Low Cost Wet Diaper Detector System

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The role of smart wet diaper detectors to health caregivers cannot be over-emphasized. Prolong wetness in patients and babies is one of the major causes of rashes especially when the wetness is not detected on time. Monitoring patients in real-time is essential for their well-being to know when to change a wet diaper and thus prevent serious skin problems. Although there are many smart diapers in the market, the high cost is a big challenge to prospective users.

The design and implementation of a low-cost wet diaper detector have been presented in this thesis. The use of advanced technologies such as Bluetooth and wireless connectivity has helped in the development of smart solutions to enable caregivers to detect the wetness of diapers by sending notifications of wetness to their mobile phones. This thesis focused on providing a proof-of-concept prototype to implement a low-cost battery-free wetness detector unit. The prototype was designed to transmit a signal to the caregiver's phone once wetness is detected. The wetness detector unit consists of the wet detector and the embedded In-play Nano-beacon Bluetooth Low Energy (BLE). Results show that the BLE operated at a very low voltage range of 1.1V to 3.6V and transmitted a wet signal to a phone up to 100m. The threshold voltage range (0.7V to 1V), at which the wet detector senses wetness was achieved using a voltage divider at the input of the wet detector. The prototype was designed using the Altium software environment and fabricated on a printed circuit board (PCB) using standard off-the-shelf components from the datasheet. Compared to other wet diaper detectors it has very low power consumption, is simple in design, and consumes a lesser amount of power. Hence it is relatively cheaper.

Acknowledgements

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First of all, I would like to thank my advisor's Prof. Normal Zhou and Prof. George Shaker for supervising my graduate research program throughout my study. They both were great mentors and supportive by giving me valuable advice and directions. None of my thesis work would have been possible without the contribution from them. I learned how to conduct quality research from them both. Whenever I encountered a problem along the way in my project, both professors knee insight guided me with new ideas.

I would like to extend my appreciation to my colleagues for their support, discussions, comradeship, and sharing of ideas during the period of my study. I wish to thank Nimesh Kotak for directives and assisting during my project work and guiding me on using printed circuit board (PCB) designs. Nathan Levi Johnston who gave me support and directives on arrival and the discussions from Jarren Theo, Sophy Li, Mariam Laghi Mrabat, and Kamalprret helped me overcome many difficulties and think wide from time to time.

Last but not least, I am thankful to my family for their support, love, sacrifices, and support from my friend Evidence for advice on writing my report. Without them, I would never have met this moment of finalizing this chapter.

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Chapter 1

INTRODUCTION

1.1 Background Study of Smart Diaper System

Health care and personal hygiene is of great importance in the society today. A diaper is a kind of undergarment designed to collect stool and urine of its wearer. Overtime, diapers have been widely used in absorbing moisture and accommodating mess, so that the diaper user remains comfortable after getting wet. Diapers are utilized not only for babies, but also for senior persons who have difficulties in controlling their bladder and are unable to use the toilet when needed [1]. However, the usage of diapers has led to skin rash as a result of the skin being exposed to protracted wetness which is the fundamental cause of diaper rash [2]. Once diapers become wet, they require to be changed as soon as possible by a parent or caregiver. If the diaper is not changed untimed after being filled, the wearer of the latter can suffer from diaper complications, which causes one or more skin problems, around the area covered by the diaper. These skin problems can be related to skin rashes, allergic reactions, toxicity, Urinary Tract Infections(UTI) etc. Most caregivers rely on manual monitoring of diapers to know when to make a change when the diaper is wet. This process requires the caregiver to frequently check whether the diaper is wet or not in order to decide on replacement. It is associated with late detection of wetness of the diaper and other inconveniences [3]. Notifying the care givers on time when diapers are fully wet and due for replacement is imperative especially for continuous monitoring of patients on wheel chair and those on the bed side [4].

This project is concentrated on improving the performance efficiency of caregivers by overcoming the drawbacks associated with manual monitoring of diapers. A smart diaper detector is a device that detects when a diaper is wet and sends notification to the caregiver's smartphone using Bluetooth technology [5]. Existing devices and products have already achieved non-contact urinary incontinence monitoring, based on capacitance sensor and transmission of moisture information through wireless network [6]. Some other products based on built-in moisture sensor and radio frequency (RF) to transmit and send an alarm when a diaper is wet [7]. Some device can monitor urinary incontinence and send alarm to wireless gateway, then to the host PC. But they have some limitation in some aspect; some of them cannot realize non-contact sensing, long-distance transmission and sending and processing the urinary incontinence alarm information [8].

This project implements an automatic wet diaper both in real and practical situations. It uses flexible sensor and PCB to detect wetness of the diaper and send a notification to the phone of the care giver whenever the diaper is wet and due for change. The device will address the issue of delay associated with manual checking of the diaper for wetness by a notification to the caregiver for quick replacement of the wet diaper.

An intended use case of full functionality of smart diaper application is as shown in Figure 1.1.

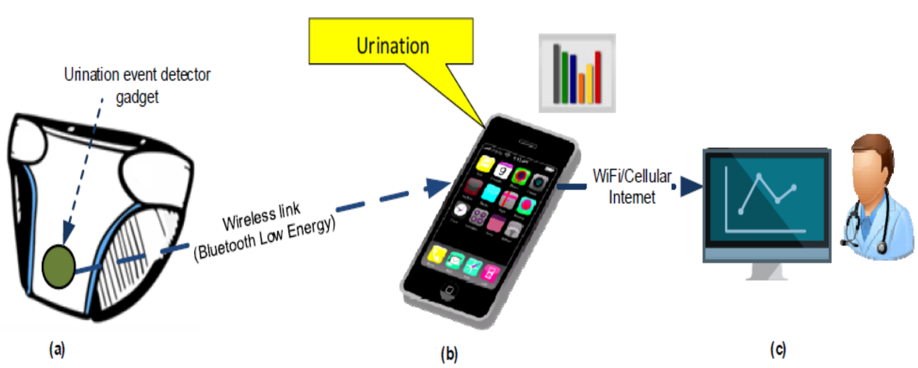

Figure 1.1 Intended use case of smart diaper: a) urination detector gadget; b) smart phone gets notification; c) Data sent to physician by online. [8]

1.2 Problem Statement

Health is something which changes on a daily basis, even if not unaware or it isn’t really apparent. In hospital, the constant monitoring of diaper wearer due to health issues is very important. The health of diaper wearer is also important to their family members and parents. Diaper monitoring is an informal, non-statutory method of surveying for wetness in the diaper. Caregivers need to constantly check diaper wearer to ascertain whether the diaper is wet or dry at regular intervals as wet diapers when not changed as at when due could result to dangerous health problem, care givers may also be faced with the problem of laziness to check the wetness of diapers from time to time.

Also, nowadays most care givers are busy with other household activities which makes their service to diaper wearer inactive and challenging; thus, wetness of diaper for a long period of time is very frequent. Since, most caregivers depend on manual check for wetness in the diaper, many parents do not feel secure living their babies or patients as the case may be in the hands of care giver. Consequently, this limits the effective performance of care givers.

The project **“Smart diaper system’’** would help to cater for diaper automation as it would initiate an automatic alarm to notify care giver on their smart phone when diaper is wet thereby putting an end to inaccuracy in detecting a wet diaper on time.

1.3 Motivation

With the increase in world population it is obvious that there is a serious need for us to start developing technologies to aid care giver in improving health and welfare for severely ill, disabled and demented patients who are unable to urinate at will. This technology would enhance the quality of care given to diaper wearer, and also minimize dangerous health problem caused by wet diaper, as warning are giving to care givers immediately wetness is being detected for the diaper to be replaced. The quality of care will be improved considerably, and the performance of caregivers that adopt such will be boosted. The potentials are enormous, and its value continues to grow profoundly. Conducting a research that will enhance the quality of care given to diaper wearer, thereby reducing health issues caused by wet diaper is one of my main motivations.

1.4 Project Aim and Objectives

The aim of this project is to design a low cost battery-free wet diaper detector system for caregivers.

The objectives of this project are to:

1. Design a system that senses urine on the diaper and sends an alert to the care giver so as to replace the diaper immediately.
2. Implement the designed wet detector system on a hardware Printed Circuit Board (PCB).
3. Link the design system to a smartphone to receive notifications using Bluetooth Technology.
4. Evaluate the effective performance of the developed smart diaper system.

