to change the power state, it toggles the current power state of the switch or socket. Apart from a command from the smart hub, if it receives a command from the local switch, it is first checked whether the switch is locked or not. If the switch is locked, the pulses from the switch are ignored, but if it is not locked, it toggles the power state of the smart switch or socket and then updates the Smart hub of the change in the state by sending an MQTT message. The flowchart in Fig. 3.26 show the procedures.

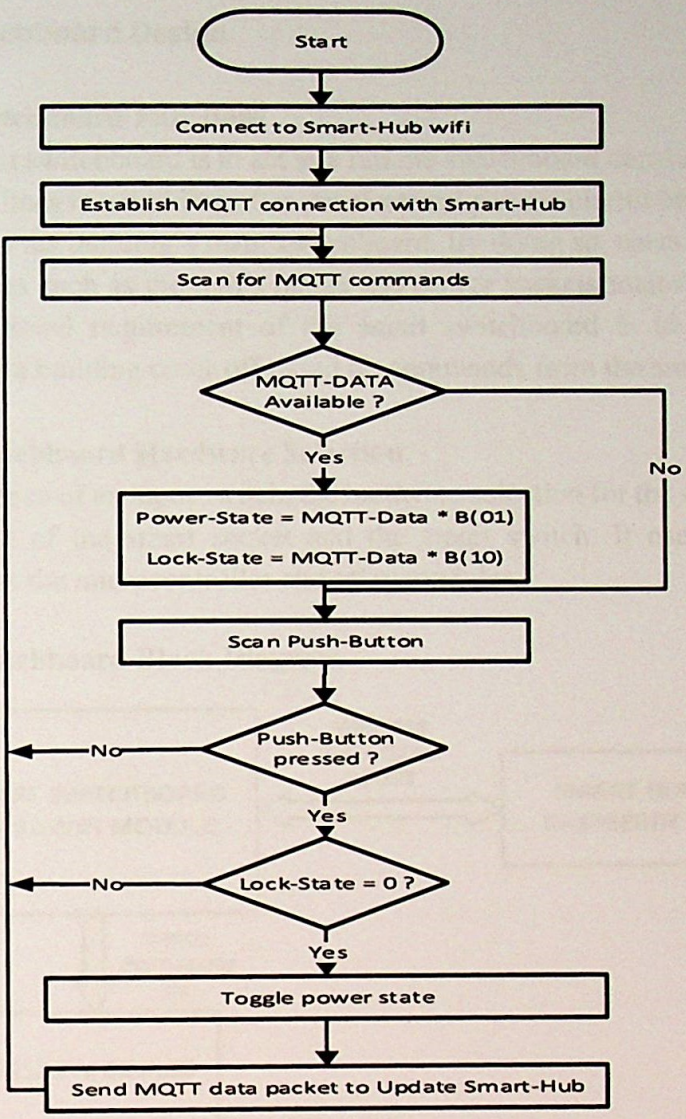


Figure 3. 24: Smart socket and smart switch flowchart

3.2.4. Smart Switchboard Design

3.2.4.1. Smart Switchboard Functions

The role of the smart switchboard is to act as a remote switchboard capable of turning on or off the distribution lines in a building after the electrical panels, circuit breakers, and safety switches installed in the building's main switchboard. By doing so, users have control over buildings mains lines such as the lights mains and power sockets mains can be turned on and off. The functional requirement of the smart switchboard is to switch the main distribution lines of a building on or off based on commands from the smart hub.

3.2.4.2. Smart Switchboard Hardware Selection

Apart from the absence of an input switch, the hardware selection for the smart switchboard is the same as that of the smart socket and the smart switch. It uses the same main components, such as the microcontroller and relay modules.

3.2.4.3. Smart Switchboard Block Diagram

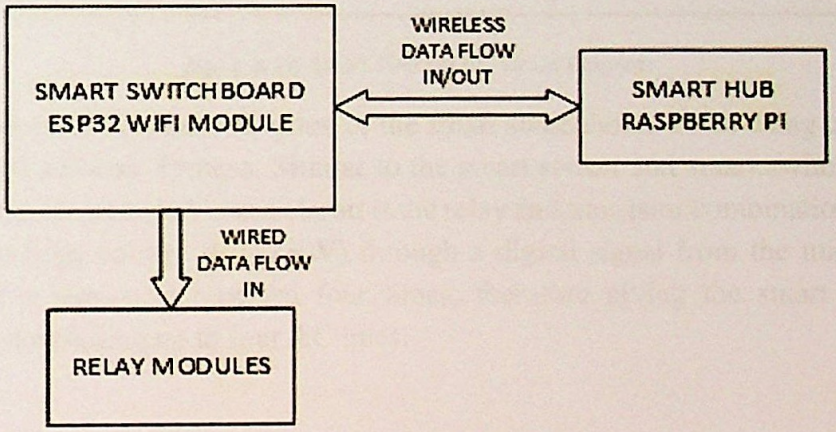


Figure 3. 25: Data flow between smart switchboard components

Fig.3.27 shows the block diagram of the smart switchboard. Similar to the smart switch and smart socket, the smart switchboard has a wireless point to point connection with the smart hub through the built-in Wi-Fi module. The relay modules enable the smart switchboard to control the state of the distribution lines from a building switchboard.

3.2.4.4. Smart Switchboard Circuit Schematic Design

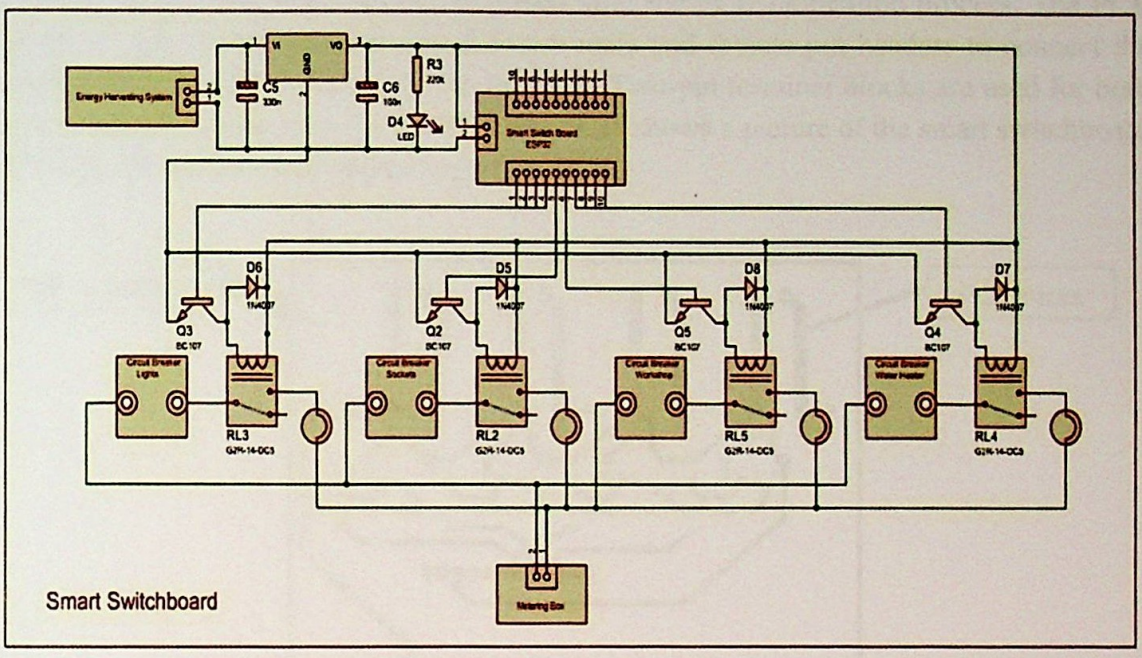


Figure 3. 26: Smart Switchboard Circuit Diagram

Fig. 3.28 shows the schematic diagram of the smart switchboard made using circuit design and simulation software Proteus. Similar to the smart socket and smart switch circuit, the main part of the smart switchboard circuit is the relay and transistor combination that is used to control the high voltage AC (230V) through a digital signal from the microcontroller GPIO pin. The design is repeated four times, therefore giving the smart switchboard capability of controlling up to four AC lines.

3.2.4.5. Smart Switchboard PCB Design

Fig. 3.29 shows a photo positive stencil image of the smart switchboard made using PCB design software KiCAD. Similar to the smart socket and smart switch PCB design, wide PCB tracks are used for the tracks between the relay modules, AC live wire terminals, and appliance line terminals. Safety is also observed by ensuring sufficient spacing/clearance above 2mm between the AC copper tracks and the microcontroller signal tracks. Fig. 3.30

shows a 3D view of the smart switchboard PCB generated in KICAD. The 3D view provides a visual depiction of what is to be expected after the PCB fabrication process. The PCB design of the smartboard also uses 2.54mm male and female pin headers to connect the Adafruit Huzzah32 breakout board to the PCB. Two-pin terminal blocks are used for both the DC and AC connections to the PCB. Fig. 3.31 shows a picture of the smart switchboard PCB after fabrication and populating of the PCB.