1.5 Scope of the Project

The work is limited to the design of battery free wet diaper detector system. The implementation of the system would be carried out printed circuit board (PCB) hardware taken into consideration the (designing, constructing and testing). This covers the power unit, sensing unit, Bluetooth communication unit, and alert recipient unit. These units work in harmony to aid in automating communication between a care giver and a diaper wearer for ascertaining whether the diaper is wet or dry.

1.6 Significance of the Study

The use of a Bluetooth enabled smart diaper for care givers will be beneficial to its user in many ways, some of which are:

1. **Better accuracy:** The designed system will ensure that the caregiver is notified at all-time when urine is detected on the diaper so as to enable the care giver replace the diaper.
2. **Convenience:** The designed system eliminates the stress associated with caregivers constantly checking whether the diaper is wet or dry from time to time.
3. **Cost:** The system is a low cost wet diaper detector system based on Bluetooth transmitter and smart phone.
4. **Quality Health:** The system will reduce dangerous health issue caused by wet diaper, as these health problems are due to wet diaper not being replaced immediately it gets wet.

Finally, this work is also important to the researcher because it is a prerequisite for obtaining Master Certificate from the University, and it will help build the researchers knowledge, giving a greater understanding of smart diaper system.

1.7 Organization of Thesis

This project is organized into five chapters;

I. Chapter one gives a brief introduction to the project highlighting the problem statement, main objectives, aim, significance, motivation and scope of the project.

II. Chapter two presents an overview of the technological analysis and the concept of related work based on smart diaper system. Further discussion on the principle of Bluetooth technology and printed circuit board is explained, and an overview of the components on the wetness detector is given into consideration for the project design.

III. Chapter three presents the methodology of the project. It illustrates the methodological approaches employed to demonstrate steps and stages followed in designing a battery-free wet diaper detector system. The operational flow chart is also part of this division with the software used for the design and simulations.

IV. Chapter four presents the results discussion and analysis. It gives an insight on the tests and results carried out on the project.

V. Chapter five the conclusion and recommendation. This chapter presents the summary and findings of the project, the limitations and other possibilities in the area of research related to this study.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides the summary of literature reviews on topics related to wet diaper detector system that has capability of sending notification to caregiver when urine is sensed on the diaper. The literature review further gives an overview about PCB, its theoretical background, principle and impact as detector unit for voltage generated when flexible sensor detect wetness. This literature review also gives an overview of Bluetooth technology and smart android phone application.

As an undergarment designed to collect feces and urine from its wearer, the diaper has been widely used by growing babies. In addition, diapers are also increasingly used by the elderly with urinary incontinence, as well as other patients who are unable to care for themselves. The absorption of waste by the diaper potentially prevents soiling of clothes, bedsores, etc. [9]. However, one of the main problems with wearing a diaper is that it must be replaced as soon as the diaper becomes saturated with debris before it can cause skin problems for diaper users such as rashes, allergic reactions, toxicity, and urinary tract infections for carriers [10]. This action is normally carried out by parents of babies or caregivers of vulnerable older people. As diaper users may not be monitored all the time, an external means of spontaneously monitoring the diaper bedwetting situation and signaling people to take action under certain conditions is increasingly urgent, not just from a point humanistic but also practical view.

Wet diaper detector sensors have proven to be an effective solution for detecting wet in diapers or underwear. In general, for most diaper wetting control system inserts a battery powered sensor system is used for detection in conjunction with active radio transmission to a remote unit. [11] [12] However, the relatively high costs of batteries and potential chemical risk may be of concern for commercialization. Additionally, exposure to unnecessary radiation bursts when the diaper is not wet could be hazardous to the health of vulnerable diaper users. Therefore, there is a great need to implement a battery-free solution, as well as new methods for more accurate, convenient, cost-effective and quality information signage for the diaper user.

During the last decades, researchers and companies have focused on developing smart diapers to improve the lives of babies and adults such as the elderly, people with reduced mobility, people with urinary incontinence, etc. sensor on the front of the diaper, which incorporates a power source such as a battery. This sensor can detect urine and identify moisture. The operating mechanism of this sensor is simple: it must be connected to a Bluetooth an application that allows a second person (parents, nurses, caregiver, etc.) to monitor the diaper indicating when the person should be changed.

2.2 Existing Technologies on Smartphone Based Wetness Detector

At the heart of the Internet of Things is the challenge of bringing information from sensors to the Internet. The requirements for the underlying communication technologies vary widely based on common criteria of power consumption, latency, throughput, distance traveled, and resilience.

However, one thing is clear: wireless technologies are leading the change in both the modernization market and the embedded system market. The most common smart phone base detector technology is:

i. Bluetooth Technology
ii. Radio Frequency Identification (RFID) Technology

2.2.1 Bluetooth Technology

The Bluetooth Low Energy (BLE) is use to communicate between two Bluetooth compatible device. Smartphones on the market today support a wide range of cellular networks (e.g. GSM, CDMA, LTE), Wi-Fi and Bluetooth. The need for energy efficient wireless technology area network on the smartphone platform has expanded the additional Bluetooth categories, with BLE targeting low data rate applications and low energy consumption. Basically, BLE has two modes of operation: peer-to-peer communication requiring contact authentication between an exchangeable transmission pair and communication receiving and transmitting devices in which a transmitting device can transmit data to an arbitrary number of non-connectable devices in the area station. BLE transmission mode is implemented in an advertising channels, the smartphone will always listen to the station as long as Bluetooth is enabled on the device. This makes the smartphone a perfect receiver for the wetness signal. The request for authentication between devices and the smartphone is always ready to receive the wetness signal. The BLE frequency channels is shown in Figure 2.1.

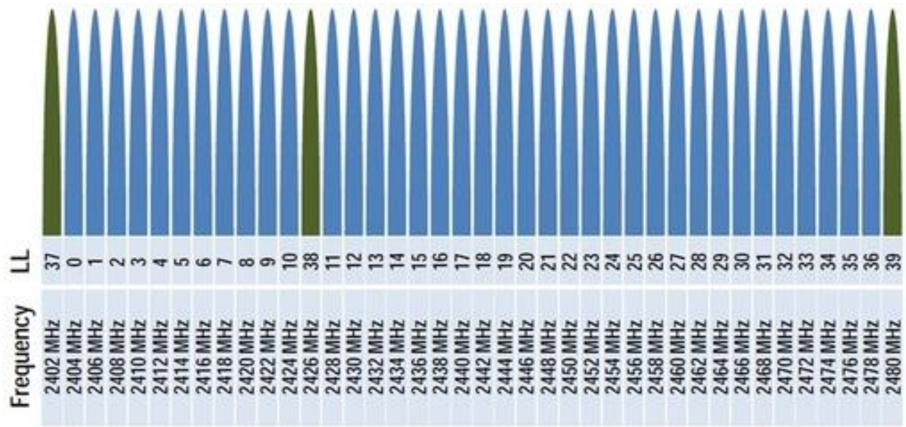

Figure 2.1: Clarified view of frequency assignment of Bluetooth channels [13]

Figure 2.1 depicts the list of BLE channel assignment pf the 2.4 GHz ISM band for some of the commonly used BLE channels. The BLE channels are spaced by 1 MHz which means each bit takes 1us to transmit. [13]. In BLE device, the broadcast mode signal is also emitted from the Bluetooth advertisement channels in the form of digital packet data. A BLE advertisement packet data structure is shown in Figure 2.2.

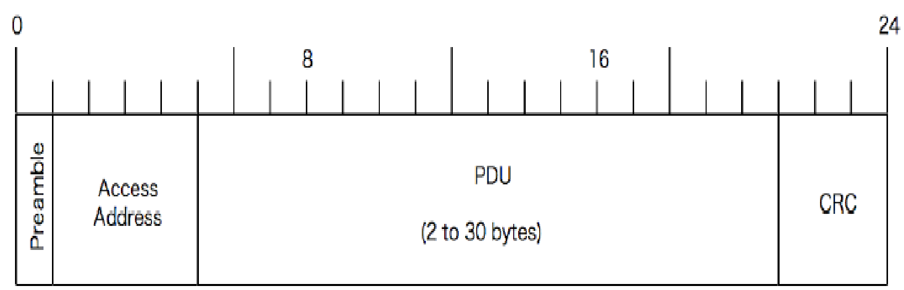

Figure 2.2 BLE packet structure format. [14]

Each frame can be between 80 bits and 376 bits long, where the actual payload data unit (PDU) is a variable depending on the need for the size of the data and how the mandatory additional ports structure contribute to the packet are defined. Main functions of BLE include:

- Preamble: To identify the start of a data structure
- Access Address: For detecting the purpose of the data structure, which is always a constant value for detecting the advertisement structure such as (0z8E89BED6)
- Payload Data Unit: The two reserved byte in the PDU is for explaining the purpose and functionality of the payload unit.
- Cyclic Redundancy Check (CRC): For checking possible data corruption during advertising or transmission.

All this functions makes it possible for proper communication with smart-phone in built BLE functions. Basically, Bluetooth utilizes a Gaussian-filtered Binary Frequency Shift Key (BFSK) modulation with a channel bandwidth of 2-MHz per channel. It is embedded into billions of products on the market today and links the Internet of Things. In 1994 a group of engineers at Ericsson, a Swedish company, invented a wireless communication technology, later called Bluetooth. The 10-meter figure for class 2 devices (of which the major mobile phones are examples) is very much a guideline. Bluetooth can wirelessly connect devices together. It can connect headsets to phones, car or computer, etc. It can connect phones or computers to speakers. Much more, it can connect lights, door locks, TV, shoes, basketballs, water bottles, toys—almost anything to an app on a phone (bluetooth.com).

Advantages of Bluetooth

i. Bluetooth is everywhere: Bluetooth is built into nearly every phone, laptop, desktop and tablet. This makes it so convenient to connect a keyboard, mouse, speakers or fitness band to a phone or computer.

ii. Bluetooth is low power: with the advent of Bluetooth Smart (BLE or Bluetooth low energy), developers were able to create smaller sensors that run off tiny coin-cell batteries for months, and in some cases, years.

iii. Bluetooth is easy to use: A consumer can turn on the Bluetooth, hit the pairing button and wait for seconds to communicate. Its relatively easier than its similar technologies.

iv. Bluetooth is low cost: A simple Bluetooth module can be purchased for a minimal cost say, (($4 to $6).

Disadvantages of Bluetooth

i. Poor security: Although Bluetooth implements several security mechanisms. Because it uses radio frequencies, the security level of Bluetooth is considerably lower. Hackers can easily acquire your personal information through Bluetooth. Only if you are within the assigned range. Therefore, it should not be used to transfer critical information.

ii. Range: The maximum range offered by a Bluetooth connection is 100 m. Generally, Bluetooth has a small communication range. Depending on the version and type of device, the range of a Bluetooth connection varies. Devices to be connected must be within this range

iii. Speed: All wireless technologies have relatively slow data transmission. This is especially true in the case of Bluetooth. Typically, Bluetooth 3.0 and Bluetooth 4.0 have a transmission speed of 25 Mbps. Since Bluetooth is energy efficient, the data transfer mechanism here is slower.

iv. Compatibility: Although most Bluetooth implementations are based on the standard, there are still Bluetooth compatibility issues. There are many reasons such as profiles, drivers and versions that explain this. This is particularly related to Bluetooth 4.0 with low power consumption technology. A Bluetooth 4.0 connection with low power technology will not be compatible with other versions of Bluetooth.

A typical Bluetooth interconnection used in different application is as shown in Figure 2.3.

Figure 2.3: Typical Bluetooth interconnection (Source Wikipedia)

Pampers developed the first smart diaper for babies [11]. They created a wearable device called Lumi that can detect moisture in diapers. This wearable device has a reusable wet detector sensor that must be attached to the front of the diaper. This sensor can alert a caregiver by notification, via a phone app, whenever it detects moisture. This sensor incorporates a battery designed to last approximately 3 months. Although the replacement is free with the Lumi diaper subscription, the price of this system is very high: $ 349 USD including the sensor, the application and the Video Baby Monitor. Similar products have also been observed in Huggies [15]. The system is battery powered and the other drawback is the effective cost of the system.

A low cost wet diaper detector system based on smart phone and BLE was developed by researchers in 2017 [16], due to the high cost of existing system and sensors available for detecting wet diaper. The system was design in such that, the flexible conductors were put into the urine absorption area of the diaper in order to decrease the resistance between two terminals connected with conductor when the diaper is wet and when the resistance at the terminal falls below the limited resistance value, Thus the Bluetooth low energy transmitter sends a warning alarm to the smart phone via wetness detection [16]. With smartphones being so prevalent, the only item required for the system is the sensor which includes very cheap components. Therefore, anyone who owns a smartphone can easily take advantage of this system at low cost A Bluetooth alert on phone for diaper wetness battery powered is as shown in Figure 2.4.

Figure: 2.4 Bluetooth receiving alert from a wet diaper [17]

Furthermore, a design was also implemented using Bluetooth based microcontroller and GSM for wetness and bleeding detection in diaper [18]. This device was made up of a wetness sensor, microcontroller, Bluetooth transceiver, microcontroller and GSM modem working in harmony to carry out wetness detection function. This system was designed to use two or four fine conductors between sheets of diaper layers made up of the wetness sensor. They also took into consideration the conductance as when the wires connected to a pair of pressing studs extending from one end of the diaper are wet, the conductance between the studs drops going beyond the pre-defined limit, thereby triggering an alarm. This alarm is triggered from the Bluetooth transceiver through the microcontroller to the GSM modem. The safety studs have a unit with electronics to sense conductivity and generate alarm. Since the contacts are very close, chemicals could build up between them and change the isolation resistance between, leading to faulty detection.

A Bluetooth enable wetness detector was also implemented in real time wireless monitoring system for people who cannot control their urinary organs [19]. The system was designed in such a way that it gets real time information of moisture content by utilizing a non-contact humidity sensor so that when urinary organs are uncontrollable, a sensor sends an alert to mobile device through Bluetooth and send information about the presence of UTI's and is composed of a sensor which is battery powered.

2.2.2 Radio Frequency Identification (RFID) Technology

The Radio Frequency Identification Tag system communicate between an antenna or a reader and a tag attached to an object. Thus, typical RFID tag has two elements: an antenna for backscattering radio frequency signals, and an RFID chip that stores tag information, such as the specific product to which the tag is applied. RFID tags do not require batteries; They receive energy in the form of radio waves emitted by an RFID reader. When an RFID tag collects this energy, its antenna activates the RFID chip, which modifies the radio waves and sends a signal to the reader, with its information encoded within the waves. In this way, for example, products tagged with RFID tags can be identified and tracked.

A RFID tags based on hydrogel to develop a low cost system for detecting wetness in diaper is utilized. They implemented a new disposable sensor realized for detecting moisture based on the materials properties of the water absorbing polymer gel always available in most diapers. The sensor designed in this research work was able to accomplish a 1m read range, a bend radius less than 20mm, insensitivity to the orientation of sensor relative to the reader and finally lower cost compared to sensors with metallic antenna [20]. An RFID tag label on diaper for wetness detection is as shown in Figure 2.5.

Figure 2.5 An RFID tag label on diaper for wetness detection [21]

Furthermore, a group of researchers developed a smart radio frequency identification tag for diaper moisture detection. The passive smart radio frequency used in this design responds to dampness in diapers once a set limit value is reached. The system was design in such a way that the High frequency tag at 13.56MHz utilized communicates with a reader coil build into bedding. The read ranges gotten in this design makes discretion possible in sensing dampness and being contactless which can be utilized without disturbing a wearer while sleeping. They went further to incorporate an external antennas attached to bed post with 1W power readers. This power reader is connected to a network for increment in the sensing range to about 1m and notification to care giver [22]. The development of a paper-based disposable moisture RFID system incorporated into the traditional cellulose based diaper was implemented by [23]. The radio frequency identification tag used in this work is a semi passive one compared to the identification tag used in [22] which was a passive one. The advantage of this tag over [22] is that the semi passive tag has no in built battery rather it incorporates an in build energy conversion sensor which works like an action activated tag and the tag with sensor unit is improved for low cost production, using screen printing with electrically conductive ink on paper based substrates and possesses very low electromagnetic radiation.

Recently a utilized internet of things technology in the development of a smart diaper moisture detection system with incorporation of a RFID device into the old cellulose based diaper was implemented by [21]. For low cost production [23] further implemented an improved BLE connection with sensor unit. This device is made up of Bluetooth connection device in diaper and it works in such a way that when a baby puts the diaper on, it starts by detecting if there is moisture or not. In a situation when there is moisture, it sends a signal to the authorized person which most likely could be the care giver. Different methods were reviewed [24] the differences of existing smart diapers for special needs of adults as most adults don’t know when they get soiled. These researchers took into consideration five different smart diapers already designed and implemented for evaluation and comparison of their capacity in servicing the needs of users since the main motive for implementing a smart diaper is to help patients serve special needs and aid caregivers in providing quality care. The work was aimed at comparing and contrasting the selected five smart diapers with the intention of giving caregivers the ability to get instant notification once the diaper of the bedridden patient is soiled.