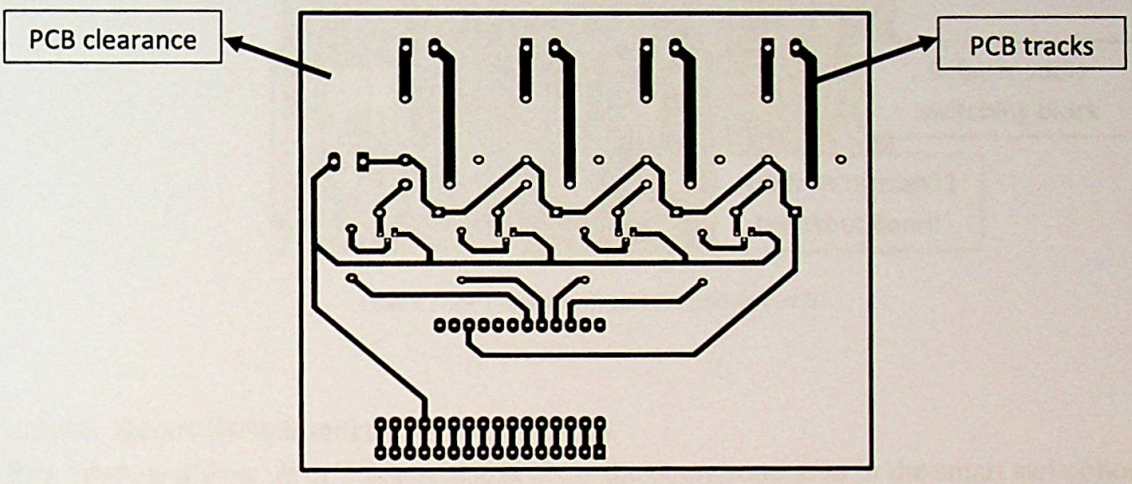


Figure 3. 27: Smart switchboard *PCB* design stencil image

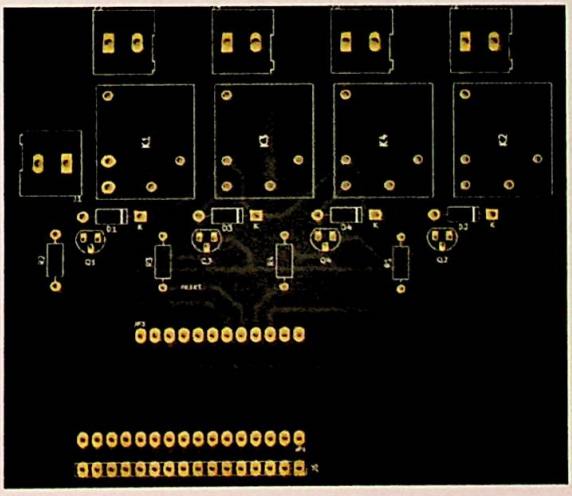


Figure 3. 28: 3D View of smart switchboard PCB design

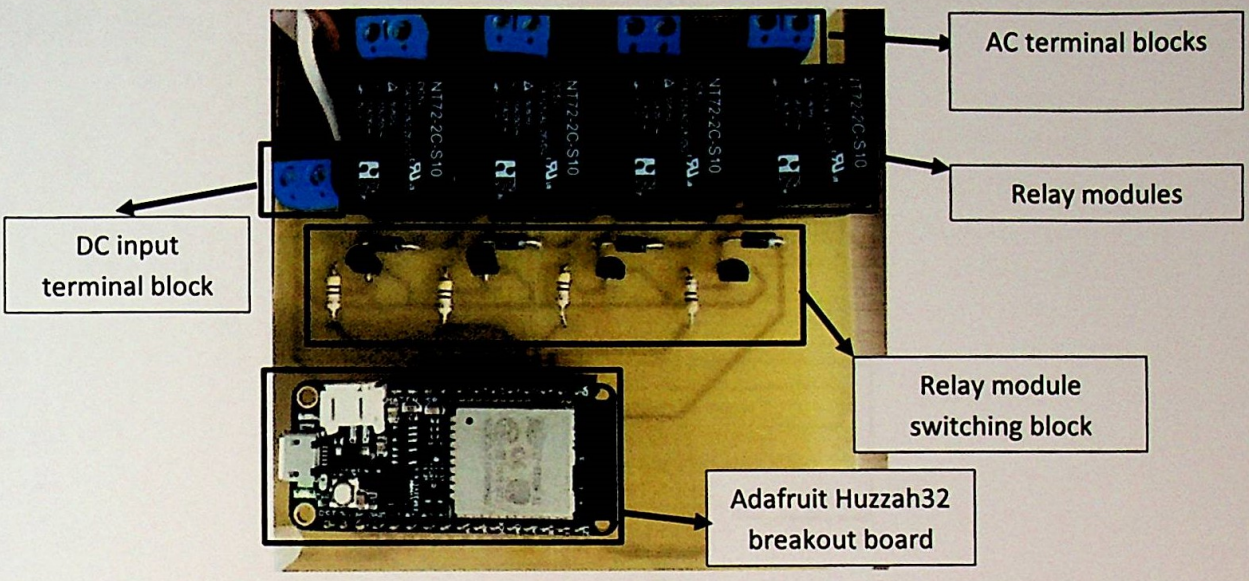


Figure 3. 29: Populated Smart Switchboard PCB

3.2.4.6. Smart Switchboard Software Design

Procedure and flow chart 7 describe and show the operations used in the smart switchboard software design. The corresponding pseudocode is in Appendix A. The software implementation for the smart switchboard is written in C++ script language.

Procedure 7: Smart switchboard

Description: This is a procedure that is used by the smart switchboard when it receives an MQTT data packet command from the smart hub. When a command is received, it is processed to extract the main appliance line that is to be turned off or on. Having obtained the appliance line, the power state of the line is set according to the command from the smart hub. The flowchart in Fig. 3.32 shows the procedures.

Flowchart 7:

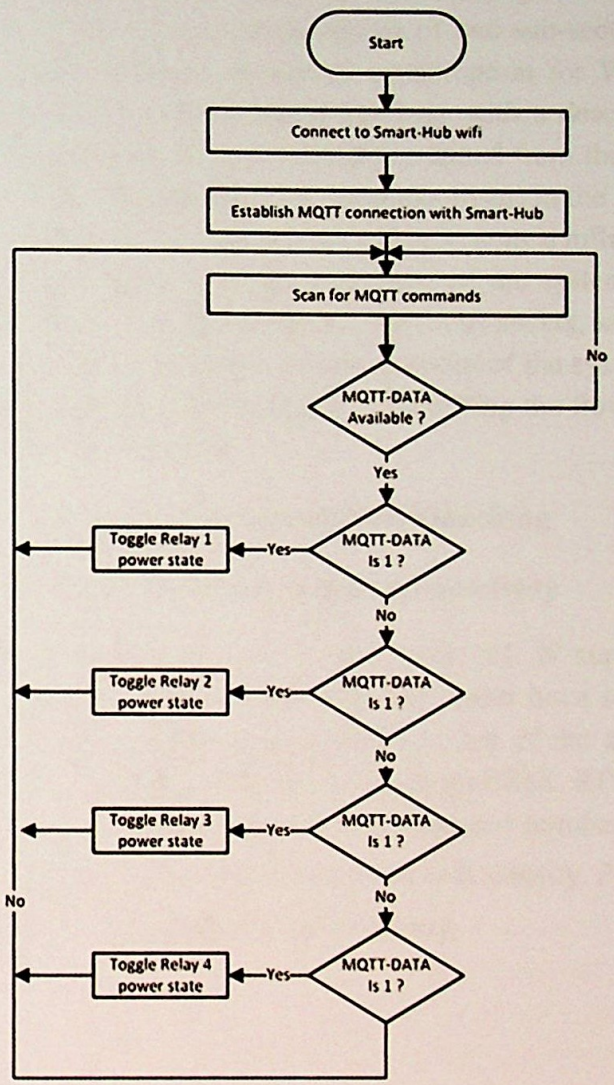


Figure 3. 30: Smart switchboard flowchart

3.3. WIRELESS SENSOR NETWORK SYSTEM DESIGN

This section presents the work that was undertaken in the design of the WSN for the secured smart home switching system. The work comprises of two sub-sections. The first section includes analytical modelling based on energy consumption for Wireless Sensor Home Network (WSHN) grid-based and line-based topology with a description of each of the networks using the same metrics. With the insight obtained from the analytical model, the second section involves the simulation of the networks to aid in the design of the system's WSN. The design of the secured smart home switching system is influenced by the structure of a WSN. The smart hub function as the sink node of the system and provides a user interface for users to interact with the network. The smart socket, smart switch, and smart switchboard are considered the endpoints or sensor nodes of the system. They perform the sensing and actuating functions of the system by controlling the flow of the AC electricity used to power appliances in a building.

3.3.1. Wireless Sensor Home Network Analytical Modelling

3.3.1.1. WSHN Description: Node distribution and connectivity

Assuming a network comprising of one (1) sink node, S1. N number of sensors nodes ranging from N1, N2, N3, ... up to node NN. The nodes have static locations and are uniformly randomly distributed over a grid model region of the area, A, comprising of perimeter dimensions RX and RY and inter grid spacing of RIX, RIY along with the X and Y directions respectively. In such a network, the expected number of nodes that can be found in a region of the network is described by the node density, P, expressed as $P = \frac{N_N}{A}$. Fig. 3.33 is an illustration of the described grid network.

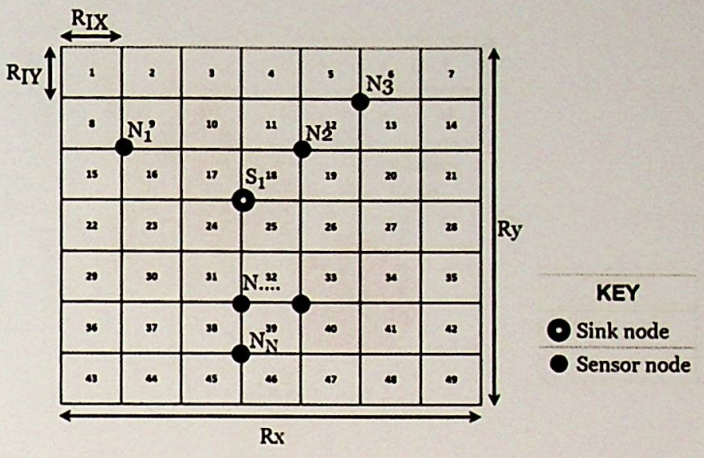


Figure 3. 31: Structure of a wireless sensor home network with a grid of x-y network topology

For connectivity amongst the nodes of the wireless sensor home network, this work adopted a model similar to the work in [77]–[79] as a simple radio link, which is used for the analysis of the network. The nodes in the network carrying a radio link model have a finite transmission range, $d_{tx,}$ and are fitted with an omnidirectional antenna, allowing for equal wireless transmission in all directions. Restriction of the node wireless transmission range is added to signify the bandwidth limitation experienced in sensor networks.

All nodes in the network are capable of bidirectional communication; therefore, they can both transmit and receive n-bit data packets. Any node in the grid network can act as a source node so long as it has information to be transmitted to the sink node. For communication to occur between nodes, only nodes that are within the transmission range of each other can establish a successful wireless link and communicate. Nodes that are completely isolated from others cannot form a wireless link and therefore are unable to communicate with other nodes. This can be seen in Fig. 3.34, where sink node S_1 is within the transmission range of nodes N_1 and N_2, hence communication between the nodes is possible. However, node N_3 is beyond the transmission range of any node. This makes it isolated and unable to form a wireless link for communication.