In the project done by [25] the wetness detector design consists of three main parts, the fine wires conductors, wetness detector analogue switch and a RF transmitter. The system is an active system which is battery operative which makes it cost effective along with other components used. This project designed, automatically sends a notification to the smart phone of the caregiver or an authorized person immediately water or urine is detected in the diaper. In 2011, Swedish researchers [26] reported in their research experiments measuring the volume of urine in diapers. Their main goal was to develop a passive sensor (which works without a battery) that provides reliable measurements and adds very little cost to the layer. Therefore, they decide to perform urine detection using radio frequency identification (RFID) antennas. They evaluated the performance of ultra-high frequency (UHF) RFID inlays. The system works as follows: a correct reading of the serial number of the UHF RFID inlay indicates a dry coat condition; while not reading the serial number indicates a saturated layer condition. This concept can be a good alternate for integration to wireless battery power sensors [26].

2.2.3 Summary

In summary the Bluetooth technology have more advantage due to pricing and other factors as discussed. It does not require a lot of hardware components which makes it easy to manage and get an easy check over the system. Though the RFID can transmit uninterrupted radio signal, the disadvantages are the system cost and use of several hardware components like tags, readers, antenna, and application software before it can be implemented [27]

2.3 Sensor

A sensor according to the American national standard institutes (ANSI) is a device which provides a usable output in response to an input. The sensor takes a physical quantity and converts it into a suitable signal for processing. Recently, common sensors have been found to convert measurement of physical phenomena into electrical signal with an active element called transducer which does the conversion of one form of energy to another [28]. The advent of sensors in today's application world has changed the quality of human life since sensing system makes it possible to study and monitor an event within few minutes or seconds [29]. The dynamic utilization of sensors has led to ever growing improvement of the existing sensors with wide range of application such as gas sensing [30] [31], monitoring of an environment etc.

2.3.1 Flexible Wearable Sensors

Flexible sensors are flexible, which are adaptive to bending and are capable of efficiently detecting several stimuli important to specific environment or biological species. They have great potential for internet of things and wearable electronics applications [32]. The advantages of flexible sensor over non flexible sensor or conventional sensors is the ability to efficiently capture target analytes and generate high signal quality [33]. The fabrication of this sensor requires a new approach in the design materials. Hence, it has been employed to various kinds of sensing in our day to day life. The utilization of wireless wearable sensors for monitoring physiological parameter is as shown in Figure 2.6.

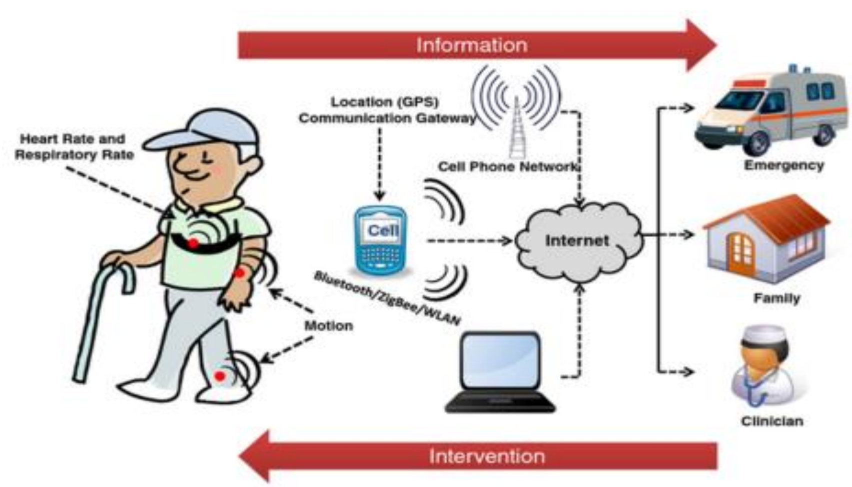

Figure 2.6 Representation of utilization of wireless wearable sensors for monitoring physiological parameter [34].

An overview of the soft and elastic materials used in the manufacture of different types of sensors are shown (Figure 2.7). Particular emphasis is placed on its most relevant aspects, properties for the development of flexible sensors, such as flexural stability, extensibility and manufacturing options.

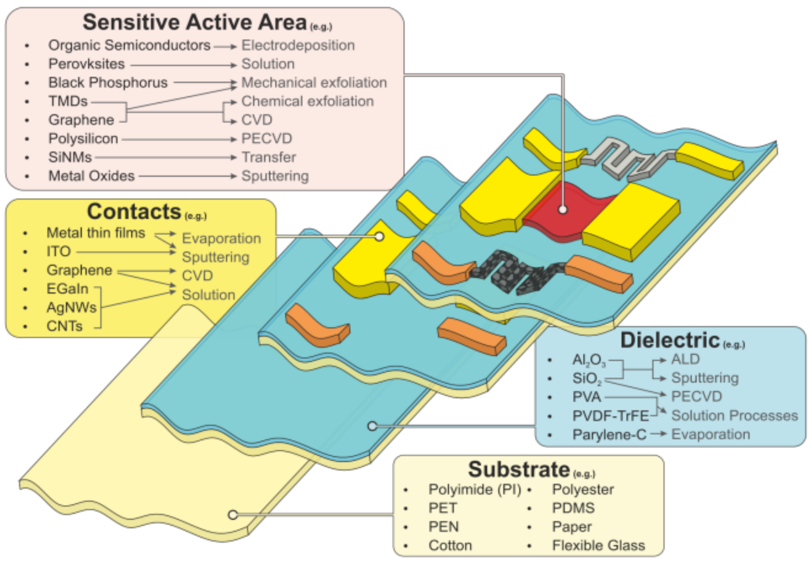

Figure 2.7: Shows common materials and respective manufacturing methods used for the fabrication of flexible sensors [35]

2.4 Energy Harvester

Energy harvesting is the process of harnessing energy from external sources (solar, wind, water, etc.), captured and stored for autonomous devices especially in wearable electronics and wireless sensor [36]. At the University of Waterloo my colleagues have been developing nanomaterials sensors/energy harvesters [37]. Energy harvesters have proven to be viable sources of power for low energy electronic devices and are particularly suitable for wetness detector application since the detector unit requires low power for its operation [36]. Considering cost and availability, energy harvester using water or urine as the external source of energy is preferable to other sources for wet detector application. In this project, energy harvester using water from urine as source of energy will be used to provide power to the wet diaper detector since the proposed wet diaper detector would require lower power to operate.

2.5 Printed Circuit Board (PCBs)

The printed circuit board is a relevant part of electronic product design. The optimization of electronic function is based on the optimization of internal electronic circuit PCB, which makes great optimization from the selection of materials, design on the board, and other requirements for the performance. With the advancement in the standard of living, waste discharge treatment in the manufacturing process of PCB board is also a problem that manufactures are concerned with. Hence, it is necessary to not also put into consideration the product function when designing a PCB but the electrical performance, production technology requirements, and economy requirement should be considered for the purpose of reducing the trial production circle of new PCB [38]. Over the years, PCB has always adopted hole metallization and electroplating in solving interlayer connection or conduction problem. PCBs are found in virtually all electrical and electronic equipment (EEE) and form the foundation of the electronics industry. As indicated in printed circuit boards can be classified in different ways according to their various attributes; for example, single-sided boards; double-sided boards; multilayer panels; and rigid and flexible boards. The IPC-2222 standard (IPC, 1998) provides design information for different types of boards [39]. An example of mounting components on both side of a board, with SMT (Surface Mounting Technology) components and TH (Through-devices) is as shown in Figure 2.8

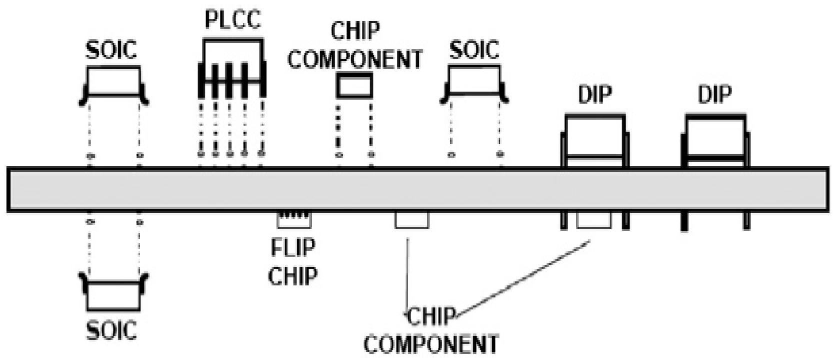

Figure 2.8: Component mounted on both sides of the board (ANSI,1998) [39].

2.6 Soldering

Soldering is an important aspect in electronics that is used to form electrical and mechanical connections between electronic devices. Through Hole Technology (THT), Surface Mount Technology (SMT), and Area Array Packages are three common methods used to assemble electronic devices on a substrate, such as a printed circuit board (PCB). THT is the process by which component wires are inserted into holes drilled in a PCB and then the wires are soldered to the bottom of the PCB. Alternatively, surface mount technology (SMT) is a method in which electronic devices, called surface mount devices (SMDs), are mounted directly to the printed circuit board (PCB) by soldering. Flip Chip technology, a sub component of matrix packages, is similar to SMT, but the method is used to mount a semiconductor device, such as an integrated circuit (IC) made up of an assembly of electrical components, on a substrate using a series of solder bumps. Due to the design of the flip chip configuration, the inverted chip allows for smaller spacing between the conductors resulting in overall smaller packages. In addition, the flip chip allows higher speeds and better performance than THT and SMD [40] [41].

The various ways of the soldering of the components of PCB according to [42] are:

- Press-fit, another mechanical method with less solder;
- Interconnection pressure, a soldering method with lesser solder, that relies on mechanical strength to force the interconnectedness of the component together to make good contact;
- Solder by reflux through surface mount technology (SMT);
- Wave-type solder (to weld components to the magnitude, usually PTH (Pin-Through Hole) components;
- Flip chip configuration similar to SMT.

Solder alloys are by far the most common interconnect materials and welds that are used in the mounting holes and are, in mass and volume, used more than solder paste in solder reflow [43]. Two most common ways of soldering components is as shown in Figure 2.9; and a complete soldered board as shown in Figure 2.10.

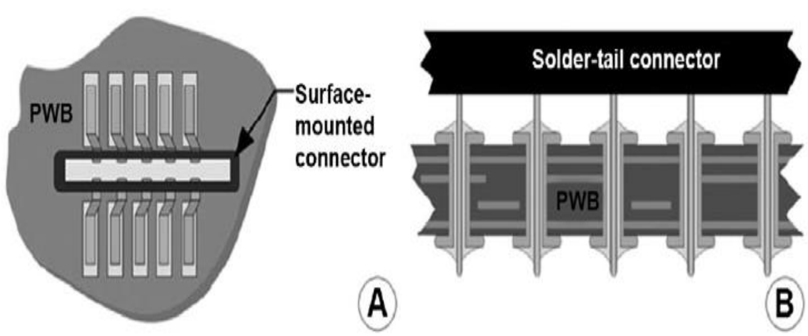

Figure 2.9 Two common methods of soldering on PCBs: (A) SMT, and (B) PTH [42]

Figure 2.10: Full soldered PCB of an electronic device (Source: Wikipedia)

2.7 Components of a Wetness Detector Unit

2.7.1 Capacitor

Capacitors are used to remove ripple from the input and output of voltage regulators. This is essential to obtain a constant output voltage. There are a variety of capacitors. available types, which have their own advantages and disadvantages for this application. The essence of this capacitor (C1) is to store energy generated by the wet sensor. Capacitors are passive devices used in electronic circuits to store energy on the form of an electric field. The three main types of capacitors, aluminum electrolytic capacitors, tantalum capacitors and ceramic capacitors differ as described below [44]

- **Aluminum electrolytic capacitors:** these are polarized and can have high values of

capacity, typically 1 to 47,000 μF. These capacitors can have a high performance voltage up to 350V and capable of handling high ripple current. The main drawback is the poor high frequency performance. This type of capacitor also has a large loss and a low tolerance.

- **Tantalum capacitors:** these capacitors are also polarized. They have a great capacity

Value in a small volume with low losses. Tantalum capacitors have a lower value Equivalent Series Resistance (ESR) compared to aluminum electrolytic capacitors. The disadvantages are that this capacitor has low ripple current capacity and is very intolerant of reverse voltages or surges.

- **Ceramic Capacitors:** this is a type of non-polarized capacitor with an even lower ESR. Values range from a few pF to about 0.1 ° F. It has a good top performance. frequencies and is widely used in both lead and SMD (surface mounted device) form.

Ceramic capacitors with low ESR generally improve the transient response of the regulator. However, some regulators require tantalum capacitors with a higher ESR to stabilize the Feedback loop [45].

2.7.2 Resistors

Resistor, an electrical component that opposes the flow of direct or alternating current, used to protect, operate, or control the circuit. The voltages can be divided using resistors, and in combination with other components, the resistors can be used to create electrical waves in ways that best suit the electrical designer's requirements. The resistors can have a fixed resistance value, or they can be made variable or adjustable within a certain range, in which case they can be called rheostats or potentiometers. [46]. The most common reason why resistor is needed in any circuit design is to adjust the current flowing through a particular part of the circuit. Resistor can be constructed in a number of ways to optimize power handling, stability or size as shown in Figure 2.11.

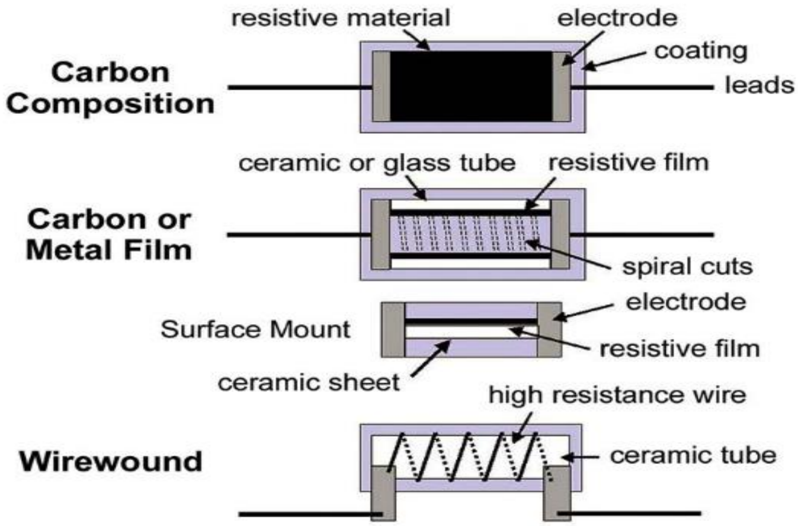

Figure 2.11: Construction of resistors in different ways [47]

- **Carbon Composition:** By composition it means, the resistive material is a mixture of carbon and stabilizing compounds [46]. The amount of carbon in the mixture determines the resistance of the material. Carbon composition resistors are available with power rating of 1/4 to 2 Watt, which makes them good choice for circuit and protection against pulses and transient.
- **Film Resistor:** The resistive material for film resistor is very thin coating of carbon or metal on an insulting substrate, such as ceramic or glass. The film resistor is available with very accurate and stable values, but unable to handle large amount of power due to the thin film [47].
- **Surface Mount Resistor:** Surface mount resistors are almost same as the film resistor. They have no leads at all, which makes the series inductance very low and very low power rating from 1/10 to 1/4 Watt.

- **Wire-wound:** Wire wound resistor is made to dissipate a lot of power in sizes from one watts to hundreds of watts. They are usually intended to be air cooled. Due to the resistive materials in the resistor is wound on a form, they have very high inductance. [46].

2.7.3 Antennas

An antenna is essentially an exposed conductor [48]. The antenna is a metal rod or antenna that picks up radio waves and converts them into electrical signals that enter devices such as the radio, television, or telephone system. If the length of a conductor has a certain ratio or a multiple of the signal wavelength, it becomes an antenna. However, this condition is called "resonance" because the electrical energy supplied to the antenna is radiated into free space. A dipole antenna basic is as shown in Figure 2.12.