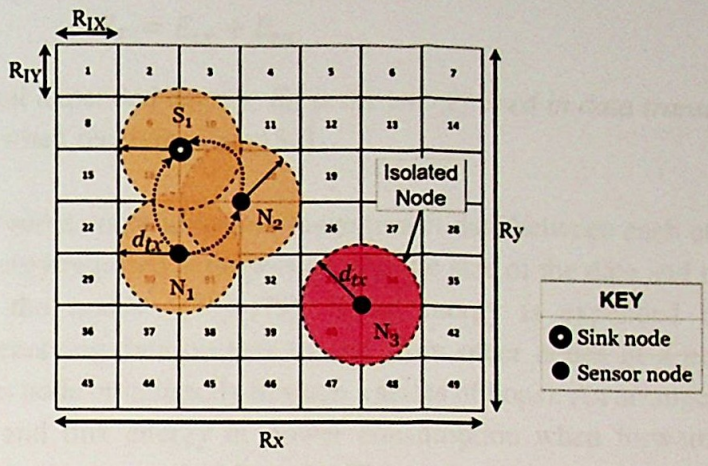


Figure 3. 32: Wireless sensor network model with an isolated node

Wireless transmission between nodes occurs via wireless channels. The source node transmits a signal at power, P_{tx} at zero distance, $d=0$ from a source node. The transmitted signal power undergoes attenuation in wireless channel medium and is received at the destination node as power, P_{rx}, at a distance, d, from the source node. The received power, P_{rx} is inversely proportional to attenuation or path loss, d^{γ} P_{tx} of the transmitted signal. Gamma, γ represents the path loss exponent and varies between 2 and 4 depending on the environment [78]–[80]. For successful transmission and reception, it is assumed that the transmitted signal, dP_{tx} is greater than the receiver sensitivity (P_{rx}). Therefore, P_{tx} $(d = d_{tx}) \geq P_{rx}$, for successful reception of a signal.

Data transmitted by a source node can reach a sink node in two ways. Either by single-hop direct transmission or multi-hop forwarding through other sensor nodes. This is also illustrated in Fig. 3.34, seeing how data packets from node N_1 are transmitted directly to the sink node by single-hop or reach the sink node by taking the path via node N_2 of which leads to 2(two) hops.

For both transmission and reception of data packets (event data) from or to other nodes in a network, energy is required by a grid node to carry out the task. The energy used up by nodes in a single hop event forwarding operation can be expressed as:

$$E_T = E_{tx} + E_{rx} \quad (3.1)$$

Where E_T is the total expended energy, E_{tx} *is the energy used in data transmission, and* E_{rx} is the energy used when receiving data [81].

When nodes of the same communication range transit data between each other, the amount of transmission energy required is proportional to the size of the data and the square of the distance between the nodes [77]–[79]. Since energy is expended by nodes when transmitting and receiving data packets to and from other nodes in a network (whether directly to the target node or indirectly through a series of hops). An arrangement is required that can consider and link energy or power consumption when forwarding data to the distance between the source and sink node. This way, one can compare single hop and multiple hop transmission.

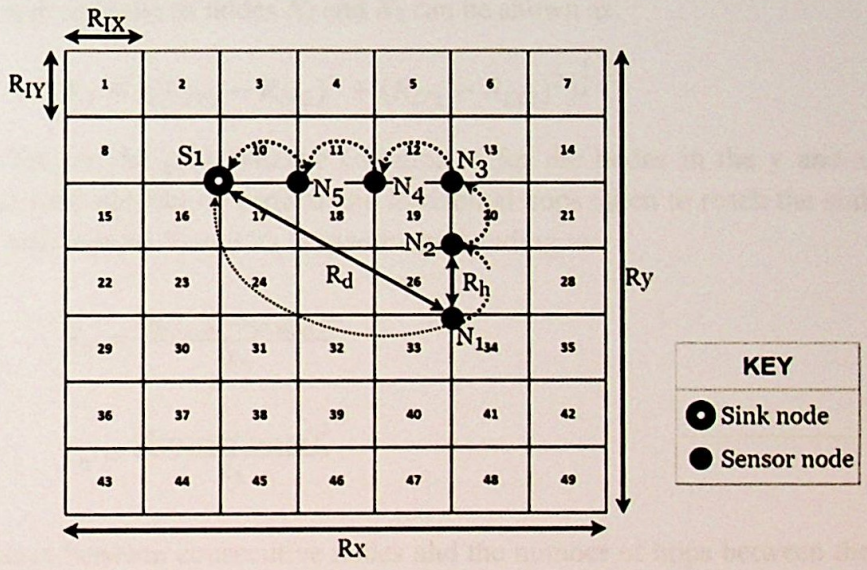


Figure 3. 33: Single hop and multi-hop routing in x-y grid topology wireless sensor network

Consider the grid network example in Fig. 3.35, where source node N_1 is sending data to sink node S_1. If the distance between the sink node and source node is short and multiple hops are used to transmit data, just like data is transmitted from N_1 to S_1 through N_2 to N_5. The number of forwarding hops to the sink node will increase energy consumption since multiple transmissions and receptions are performed. Then again, if the distance between the source and sink nodes is too high and a data packet is transmitted directly to the sink node, more energy will be used by the source node to send the signal across the large space.

In determining the energy costs of using either method of data forwarding, whether direct or indirect. Information such as distances and the number of hops between nodes is required to perform the calculations. Again, using Fig. 3.35 as an example, the distance between consecutive grid nodes, R_h, such as between nodes N_1 and N_2 can be shown as:

$$R_h = ((R_{IX1} - R_{IX2})^2 + (R_{IY1} - R_{IX2})^2)^{\frac{1}{2}} \tag{3.2}$$

Where R_{IY} and R_{IX} are the grid distance coordinates for the nodes in the y and x directions, respectively. The total number of vertical and horizontal hops taken to reach the sink node from the source node will then be Y_h and X_h, respectively. Leading to:

$$X_h = \frac{(R_{IXmin} - R_{IXmax})^2}{R_h} \tag{3.3}$$

$$Y_h = \frac{(R_{IYmin} - R_{Iymax})^2}{R_h} \tag{3.4}$$

Having the distance between consecutive nodes and the number of hops between the source and sink node. The direct transmission distance, R_d, from the source to the sink node, is taken as:

$$R_d = ((R_h X_h)^2 + (R_h Y_h)^2)^{\frac{1}{2}} = R_h(X_h{}^2 + Y_h{}^2)^{\frac{1}{2}} \tag{3.5}$$

To calculate the average cost of communication, T_{avg}, of forwarding data using multiple hops from the source to sink node. T_{avg} is expressed such that it shows the average energy expenditure for every unit distance as:

$$T_{avg} = \frac{\Sigma_{(X_h + Y_h)hops}(E_{tx} + E_{rx})}{R_d} \tag{3.6}$$

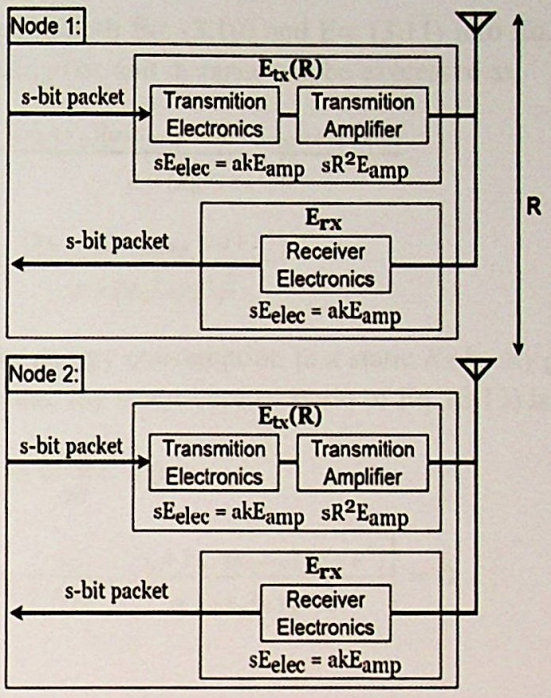


Figure 3. 34: Single hop transmission first order radio model

Assuming a first order radio model, as illustrated in Fig. 3.36, per [82]–[84]. The data transmission energy in a node, E_{tx}, can be attributed to two factors. These being the energy used by the radio transmitter circuitry, taken as radio dissipation, E_{elec} (J/bit), and the transmit amplifier energy, E_{amp} (J/bit*m^2). Hence, a single-hop transmission of a data packet of size s-bits, over R distance, using the first order radio model and taking the free space path loss exponent as, γ=2, leads to data transmission energy, E_{tx}, of:

$$E_{tx}(s,R) = E_{tx-elec}(s) + E_{tx-amp}(s,R) \tag{3.7}$$

$$E_{tx}(s,R) = sE_{elec} + sR^{\gamma}E_{amp}, \tag{3.8}$$

Taking alpha, α, as an amplification factor, where $\alpha = \frac{E_{elec}}{E_{amp}}$, this gives;

$$E_{tx}(s,R) = s\alpha E_{amp} + sR^{\gamma}E_{amp} \tag{3.9}$$

$$E_{tx}(s,R) = sE_{amp}(\alpha + R^2) \tag{3.10}$$

On the other hand, when receiving data from a single hop transmission of data packets s-bits in size. Only the radio dissipation, E_{elec} *(J/bit)*, by the radio receiver circuitry is needed. Hence leading to data reception energy, E_{rx}, of:

$$E_{rx}(s) = E_{rx-elec}(s) = sE_{elec} = \alpha sE_{amp} \tag{3.11}$$

By substituting and expanding both Eq. (3.10) and Eq. (3.11) into Eq. (3.6), the average energy expended for event forwarding per unit distance can be expressed as:

$$T_{avg} = \frac{(X_h+Y_h)[\alpha sE_{amp}+sR^2E_{amp}+\alpha sE_{amp}]}{R\times(X_h{}^2+Y_h{}^2)^{\frac{1}{2}}} \tag{3.12}$$

$$T_{avg} = \frac{(X_h+Y_h)\,sE_{amp}\,(2\alpha+R^2)}{R\times(X_h{}^2+Y_h{}^2)^{\frac{1}{2}}} \tag{3.13}$$

To find the upper bound for energy consumption in a static R_X by R_Y grid-based network, where X_h, Y_h, n, and E_{amp} are constant, the worst-case scenario of Eq. (3.13) is considered as:

$$T'_{avg} = \frac{d(T_{avg})}{dR} = 0 \tag{3.14}$$

$$T'_{avg} = \frac{R_d}{R\times R_d}\left[\frac{(X_h+Y_h)\,sE_{amp}\,(2\alpha+R^2)}{R\times(X_h{}^2+Y_h{}^2)^{\frac{1}{2}}}\right] = 0 \tag{3.15}$$

That is to say;

$$\frac{(X_h+Y_h)\,sE_{amp}}{(X_h{}^2+Y_h{}^2)^{\frac{1}{2}}}\left[\frac{R_d}{R\times R_d}\left[\frac{(2\alpha+R^2)}{R}\right]\right] = 0 \tag{3.16}$$

or;

$$\frac{R_d}{R\times R_d}[(2\alpha R^{-1}+R)] = 0 \tag{3.17}$$

Leading to;

$$-2\alpha R^{-2}+1=0 \tag{3.18}$$

$$-2\alpha = -R^2 \tag{3.19}$$

Finally;

$$R = (2\alpha)^{1/2} \tag{3.20}$$

This implies that the average cost of transmission happens when $R=(2\alpha)^{1/2}$.

3.3.1.2. Wireless Sensor Network Description: Energy modelling and Network reliability

When dealing with energy and reliability of a WSN, according to [77], [83]–[86], [83]–[85], [87]–[90], reducing the network energy consumption can improve network reliability. This is because

in most applications of WSN, and nodes are battery powered. High energy consumption leads to fast depletion of the node batteries which leads to reduced network lifetime. Thus, by analyzing the energy consumed during sending and receiving of data between nodes, network reliability can be improved by selecting the right topologies and protocols.

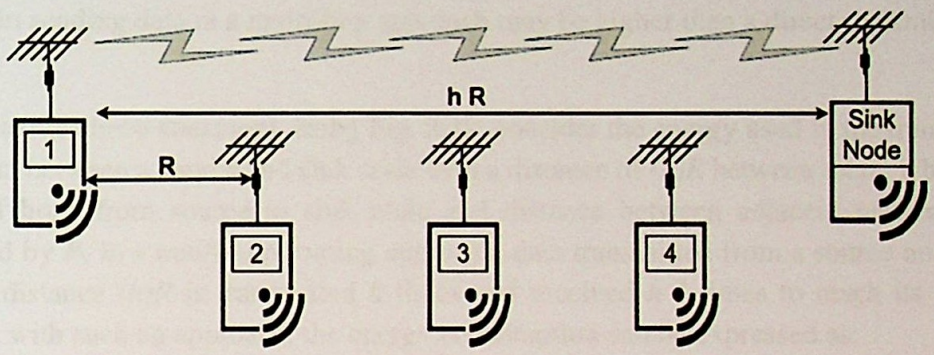


Figure 3. 35: A Single hop approach of Wireless Sensor Home Network

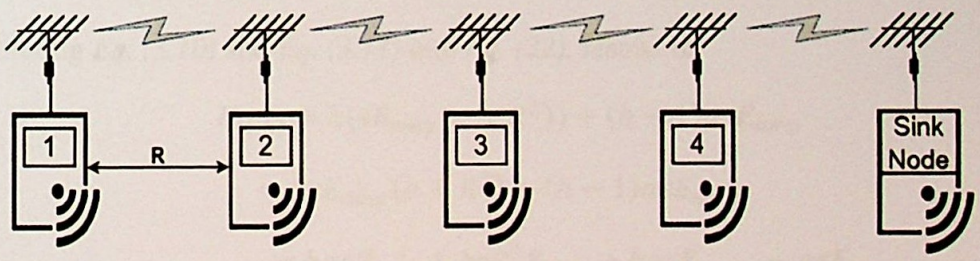


Figure 3. 36: A Multi-hop approach of Wireless Sensor Home Network

In a single-hop communication approach, data is sent directly from a source to a sink node. This is shown in Fig. 3.37, where the sensor node (1) is sending directly to the sink node. If the distance between the two (2) nodes is large, so is the amount of energy used by the source node to transmit the data to the sink.

For a multi-hop communication approach, data from a source node reaches the sink node through a chain of hops by using other network sensor nodes as relays to forward the data until it reaches the sink node. This can be seen in Fig. 3.38, where data from a node (1) reaches the sink node by using node (2) to a node (4) as relays. If the distance between the source and sink node is large, the number of hops required to transmit the message also increases, hence more energy is used.

In terms of energy dissipation, the main difference between the two approaches is how the transmission cost affects the nodes in the network. With the single-hop approach, all the energy for data transmission is provided by the participating source node. Therefore, its battery will reduce at a faster rate, leading to a reduction in network lifetime. Whereas, for a multi-hop approach, the cost of transmission is distributed across the source node and the intermediate nodes. However, depending on the energy costs of the radio electronics and transmitter amplifier, the total energy expended in sending data in a multi-hop approach may be higher than a direct transmission to the sink node.

To illustrate the above statement, using Fig. 3.38, consider the energy used in the transmission of s-bit of data between a source and sink node with a distance of $(h)R$ between them, where h, is the number of hops from source to sink node and distance between adjacent network nodes is represented by R. In a multi-hop routing approach, data transmitted from a source node to a sink node at a distance $(h)R$ is transmitted h times and received h-1 times to reach its destination. Therefore, with such an approach, the energy consumption can be expressed as:

$$E_{MHR} = E_{tx} + E_{rx}$$

$$E_{MHR} = hE_{tx}(s, R) + (h - 1)E_{rx}(s) \tag{3.21}$$

Substituting *Eq. (3.10)* and *Eq. (3.11)* into *Eq. (22)*, results in:

$$E_{MHR} = h(sE_{amp}(\alpha + R^2)) + (h-1)\alpha sE_{amp}$$

$$= hsE_{amp}(\alpha + R^2) + (h-1)\alpha sE_{amp}$$

$$= h\alpha sE_{amp} + hsR^2E_{amp} + h\alpha sE_{amp} - \alpha sE_{amp}$$

$$= sE_{amp}(2\alpha h + hR^2 - \alpha) \tag{3.22}$$

If a direct routing approach is used, as seen in Fig. 3.37. The energy consumption for direct routing can be expressed as:

$$E_{DR} = E_{tx}(s, hR) \tag{3.23}$$

Substituting *Eq. (3.10)* into *Eq. (3.23)*, results in:

$$E_{DR} = sE_{amp}(\alpha + (hR)^2) = sE_{amp}(\alpha + h^2R^2) \tag{3.24}$$

When comparing the two data transmission approaches, for the energy used in a multi-hop transmission approach to be smaller than that of a single-hop transmission approach, the condition of $E_{MHR} < E_{DR}$, has to be met, therefore:

$$sE_{amp}(2\alpha h + hR^2 - \alpha) < sE_{amp}(\alpha + h^2R^2) \tag{3.25}$$

If the linear network is considered in terms of the strength of transmitter electronics, receiver electronics, and transmission amplifier, starting again with the multi-hop transmission approach. The expected energy consumption is:

$$\begin{aligned} E_{MHR} &= hE_{tx}(b,R) + (s-1)E_{rx}(h) \\ &= h(sE_{elec} + sR^2E_{amp}) + (s-1)sE_{rx} \\ &= s[(hE_{elec} + hR^2E_{amp} + sE_{elec} - E_{elec})] \\ &= s[2hE_{elec} - E_{elec} + hR^2E_{amp}] \\ &= s[hR^2E_{amp} + (2h-1)E_{elec}] \end{aligned} \quad (3.26)$$

The direct transmission approach has the following:

$$E_{tx}(s,R) = E_{tx}\big(s,(hR)\big) \quad (3.27)$$

Hence direct transmission energy consumption will become;

$$E_{DR} = sE_{elec} + s(hR)^2E_{amp} \quad (3.28)$$

Further simplified to;

$$E_{DR} = s(E_{elec} + h^2R^2E_{amp}) \quad (3.29)$$

Also comparing the two data transmission approaches, for the energy used in a multi-hop transmission approach to be less than that of direct transmission approach, $E_{MHR} < E_{DR}$, therefore:

$$s[hR^2E_{amp} + (2h-1)E_{elec}] < s(E_{elec} + h^2R^2E_{amp}) \quad (3.30)$$

Further simplified to:

$$\frac{E_{elec}}{E_{amp}} > \frac{hR^2}{2} \quad (3.31)$$

Where α is the amplification factor, such that;

$$\alpha > \frac{hR^2}{2} \quad (3.32)$$

3.3.2. Simulation of WSN

This work considered two different network scenarios for the computational and simulation experiments, these being the linear based WSHN and randomly distributed WSHN. In both network scenarios, this work adopted the parameters used in [91]. In the first part of the experiment, this work observed the variation of the average transmission cost of a grid-based WSHN for the distance between grid-based Wi-Fi nodes, the packet size of information, and the number of Wi-Fi nodes in the enclosure (room). In the second phase of the experiment, this work considers the comparison of the energy consumption of direct and multi-hop communication in WSHM, where this work also observed the variation or behaviour of different network types for the number of nodes in the enclosure, packet size and the distance apart of the node distribution in the enclosure. In both experiments, this work was limited to a maximum of 150 feet for the Wi-Fi modules transmission (indoor). However, the ESP 32 used can extend to about 1kilometer (3,280 feet) line of sight communication using the Espressif proprietary Wi-Fi long-range wireless protocol [92], for which this work conducted experiments to see the viability in the said range of transmission. This is because this work is an application-specific to a building. The maximum current drawn is 260mA at 2.4GHz operating frequency. This is follows with [91], [92].

3.4. ENERGY HARVESTING SYSTEM

This section of the paper describes the design process for the energy harvesting system used to power the electronic devices in the implementation of the secured smart home switching system. Fig. 3.39 shows the block diagram of the power supply design.