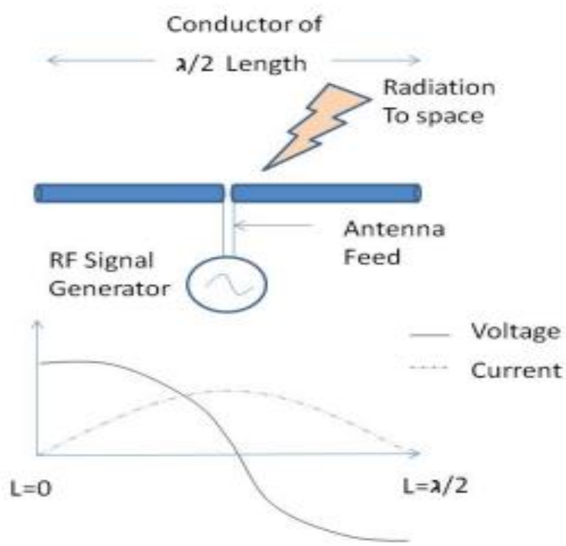

Figure 2.12: Basic Dipole Antenna structure [48]

In Figure 2.12, the conductor has a length λ/2, where λ is the wavelength of the electric signal. The signal generated feeds the antenna at its center point by a transmission line known as "antenna feed" [49]. At this length, the voltage and current standing waves are formed across the length of the conductor as shown in Figure 2.12. The electrical energy input to the antenna is radiated in the form of electromagnetic radiation of that frequency to free space. The antenna is fed by an antenna feed that has an impedance of, say, 50 Ω, and transmits to the free space, which has an impendence of 377 Ω^2. However, most PCBs in PCBs achieve the same performance by having a λ/4-length conductor in a particular way called monopole antenna. Most antennas on PCB are implemented as quarter-wave antennas on a copper ground plane. A quarter-wave antenna is as shown in Figure 2.13 and when using it for PCB it is important to put into consideration the antenna length, feed, the shape and size of the ground plane, and return path.

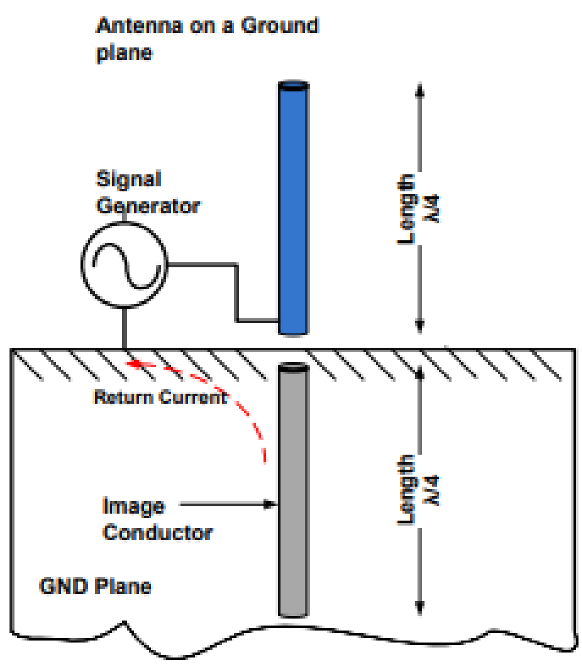

Figure 2.13: Quarter-wave antenna [50]

As already described, any conductor of length λ/4 exposed in free space, over a ground plane with a proper feed can be an effective antenna. Depending on the wavelength, the antenna can be as long as the FM antenna of a car or a tiny trace on a beacon [48]. For 2.4-GHz applications, most PCB antennas fall into the following types:

- **Wire Antenna**: It is a piece of wire that extends over the PCB in a free space with its length adapted to $\lambda / 4$ on a ground plane. It is usually powered by a 50 Ω transmission line. It offers the best performance base in the RF range due to its size and three-dimensional exposure. The wire can be in the form of a straight line, a helix or a loop 4 to 5 mm above the plane of the circuit board, protruding into space.
- **PCB Antenna:** It is a trace drawn on the PCB. The trace can be a straight trace, an inverted F-type trace, a sinuous trace, a circular trace or a wavy curve depending on the type of antenna and the space constraints. It is a two-dimensional structure which requires more PCB area, has lower efficiency than a wire antenna, but is cheaper. It is easy to manufacture and has acceptable wireless range for a BLE application.
- **Chip Antenna:** It is an antenna on a small form factor IC that has a conductor packed inside. It is useful when the space is limited to print a PCB antenna and it is very sensitive to the size of the RF ground and it is very cheap at 10 to 50 cents.

2.8 Wireless Communication System

Wireless communication is the process of passing information or data, between two or more points without an electrical conductor. Wireless communication has been very useful in improving technological advancements, reducing the hitherto limitations of cables [51] Some important components of wireless communication include:

- **Source:** This is where the communication process is originated from. It could be a data or human voice. It is a meaningful data that the receiver consumes.
- **Input Transducer:** It is a device which converts one form of energy or signal into another form of energy or signal. It is always present at the input and outside of the communication system.
- **Transmitter:** it is a device that takes the information from the sender and converts it into a signal. The source is usually converted by an input transducer into an electrical waveform known as the message signal then the transmitter modifies the message signal for efficient transmission. The transmitter is generally made up of one or more of the following subsystems: a pre-emphasizer, sampler, quantizer, modulator and coder.
- **Transmission medium:** This is a physical medium that carries the signal.
- **Communication channel:** This is saddle with the responsibility of transferring a signal from source to destination without loss or distortion. Based on the channel type, modern communication systems are classified into two categories namely: wired communication system and wireless communication systems. It’s used to send the signal from the source (transmitter) to the destination (receiver).
- **Receiver:** Something that receives the signal from the transmission medium and converts it back to useable information. The receiver reprocesses the signal received from the channel by undoing the signal improvement made at the transmitter and the channel. The receiver may consist of demodulator, decoder,

filter, and de-emphasizer. Communication components for wireless communication is as shown in Figure 2.14.

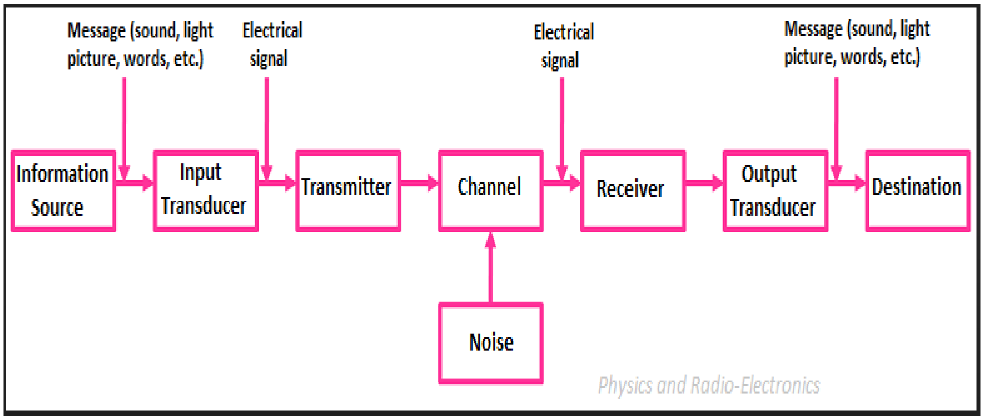

Figure 2:14 Block diagram of wireless communication system (Source: physics and Radio Electronics)

2.9 Software Implementation of Smart-Phone Base Wetness Detector.

Android software is very similar in function to conventional pc software. Software's are generally programs that allows the user to interact with the computer's hardware, in order to solve problems. Android software application finds application in the business world, the entertainment industry, and telecommunications industry. It's not an overstatement to say that computer software builds the neural system of our contemporary society and it is difficult to imagine its existence without them. Android is currently the world's most popular mobile platform(Motorola.com). Common popular android mobile devices are shown in Figure 2.15.

Figure 2.15: Popular Android Mobile Devices for communication. (Android Tech)

The android app inventor is an open-source web application firstly made available by Google, and now maintained by the Massachusetts Institute of Technology(MIT). It allows easier creation of software applications for the android operating system. MIT App inventor is an application characterized by the creation of new ideas to programming and application development that changes greatly the complex language of text-based coding into, drag and drop building blocks(appinventor.mit.edu). The app inventor has been in existence since 2009, co-created by Google’s Mark Friedman and MIT professor Hal Abelson. In 2015 the MIT inventor community consisted of nearly 3 million users, representing 195 countries. The MIT App Inventor servers store the work and help one keep track of projects as shown in Figure 2.16.