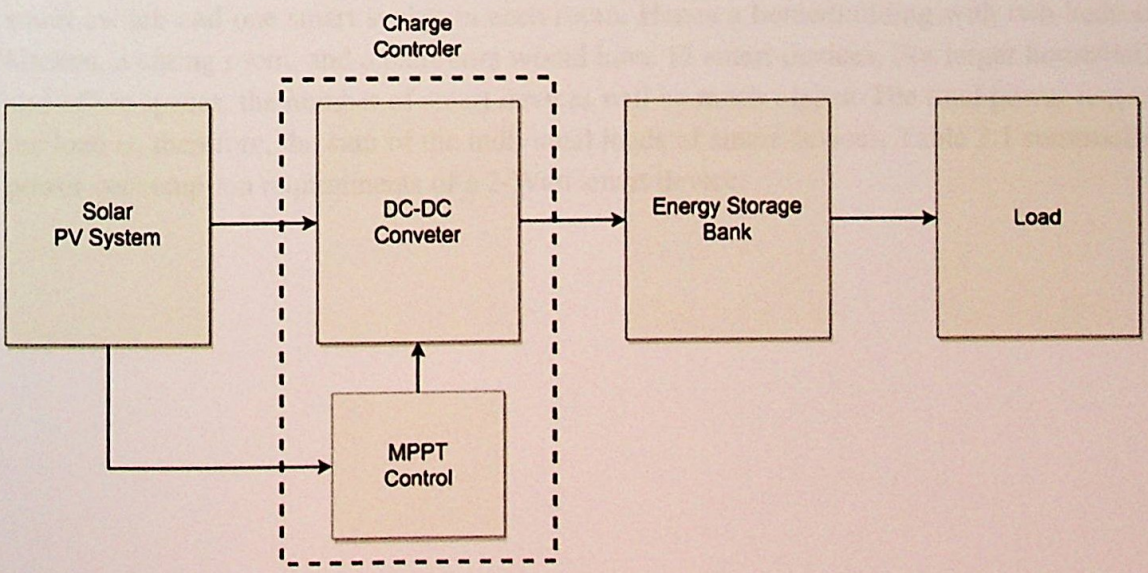


Figure 3. 37: Solar Energy Harvesting and Storage System Block Diagram

As shown in Fig. 3.39, the energy harvesting system consists of solar panels, DC-DC converter, MPPT, energy storage bank, and load. The role of the solar PV system is to convert solar irradiation/sunlight into electricity. Since factors that affect the solar PV systems electricity generation performance such as temperature, solar irradiation, and also loading conditions fluctuate throughout the day, additional electronics devices are added to ensure that the panel system is operating close to its maximum power generation point. These devices are the Maximum Power Point Tracker control, DC-DC converter, and energy storage bank. Using a DC-DC converter, the MPPT control ensures that the panel array is producing its maximum power. Some of the electrical energy produced by the PV system is used to drive the load, and some of it charges the energy storage bank. If there is no power generation or it falls below the required power output, the energy storage bank will provide the load with the stored energy until it is depleted, or power generation reaches sufficient levels. Each part of the energy harvesting is described in detail in the subsequent sections.

3.4.1. Load (Sizing of Load Power Consumption demands)

In designing the energy harvesting system, the characteristics of the load must be taken into consideration to aid in the sizing and rating of the other parts of the PV system, such as the Panel array size, Energy storage bank size, and all the other conversion electronics. The PV system is intended to provide the DC power for the operation of the secured smart home switching system. This means that it will be the source of power for the smart sockets, smart switches, smart switchboard, and smart hub that will be installed in a building or home. Based on the design of the secured smart home switching system, a building has one smart hub, one smart switchboard, and a variable number of smart sockets and smart switches. The number of smart sockets and smart switches in a building is determined by the number of rooms. Ideally, there should be at least one smart switch and one smart socket in each room. Hence a home/building with two bedrooms, a kitchen, a sitting room, and a bathroom would have 12 smart devices. For larger home/buildings and office spaces, the number of smart devices will be much higher. The total power required by the load is, therefore, the sum of the individual loads of smart devices. Table 3.1 summarised the power consumption requirements of a 2-Watt smart device.

Table 3. 1: Power Consumption of 2 Watt Smart Device

Smart Device Standby Energy Consumption (2W)							
Number of Smart Devices	Load Power Demand (W)	Daily Energy Consumption (24hrs) (Wh)	Monthly Energy Consumption (31 Days) (KWh)	Annual Energy Consumption (365.15 Days) (kWh)	Energy Consumption Cost After 10 years (P)		
					Electricity Tariff (1.0682)	Electricity Tariff (1.3801)	Electricity Tariff (1.969)
1	2	48	1.488	17.5272	P187.23	P241.89	P345.11
5	10	240	7.44	87.636	P936.13	P1,209.46	P1,725.55
10	20	480	14.88	175.272	P1,872.26	P2,418.93	P3,451.11
15	30	720	22.32	262.908	P2,808.38	P3,628.39	P5,176.66
20	40	960	29.76	350.544	P3,744.51	P4,837.86	P6,902.21
50	100	2400	74.4	876.36	P9,361.28	P12,094.64	P17,255.53
100	200	4800	148.8	1752.72	P18,722.56	P24,189.29	P34,511.06
150	300	7200	223.2	2629.08	P28,083.83	P36,283.93	P51,766.59
200	400	9600	297.6	3505.44	P37,445.11	P48,378.58	P69,022.11
250	500	12000	372	4381.8	P46,806.39	P60,473.22	P86,277.64
300	600	14400	446.4	5258.16	P56,167.67	P72,567.87	P103,533.17

Commercial smart devices such as smart sockets and smart switches are often advertised to have power consumption at about 1 Watt, but devices such as smart hubs and smart switchboards can reach values up to 3 Watts. To simplify the design, the power consumption of each smart device is limited to 2 Watts (W). Table. 3.1 shows the power demand, energy consumption of a different number of smart devices, and the electrical costs to be expected when running the system using grid power in Botswana. The electricity tariffs data used to calculate the costs can be found in the Botswana Power Cooperation website documentation [93]. The design is further simplified by selecting a load for a building with up to 15 smart devices. This represents buildings such as homes or small offices. With a load of 15 smart devices, the load demand is 30W with a daily power consumption amounts to 720 Watt Hours (Wh) to keep the smart devices running for 24 hours.

3.4.2. PV Array (Panel Sizing)

To determine the size of the PV panel array, the PV panel properties in Table 3.2 are taken into consideration.

Table 3. 2: 18 W Solar Panel Properties

Solar Panel Properties	
Maximum Power Point Output (Pmp)	18 W
Maximum Power Point Voltage (Vmp)	12 V
Maximum Power Point Current (Imp)	1.5 A
Open Circuit Voltage (Voc)	14.16 V
Short Circuit Current (Isc)	1.68 A
Max System Voltage	100 V
Standard Test Condition (STC)	1000 W/m3, AM 1.5, 25 C

The actual power output of a single PV panel, P_{pv} is calculated as;

$$P_{pv} = P_{mp} \times D_f \times B_{eff} \tag{3.33}$$

Where P_{mp} is the maximum power output of a panel at factory Standard Test Conditions (STC), D_f is the PV panel derating factor and B_{eff}, is the battery charging-discharging efficiencies.

The derating factor is a scaling factor that applies to a PV array power output to factor in the reduced output in real-world operating conditions compared to the STC conditions under which the PV panel was rated. The use of a derating factor accounts for factors such as dirt or dust on panels, wiring losses, shading, aging, temperature, and so forth. On another note, since the load of the smart device will be operating for 24 hours. A battery storage bank is required for providing power to the loads when there is insufficient solar irradiation. During the day, the solar PV system will need to charge the battery bank and supply power to the load. Hence the battery charging-discharging efficiencies/losses, B_{eff}, must be included.

Taking, P_{mp} as 18W, D_f as 0.8 and B_{eff} as 0.9 Eq. (3.33) becomes.

$$P_{pv} = 18\,\text{W} \times 0.8 \times 0.9 = 12.96\,\text{W}$$

To find the total energy produced by one 18 W panel in a day, E_p;

$$E_p = P_{pv} \times T_{psrh} \tag{3.34}$$

Where;

- P_{pv} is the actual power output of a single PV panel
- T_{psrh} is the number of peak sun radiation hours of a particular location (solar radiation is 1KW/m^2). In the case of Botswana, the average T_{psrh} is 5.16 hours [20].

Hence;

$$E_p = 12.96 \times 5 = 64.8 \text{ Wh}$$

The number of solar panels needs to meet the daily load of the smart devices can be found as;

$$\begin{aligned} P_{size} &= \mathrm{D_{ec}} \div E_p \\ &= 720 \div 64.8 \\ &= 11.1 \\ &= 12 \text{ Panels (rounded up)} \end{aligned} \tag{3.35}$$

Where D_{ec} is the daily energy consumption of the smart device loads over 24 hours.

To reduce wire costs and power losses due to current flowing in wire connections, the 12 solar panels will be configured in a 2 Series by 6 Parallel layout. This will result in a 24V maximum power point voltage, 9A maximum power point current, and 216W maximum power point output.

3.4.3. Energy Storage (Battery Storage Sizing)

There is generally a rule of thumb that is used in the recommendations of a battery bank system operating voltage depending on the solar system power [94]. The guidelines are presented in Table 3.3.

Table 3. 3: Battery Bank System Voltage Recommendations

System power rating (W)	Battery bank voltage rating (V)
Up to 500	12
500 - 2000	24
2000 - 10000	48
Above 10000	96

Since most the popular battery technology for PV systems are lead-acid batteries [17], the battery of choice to be considered for the PV system based on the selected battery operating voltage, is a 12 V, 120 Ah capacity lead-acid batteries with a maximum Depth of Discharge (DoD) of 70%.

The energy capacity of the battery bank, B_{cap}, can be represented as;

$$B_{cap} = \frac{D_{ec} \times D_a}{B_{dis} \times B_v \times B_{eff}} \tag{3.36}$$

Where ;

- D_{ec} is the daily energy consumption of the smart device loads over 24 hours
- D_a is the days of autonomy (the number of days the system will operate when there is no power produced by PV panels)
- B_{dis} is battery depth of discharge
- B_{eff} is battery charging-discharging efficiencies
- B_v is the nominal battery voltage

Taking D_{ec} as 720Wh, D_a as 2, B_{dis} as 0.7, B_{eff} as 0.9 and B_v as 12V, Eq. (3.35) amounts to;

$$B_{cap} = \frac{720 \times 2}{0.7 \times 12 \times 0.9}$$

$$= 190.5 \text{ Ah}$$

Hence the required number of 12 V, 120 Ah lead-acid batteries, B_{num} is;

$$B_{num} = \frac{B_{cap}}{120} \tag{3.37}$$

$$= \frac{190.5}{120}$$

$$= 1.6$$

$$= 2 \text{ batteries (rounded up)}$$

Thus, the selected battery connection layout consists of 1 Series by 2 Parallel layout.

3.4.4. Solar Charge Controller (MPPT + DC-DC Converter)

A solar charge controller plays a very important role in the operation of a solar PV system. It is an electronic device that stands between the power generated by the PV panel array and the battery bank. The purpose of the solar charge controller is to control and monitor the charging of the battery bank, ensuring that it prevents conditions such as overcharging and over-discharging of the battery bank. Furthermore, the charge controller also provides the correct charging sequence of the PV system battery bank. This promotes good battery performance and longer life cycle. There are different types of solar charge controllers. However, the most recommended ones based on their good performance are the PWM and MPPT charge controllers. Between the two, MPPT charge controllers provide the best performance due to their ability to track and utilize the maximum power output from the solar PV system. This is done by use of MPPT tracking algorithms and power conditioners such as DC-DC converters. The perturb and observe is the most widely used MPPT algorithm due to its simple design and ease of implementation through digital systems. Amongst the DC-DC converters, the buck is preferred for battery voltage below 48V and a booster for battery voltages higher than 48V [16].

Based on the advantages of MPPT charge controllers and the battery bank operating voltage, the charge controller for the energy harvesting system design is based on a 12V MPPT buck converter charge controller. According to [16] the current rating for the charge controller is calculated as;

$$I_{ch} = I_{sc} \times N_p \times SF \quad (3.38)$$

Where ;

- I_{ch} is the short circuit current of PV panel
- N_p is Number of parallel panels in PV system
- SF is safety factor

Taking I_{ch} as 1.68A from Table. 3.2, N_p as 6 from the 2S 6P panel configuration and SF as 1.25;

$$I_{ch} = 1.68 \times 6 \times 1.25$$
$$= 12.6 \text{ A}$$

Hence the selected solar charge controller must be rated for an output voltage of 12V and output current equal to or greater than 12.6A.

3.5. HARDWARE TESTING

All system designs underwent testing before implementation. The tests are performed to ensure that each sub-system met the functional requirements.

3.6. IMPLEMENTATION OF SECURED SMART HOME SWITCHING SYSTEM

The secured smart home switching system design was first implemented as a scaled-down model of a house. Fig. 3.40 shows a picture of the first implementation, Prototype 1. Prototype 1 was designed to be portable and used for demonstration of the secured switching system. Following prototype 1, the system was then implemented in the BIUST off-grid secured smart house as prototype 2. Fig. 3.41 shows a picture of the BIUST Off-Grid secured smart house. Prototype 2 is designed to integrate the secured switching system and the energy harvesting system. The building of prototype 2 is fully Off-grid; hence changes were made to the energy harvesting system to make it into an off-grid harvesting system with an inverter to provide AC power to the loads. More pictures of prototype 1 and prototype 2 implementations can be seen in Appendix B and Appendix C.

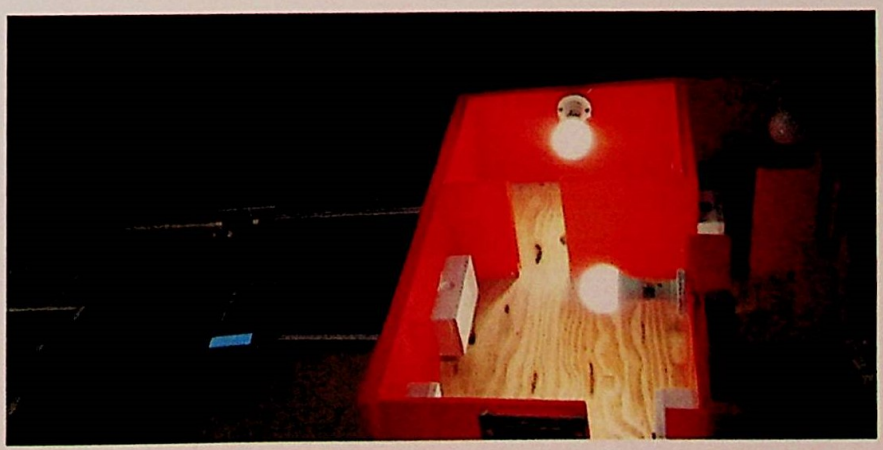


Figure 3. 38: Picture of Prototype 1 of system implementation



Figure 3. 39: BIUST Off-Grid secured smart house front side picture

In both implementations, smart switches are made by enclosing a smart switch PCB into a single gang electrical switch box, as shown in Fig. 3.42. The smart sockets are made by connecting the output live wire from a smart switch as a live wire into an electrical socket. Fig. 3.43 shows a picture of the smart socket implementation.



Figure 3. 40: Secured Smart Home Switching System Smart Switch Implementation

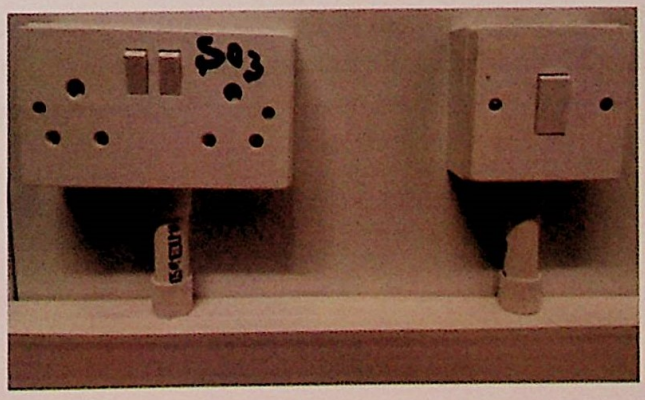


Figure 3. 41: Secured Smart Home Switching System Smart Socket Implementation

CHAPTER 4

RESULTS AND ANALYSIS

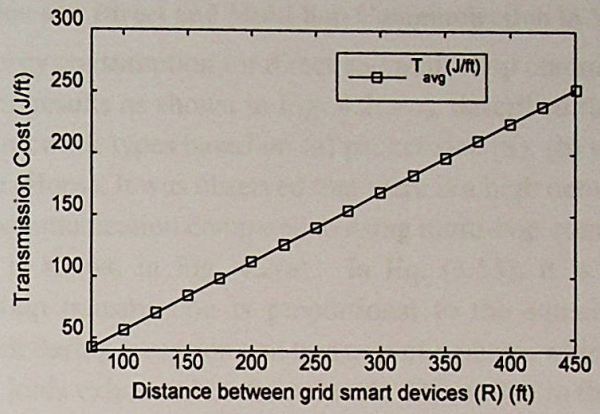
INTRODUCTION

This chapter presents the results of the work carried out in chapter 3. This includes results obtained from the WSN simulations and the secured smart home switching system testing and implementations.

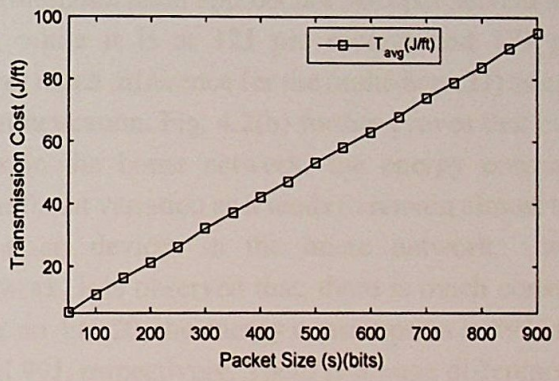
4.1. RESULTS FROM WIRELESS SENSOR NETWORK SIMULATION

4.1.1. Average Transmission Cost of a Grid-Based WSHN

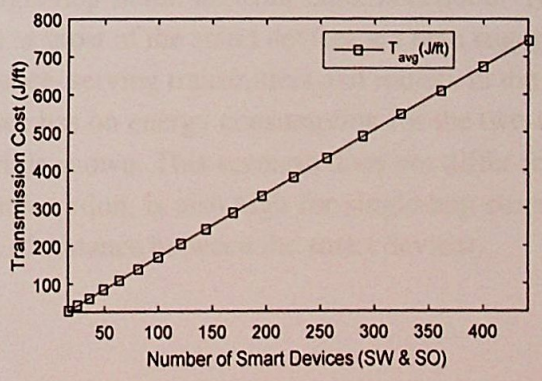
This part of the thesis presents the results of the average transmission cost for a typical WSHN deploying grid-based transmission in a grid network. As can be seen in Fig. 4.1, from using Eq. (3.13), it was observed that the cost of transmission measured in joules per feet (J/ft), is a function of packet size (S) being sent, the distance between the smart devices, packet, and the total number of hops the message makes to reach its destination. In Fig. 4.1(a), the impacts of transmission distance effects on the average cost of transmission is observed. For a small increase in transmission distance, the energy consumed per foot is obvious for each of the smart sockets or switches in the network. This justifies the relationship in Eq. (3.13). In this, it is evident that limiting the transmission distance in the network will favour the lifetime of the entire network due to the limited energy available per sensor node (smart device). For a typical Wi-Fi node (ESP 32) as in [92], each module can transmit at 150 feet indoor but up to 1km outdoor without obstruction. For a high transmitting node, it comes with a high cost of energy consumption, as can be seen in Fig. 4.1(a). Fig. 4.1(b), shows the relationship between average transmission cost and information packet size. This is similar to Fig. 4.1(a), where the increase in bits of information directly affects the energy consumed by the smart devices in the network. The effect of the packet size on the average transmission cost is also shown in Eq. (3.13), which is translated in Fig. 4.1(b). Fig. 4.1(c), shows the effect of the number of smart devices in the home network, which also correspond to the relationship in Eq. (3.13) as the average transmission cost is directly affected by the density of smart devices in the home network.



(a)



(b)

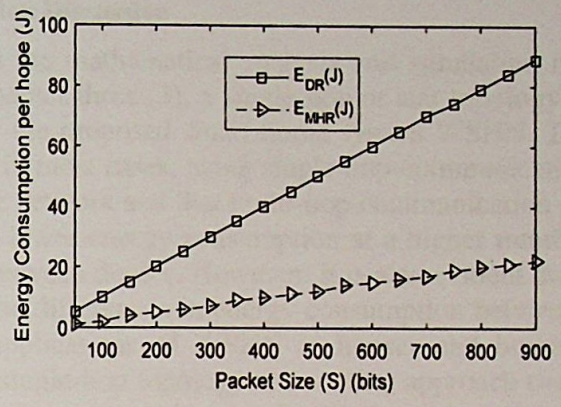


(c)

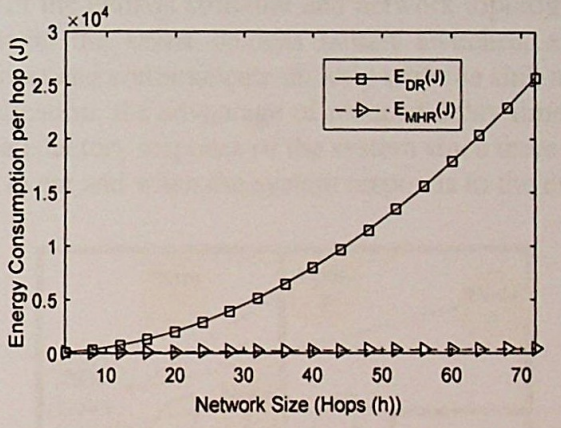
Figure 4.1: Relationships of (a) Transmission distance (R) (b) Packet Size (S), and (c) Number of Smart Devices (SW & SO) on the Transmission cost for a grid-based wireless sensor home network