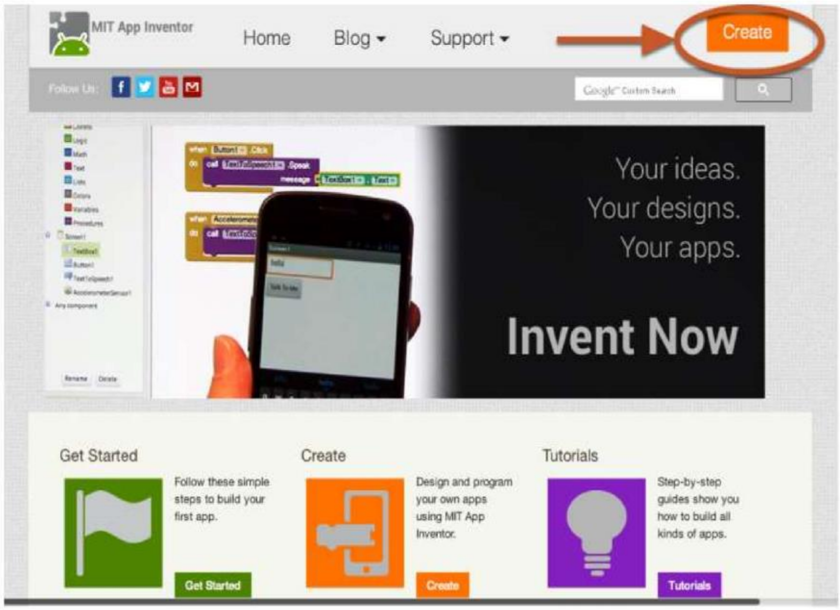

Figure 2.16: MIT App inventor development environment.

2.10 Boost Converter

In many technical applications, it is necessary to convert a set DC voltage source to a variable DC voltage output using DC to DC circuit convert. A boost converter is a DC-DC converter that steps up an input source voltage why stepping down current. In a boost converter, the output voltage is greater than the input voltage. Thus the name boost is derived. A DC converter is equivalent to an AC transformer with a continuously variable rotation ratio. It can be used to reduce or increase a DC voltage source, just like a transformer.

The Efficiency, size and cost are the main advantages of switching power converters over linear converters. The efficiency of switched power converters can range from 70-80%, while linear converters typically have an efficiency of 30%. The DC to DC Boost Converter is designed to provide an efficient method of taking a given DC voltage supply from the source and increasing it to a desired value [52]. The circuit diagram of a boost converter is as shown in Figure 2.17.

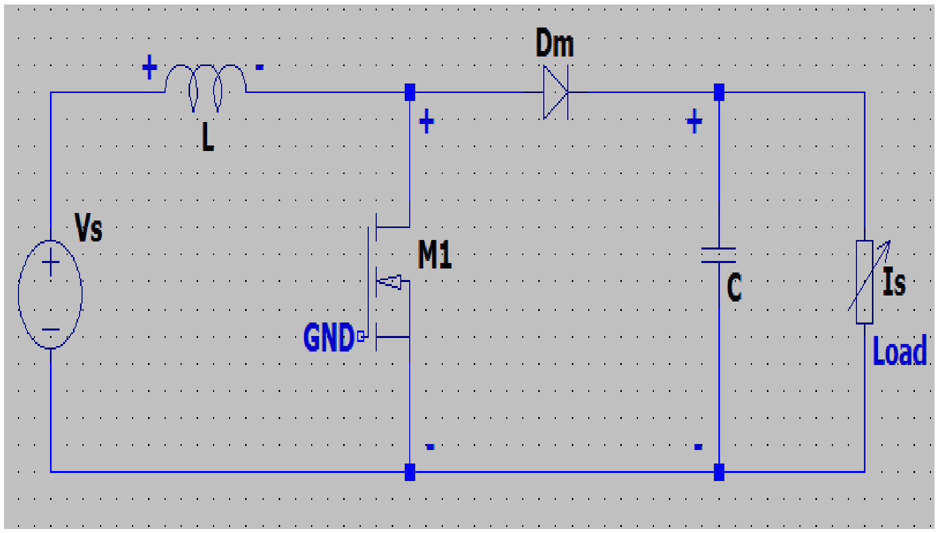

Figure 2.17 Circuit diagram of boost converter

It consists of an inductor which stores voltage in the form of magnetic field, a diode that allow current flow in one direction, a switch for "ON and OFF purpose and a capacitor that store energy in the form of electric field. The voltage-current relation for the inductor "L" is given by:

$$i = \frac{1}{L}\int_0^t V dt + i_0 \tag{2.1}$$

OR

$$V = L\frac{di}{dt} \tag{2.2}$$

Where

- V = desired voltage
- i = desired current

- L = desired inductor
- i_0 = desired output current

During the on state of the MOSFET, the pick current is given by

$$i_{pk}= \frac{(V_{in} - V_{Trans})T_{on}}{L} + i_0 \qquad (2.3)$$

OR

$$\Delta i = \frac{(V_{in} - V_{Trans})T_{on}}{L} \qquad (2.4)$$

Where

- i_{pk} = peak current
- V_{in} = input voltage
- V_{Trans} = voltage drop across transistor (switch) M_1
- T_{on} = on state of transistor
- Δi = ripple current

During the off state of the MOSFET

$$i_0 = i_{pk} - \frac{(V_{out} - V_{in} + V_D)T_{off}}{L} \qquad (2.5)$$

OR

$$\Delta i = \frac{(V_{out} - V_{in} + V_D)T_{off}}{L} \qquad (2.6)$$

Where

- V_D = the voltage drop across diode D_m

Thus by equating equation (5 and 6) ΔV_{out} can be obtained as followed.

$$\frac{(V_{in} - V_{Trans})T_{on}}{L} = \frac{(V_{out} - V_{in} + V_D)T_{off}}{L}$$

$$V_{in} - V_{Trans}\,\mathrm{D} = (V_{out} + V_D)(1 - D) \qquad (2.7)$$

$$V_{out} = \frac{V_{in} - V_{Trans}D}{L} - V_D$$

Neglecting the voltage drops across the diode and MOSFET the equation reduces to

$$V_{out} = \frac{V_{in}}{1-D} \qquad (2.8)$$

Where

D = Duty circle, which is a fraction of one period of a device or signal in which it is active and it is usually expressed in percentage.

The boost converter function can be divided into two modes, Mode 1 and Mode 2. Mode 1 begins when the MOSFET (switch)M_1 turns ON at time t = 0. The input current increases and flows through inductor L and MOSFET M_{1}. The mode one operation is as shown in Figure 2.18.

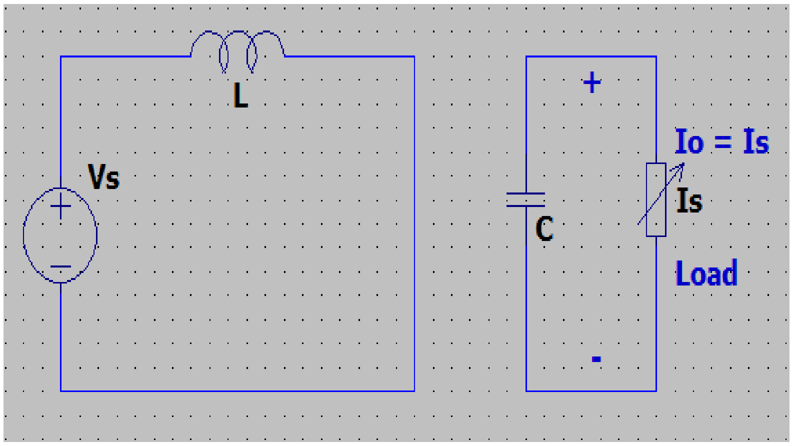

Figure 2.18: Circuit diagram mode 1

The Mode 2 operation begins when the MOSFET M_1 turns off at time $t = t_1$. The input current now flows through L, C, the load, and the diode D_m. The inductor current decreases until the next cycle. The energy stored in the inductor L flows through the load. The circuit diagram of the boost converter for mode 2 operational is shown Figure 2.19.