4.1.2. Energy Consumption of a Direct and Multi-hop Communication in WSHN

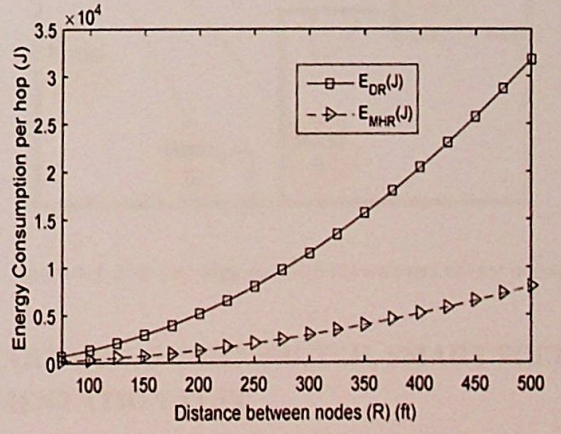
In the comparison of energy consumption for direct and multi-hop communication as given in Eq. (3.23) and Eq. (3.24).The results as shown in Fig. 4.2(a-c), described the variation of consumed energy for the different network types based on (a) packet size (S), (b) transmission distance (R) (ft), and (c) network size (Hops). It was observed that there is a high network energy consumption when using single-hop communication compared to using multi-hop communication as the packet size is increased. This is shown in Fig. 4.2(a). In Eq. (3.23), it is evident that the energy consumption of single-hop transmission is proportional to the square of the number of bits transmitted in the network during reception and transmission phase, which is an indicator of many bits transmitted per unit joule exhausted in the network. This refers to the fact that, for multi-hop communications, energy is saved due to the transmission of bits at a shorter distance. As can be seen in Fig. 4.2(a), when the packet size value rises to 500bits, the energy consumption per smart device for the single-hop communication approaches 50 J per second and rises to the value of 70 J per second at 700bits, while it is at 12J per second and 17J per second for multi-hop communication. There is not much difference for the multi-hop (2J) as against 20J between 500bits and 700bits for direct communication. Fig. 4.2(b) further proves that even with an increase in the number of smart devices in the home network, the energy consumed using the multi-hop communication has no significant variation as it tends to remain almost the same value as the initial consumption for fewer smart devices in the home network, whereas, using the direct communication in the network, it is observed that, there is much consumption in the network as the number of hops vary from 4 to 20, the energy consumption is 79J and 1986J respectively. But for multi-hop, it is 20J and 99J, respectively. There is a huge difference in the said number. This is to be expected to be that as the network size increases, there is an increase in transmission range, which does not favour single-hop home network communication. The multi-hop achieved this reduced energy conception as most of the smart devices are then engaged in helping other devices to route the information, hence, serving transmitters and routers in the network. In Fig. 4.2(c), the impact transmission distance has on energy consumption for the two-transmission type in a grid-based sensor home network is shown. This scenario does not differ from that of Fig. 4.2(a-b), as the variation of energy consumption, is also high for single-hop communication as compared to multi-hop for the variation of distance between the smart devices.



(a)



(b)



(c)

Figure 4.2: Variation of Consumed Energy for the different network type: Multi-hop and Direct Communication in WSHN to (a) Packet Size (S) (b) Network Size (Hops), and (c) Transmission distance (R) (ft)

4.1.3. WSHN Implementation Discussion

Taking into consideration the mathematical analysis and simulation results on wireless sensor networks carried out in chapter three (3), a single-hop or star topology network is more suitable for the implementation of the proposed smart home system WSHN. Taking from the graphs of Fig. 4.2, it is evident that in most cases, using single-hop communication might cause excessive energy consumption in the network and that multi-hop communication is seen to be of preferable communication due to its lower energy consumption at a higher number of nodes, large packet size and longer distance between device. However, it is also evident that at small distances, such as below 50ft (15.24m), the differences in energy consumption between the two methods is less pronounced. Hence for applications of WSHN in houses and buildings where distances are typically small, using the single-hop topology and routing approach over multi-hop will not only have little comparable energy consumption, but it will also reduce the complexity of the network and promote the responsiveness of the network since messages will travel directly to the sink node. Fig. 4.3 gives an example of the general structure and network topology to be implemented. The nodes in Fig. 4.3 represents the smart devices (smart switches, smart sockets, and smart switchboard) that will connect and communicate directly with the sink node (smart hub). For such a mostly event-driven application, the advantage of reduced delay time in direct communication will provide users with a satisfactory response of the system since there will be a little pause from the time a user initiates an event and when the system responds to the event or stimuli.

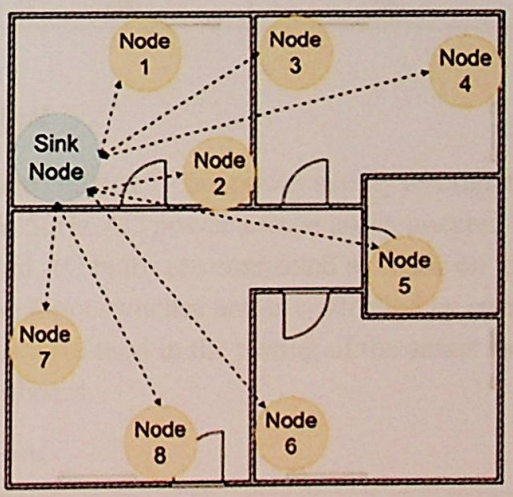


Figure 4.3: Star topology (single hop) wireless sensor network

4.2. RESULTS FROM SMART HUB, SMART SWITCH, SMART SOCKET, AND SMART SWITCHBOARD IMPLEMENTATION TEST

The secured switching system achieved its expected functions, as stated in the design. Tables 4.1, 4.2, and 4.3 show the results of the tests carried out on each of the smart home subsections. A further test of system functionality was carried out in the two system implementations.

4.2.1. Smart Switch and Smart Socket Test

The smart switch is connected to a 5V lab power supply through the DC input power terminal block. A 230V 50Hz live wire from an AC power source is connected to the smart switch through the AC input power terminal, and an AC bulb is connected as a load on the AC output terminal end. A push-button switch is connected to the switch input terminal block. Since both the smart switch and smart socket are of the same design, the tests and connections made on the smart switch are the same as those on the smart socket. Table 4.1 shows the results for the smart socket and smart switch.

Table 4. 1: Smart Socket and Smart Switch Test Results

Lock State	Test	Current Load State	Expected Load State	Test Results
Unlocked	Turn ON Load	OFF	ON	Positive
	Turn OFF Load	ON	OFF	Positive
Locked	Turn ON Load	OFF	OFF	Positive
	Turn OFF Load	ON	ON	Positive

4.2.2. Smart Switchboard Test

The smart switchboard is connected to a 5V lab power supply through the DC input power terminal block. Live wires from 230V 50Hz AC power source are connected to the smart switchboard at AC input power terminals, and AC bulbs are connected as loads on the AC output terminals end. The smart switchboard has no input switches and is controlled by commands from the smart hub. However, temporary switches were used in the testing of the smart switchboard. Table 4.2 shows the results of the smart switchboard.

Table 4. 2: Smart Switchboard Test Results

Test	Current Load State	Expected Load State	Test Results
Turn ON Relay 1-4	OFF	ON	Positive
Turn OFF Relay 1-4	ON	OFF	Positive

4.2.3. Smart Hub Test

The smart hub is connected to a 5V lab power supply through the USB power port located on the Raspberry pi. The smart switch, smart socket, and smart switchboard are connected, as explained

in their tests. Once the smart hub is powered on, it establishes a Wi-Fi access point that the smart devices connect to. Table 4.3 shows the results of the smart hub tests.

Table 4. 3: Smart Hub Test Results

Test	Current Load State	Expected Load State	Test Results
Turn ON smart socket	OFF	ON	Positive
Turn OFF smart socket	ON	OFF	Positive
Turn ON smart switch	OFF	ON	Positive
Turn OFF smart switch	ON	OFF	Positive
Turn ON Smart Switchboard Relay 1-4	OFF	ON	Positive
Turn OFF smart switchboard Relay 1-4	ON	OFF	Positive
Lock smart socket	Unlocked	Locked	Positive
Unlock smart socket	Locked	Unlocked	Positive
Lock smart switch	Unlocked	Locked	Positive
Unlock smart switch	Locked	Unlocked	Positive
Receive SMS Command	N/A	N/A	Positive
Execute SMS command	N/A	N/A	Positive
Send SMS reply	N/A	N/A	Positive

4.2.4. Secured Smart Home Switching System Implementation Test

In the implementations of both scaled-down house model with secured switching system and BIUST off-grid secured smart house, the secured smart home switching performs the required functions in providing security and access control to a building's electricity supply. Installing the smart socket, smart switch, smart switchboard, and smart hub in a home or building enables home and building owners to remotely through SMS and locally turn on or off electricity to appliances and lock them to prevent unauthorized use of the buildings electricity. The renewable energy harvesting system provides renewable energy required to power the secure switching system as

intended but implementation of the energy harvesting system consequently has high implementation costs.

CONCLUSIONS

Through the simulation results of the WSN shown in Fig. 4.1, and Fig. 4.2, a topology for the secured smart home switching system, was selected. The insight from the WSN analytical modelling and results of the WSN simulation guided in the design decisions to use a single-hop star topology for the WSN, such as the one shown in Fig. 4.3. The advantages of such a topology promote a simple and responsive network with little delay. Table 4.1 -Table 4.3 shows the results of the functionality tests carried out on the smart switch, smart socket, smart switchboard, and smart hub. All the device tests yielded positive results and met the device requirements. The implementations of the secured smart home switching system perform as intended in providing a security system that controls access to a building the power supply. The energy harvesting system provides an energy harvesting and storage system to remove the operational costs of the smart sockets and switches from a home user electricity bill but consequently has high implementation costs and is better integrated into an off-grid system.

CHAPTER 5

CONCLUSIONS AND FUTURE DIRECTIONS

INTRODUCTION

In this chapter, the objectives presented in chapter 1 are evaluated to identify if the intended outcomes have been met through the research. Furthermore, future work directions for improving and the work are provided.

5.1. CONCLUSIONS

Regarding the main aim and objectives of the research work stated in chapter 1, as well as evident from the results from chapter 4, the project has achieved the intended outcomes. The implemented system has both a secured switching system to introduce security and access control to a building's electricity supply and a model of energy harvesting and storage system to remove the operational costs of the smart sockets and switches from a home user electricity bill. The secured switching system performed as intended in adding access control to a building's electricity. Installing the secured smart home switching system enables home and building owners to remotely through SMS and locally turn on or off electricity to appliances and lock them to prevent unauthorized use of the building's electricity. The renewable energy harvesting system provides renewable energy as intended but consequently has high implementation costs. The energy harvesting system provides an energy harvesting and storage system to remove the operational costs of the smart sockets and switches from a home user electricity bill, but consequently has high implementation costs and is better integrated into an off-grid system.

5.2. FUTURE WORK DIRECTIONS

Though the designed system meets the stated functional requirements, there is room for future improvements that can make the system more secure, functional, and reliable for home and building owners.

5.2.1. Security

Despite the fact that the systems added security of preventing unauthorised use of a building's electricity. The smart switches and smart socket devices remain vulnerable to physical attacks such as;

1. Tempering with device enclosures to gain access into the system's circuits and bypassing the security.
2. Disconnecting appliances from the smart sockets as a way to turn them off.

Therefore, physical hardware security or temper detection mechanisms need to be investigated and implemented to improve upon the system's security.

5.2.2. Usability and Functionality

The current secured smart home switching system has a limited number of methods users can use to interact with the smart hub and other smart devices. Adding more methods to interaction will improve the usability, functionality, and use cases for the system.

Possible future works include;

1. Dedicated remote controllers
2. Schedule based locking
3. Sensor and power consumption-based locking

5.2.3. Improved evaluation metrics

The secured smart home switching system is connected to and controls a building's electrical lines. Failure of the system can result in users being unable to access a building's electricity. Hence, more work needs to be done in the collection of data to include evaluation metrics such as Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR) and Mean Time To Failure (MTTF) to track the reliability and availability of the system. With the added data and included metrics, system failures and repair times can be better predicted.

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APPENDICES

APPENDIX A: Pseudo codes used in the software design for the smart hub, smart switch, smart socket and smart switchboard.

Pseudo Code 1:

```
1
1.  START
2.  Create network Wi-Fi access point.
3.  Establish MQTT access point connection
4.  Establish GSM connection
5.  Display Locked-Screen
6.      "Pin code Request."
7.      "Sockets or Switch list."
8.  WHILE forever
9.     Scan for GSM-Data
10.    IF GSM-Data available
11.       THEN
12.       CALL GSM-CALL
13.    ENDIF
14.    Scan for MQTT-Data
15.    IF MQTT-Data available
16.       THEN
17.       CALL MQTT-CALL
18.    ENDIF
19.    Scan Keypad
20.    IF Keypad input available
21.       THEN
22.       IF Keypad input = "any number 0-9"
23.          THEN
24.          Display Keypad input
25.        Stored key= Pressed key
26.        Increment Key-Count
27.        IF key-count ==4
28.             THEN
29.             Reset Key-Count to 0
30.           IF Entered-Pin == Stored-Pin
31.              THEN
32.              Reset Key-Count to 0
33.              Call System-Unlocked
34.           ELSE
35.              Display error message
36.              Display Locked-Screen
37.           ENDIF
38.        ENDIF
39.      ELSE
40.      IF Keypad input == 'C'
41.         THEN
42.         Clear Display
43.         Reset Key-Count to 0
44.         Display Locked-Screen
```

```
45.       ENDIF
46.       ELSE
47.       IF Keypad input == 'D'
48.         THEN
49.         Toggle Locked-Screen Device-Type-List
50.       ENDIF
51.       ELSE
52.       IF Keypad input == '#'
53.         THEN
54.         Toggle Locked-Screen Device-Number
55.       ENDIF
57.    ENDIF
58. ENDWHILE
```

Pseudo Code2:

```
1.  START
2.  Display Unlocked-Screen
3.      "List of devices."
4.      "List of available commands."
5.  WHILE forever
6.    Scan for GSM-Data
7.    IF GSM-Data available
8.      THEN
9.      CALL GSM-CALL
10.   ENDIF
11.   Scan for MQTT-Data
12.   IF MQTT-Data available
13.     THEN
14.     CALL MQTT-CALL
15.   ENDIF
16.   Scan Keypad
17.   IF Keypad input available
18.     THEN
19.     IF Keypad input = "any number 0-9"
20.       THEN
21.       IF key-count =< 2
22.         THEN
23.         Display Keypad input
24.         Store Keypad input in Target-Devices number
25.       ELSE
26.       IF Keypad input = 'A'
27.         THEN
28.         IF Target-Device number available
29.           THEN
30.           CALL Target-Device-EDIT
31.           Clear Target-Device number
32.         ENDIF
33.       ELSE
34.       IF Keypad input = 'B'
```

```
35.             THEN
36.             Clear Display
37.             RETURN
38.           ENDIF
39.           ELSE
40.           IF Keypad input = 'C'
41.             THEN
42.             Clear Target-Device Number
43.           ENDIF
44.           ELSE
45.           IF Keypad input = 'D'
46.             THEN
47.             Toggle Unlocked-Screen Device-Type-List
48.           ENDIF
49.           ELSE
50.           IF Keypad input = '#'
51.             THEN
52.             Toggle Unlocked-Screen Device-Number-List
53.           ENDIF
54.       ENDIF
55.   ENDWHILE
```

Pseudo Code 3:

```
1.  START
2.  Display blinking cursor on Target-Device power state
3.  WHILE forever
4.     Scan for GSM-Data
5.     IF GSM-Data available
6.     THEN
7.        CALL GSM-CALL
8.     ENDIF
9.     Scan for MQTT-Data
10.    IF MQTT-Data available
11.      THEN
12.      CALL MQTT-CALL
13.    ENDIF
14.    Scan Keypad
15.    IF Keypad input available
16.      THEN
17.      IF Keypad input = 'A'
18.        THEN
19.        IF blinking cursor on Target-Device power state
20.          THEN
21.          Toggle Target-Device power state
22.        ELSE
23.          Toggle Target-Device lock state
24.        ENDIF
25.        Update Device-Database
26.      ELSE
27.      IF Keypad input = 'B'
```

```
28.           THEN
29.           Stop blinking cursor
30.           RETURN
31.         ENDIF
32.         ELSE
33.         IF Keypad input = '#'
34.           THEN
35.           IF blinking cursor on Target-Device power state
36.             THEN
37.             Blink cursor on Target-Device lock state
38.           ELSE
39.             Blink cursor on Target-Device power state
40.           ENDIF
41.         ENDIF
42.       ENDIF
43.   ENDWHILE
```

Pseudo Code 4:

```
1.  START
2.  Process Received MQTT data-packet
3.      "Device-ID."
4.      "Commands."
5.  IF data-packet is a command
6.     THEN
7.     Send MQTT data packet to Target-Devices
8.  ENDIF
9.  Update Device-Database
10. RETURN
```

Pseudo Code 5:

```
1.  START
2.  Process Received text message
3.      "Cell-Phone-Number."
4.      "Commands."
5.      "Target-Device-ID."
6.  IF text message command is an information request
7.     THEN
8.     Search Device-Database for Target-Device-ID
9.     Extract Target-Device information
10.    Send GSM SMS response to Cell-Phone-Number
11. ELSE
12. IF text message command is an action request
13.    THEN
14.    Send MQTT data packet to Target-Devices
15.    Update Device-Database
16.    Send SMS success response to Cell-Phone-Number
17. ELSE
18.    Send SMS error response to Cell-Phone-Number
```

```
19. ENDIF
20. RETURN
```

Pseudo Code 6:

```
1.  START
2.  Connect to Smart-Hub Wi-Fi network
3.  Establish MQTT connection with Smart-Hub
4.  WHILE forever
5.     Scan for MQTT commands
6.     IF MQTT-Data available
7.        THEN
8.        Power-State = MQTT-Data * B(01)
9.        Lock-State = MQTT-Data * B(10)
10.    ENDIF
11.    Scan Push-Button
12.    IF Push-Button pressed
13.       THEN
14.       IF Lock-State = 0
15.          THEN
16.          Toggle power state
17.          Send MQTT data packet to Update Smart-Hub
18.       ENDIF
19.    ENDIF
20. ENDWHILE
```

Pseudo Code 7:

```
1.  START
2.  Connect to Smart-Hub Wi-fi network
3.  Establish MQTT connection with Smart-Hub
4.  WHILE forever
5.     Scan for MQTT commands
6.     IF MQTT-Data available
7.        THEN
8.        IF MQTT-Data = 1
9.              Toggle relay 1 power state
10.       ELSE IF MQTT-Data = 2
11.             Toggle relay 2 power state
12.       ELSE IF MQTT-Data = 3
13.             Toggle relay 3 power state
14.       ELSE IF MQTT-Data = 4
15              Toggle relay 4 power state
16.    ENDIF
27. ENDWHILE
```

APPENDIX B: Fig. 1 and Fig. 2 are pictures of prototype 1 as the implementation of a Secured Smart Home Switching System in a scaled-down model of a house with smart sockets and switches.



Figure 1: Picture of Prototype 1 smart hub and smart switchboard



Figure 2: Top view Picture of Prototype 1

APPENDIX C: Pictures of Complete Secured Smart Home Switching System Based on Wireless Sensor Network Implemented in the BIUST Off-Grid Secured Smart House Project are shown in Fig. 3- Fig. 5.



Figure 3: BIUST Off-Grid secured smart house side picture

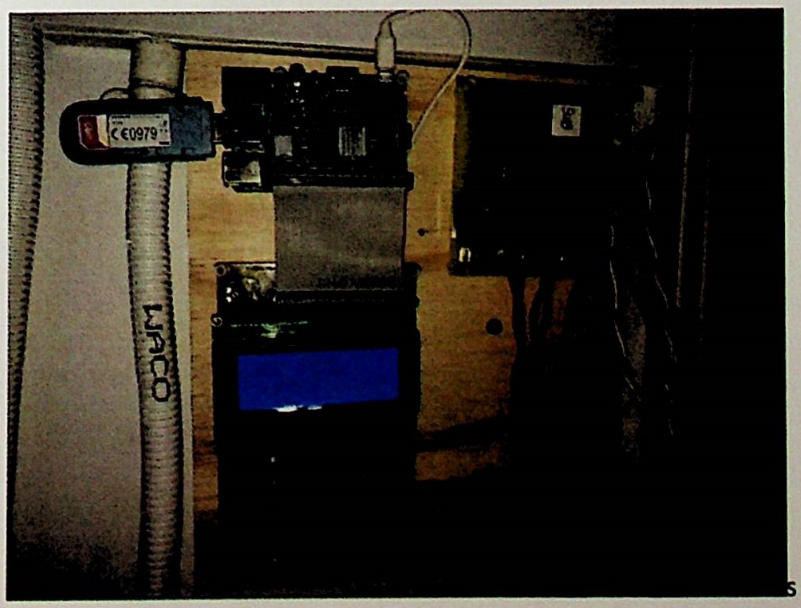


Figure 4: Secured Smart Home Switching System Smart Hub and Smart Switchboard Implementation



Figure 5: Energy harvesting MPPT charge controller, battery bank and inverter