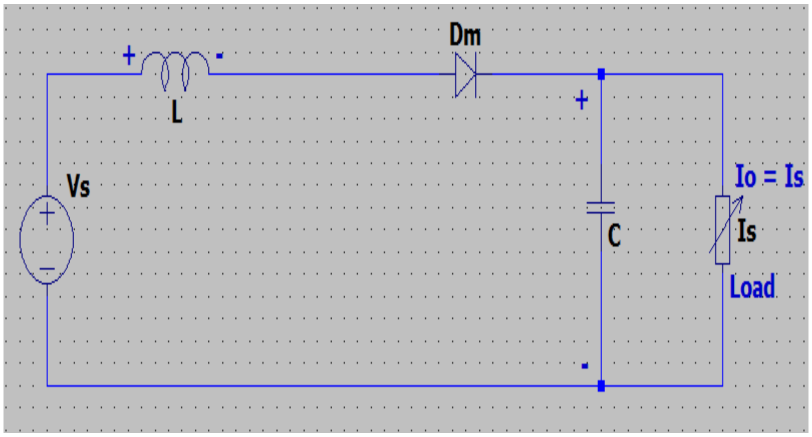

Figure 2.19: Circuit diagram mode 2

The waveform of the boost converter showing the boosted output voltage is shown in Figure 2.20 it is a plot of capacitor output voltage over time. From the output waveform, the output voltage of the capacitor increases with time.

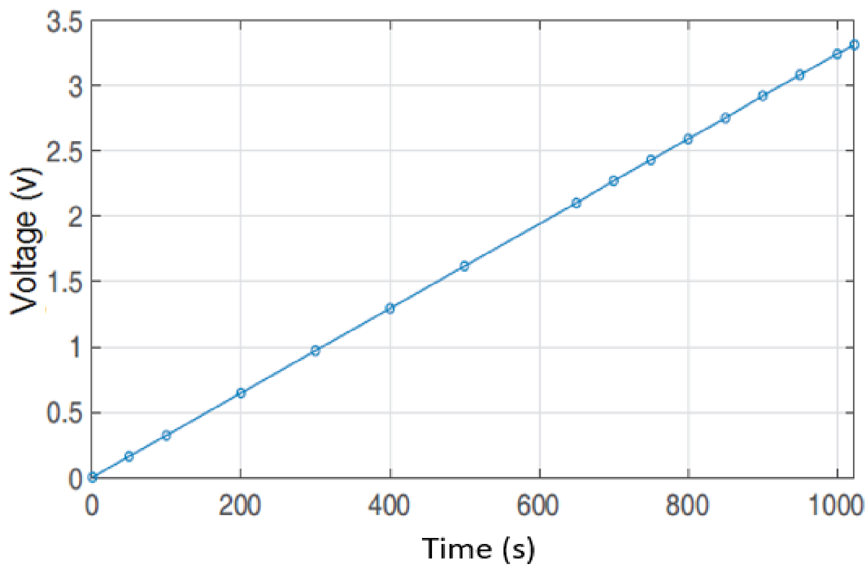

Figure 2.20: Waveform of boost converter output voltage

2.11 Low Cost Wet Diaper Detector System

This research seeks to bridge the gap in previous designs done by other researchers as reviewed. It is aimed at improving wetness detection accuracy by interfacing nanomaterial sensors and employing a low-cost Bluetooth detector as a means of notifying the user. The design is implemented using a battery-free wet detector system to make it very affordable. It consists of a flexible wet sensor and embedded Bluetooth for notification. A smartphone will be used for testing purpose along with water, since 94% of urine contains water. How these separate components are put together to form a low-cost battery-free wet diaper detector system for smart diaper application will be discussed further in the chapter 3.

Chapter 3

DESIGN METHODOLOGY

3.1 Introduction

Optimizing the performance of caregivers by getting notification of wetness through the wetness detector unit via smart phone is essential in the design process for the prototype. The design of the smart-diaper wetness detector consists of four basic stages as shown in Figure 3.1. In this section, the step-by-step procedures followed in designing the various unit will be discussed.

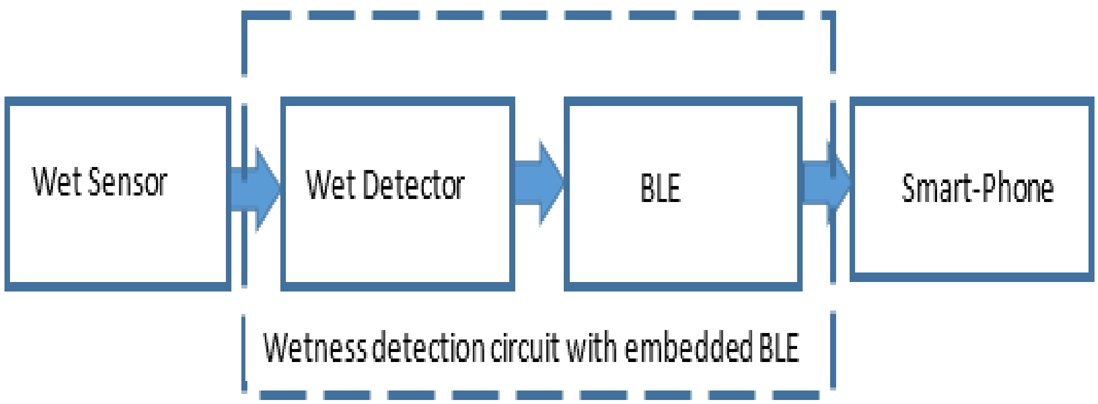

Figure 3.1: Block diagram of Low Cost Bluetooth Enable Smart-Diaper

3.2 Wetness Sensor

Energy harvesting from the sensor has been demonstrated as an effective source of energy for the diaper application system [53]. The effective performance of the system is dependent on the system design and specifications of the parameters. The design of the wetness detector unit is carried out using Altium Designer Software, why Key-Sight Bench-Vue is used to study the behavior of the system and well as oscilloscope.

The main characteristics of the flexible wet sensor include:

- To detect the amount of the liquid or wetness inside the diaper and give an electrical signal to the caregiver via the wetness detector unit.
- Low cost-effective
- To be flexible and stretchable if possible
- To be easily integrated into a standard diaper
- Wireless interface compatible with standards in medical systems.

Of the many physical principles (for example, optical, chemical, and electrical), which are suitable for measuring humidity, resistive and capacitive methods have many advantages, such as simple manufacturing and standard electronics for data acquisition. The resistive and the capacitive structures could be integrated directly onto flexible substrates. The sensor concept is as shown in Figure 3.2.

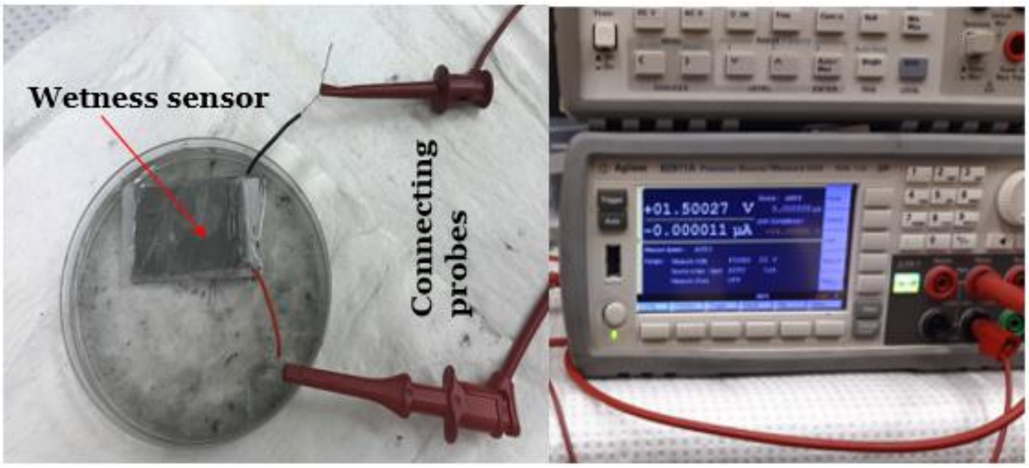

Figure 3.2: Flexible sensor concept for detection of urine in incontinence material.

The resistance and capacitance of the sensor depend on the material and the amount of urine. The flexible sensor is designed using nanomaterial such as carbon material solution deposition. When immense inside water (as urine) as shown in Figure 3.2, a reaction occurs between the water and nanomaterials such as carbon material mixtures as seen in [53] and a signal is generated which is a form of voltage that is sent through the thin wire probes. This voltage signal is sent to the wetness detector unit which in turn analysis the voltage signal, which ranges from 1.1V to 1.6V. The Bluetooth senses the signal which operates within the range of 1.1V to 3.6V and sends a wireless signal to the smart-phone which then notifies the user or caregiver of a wet diaper and needed for change. The output voltage generated by the flexible sensor is shown in Figure 3.3.

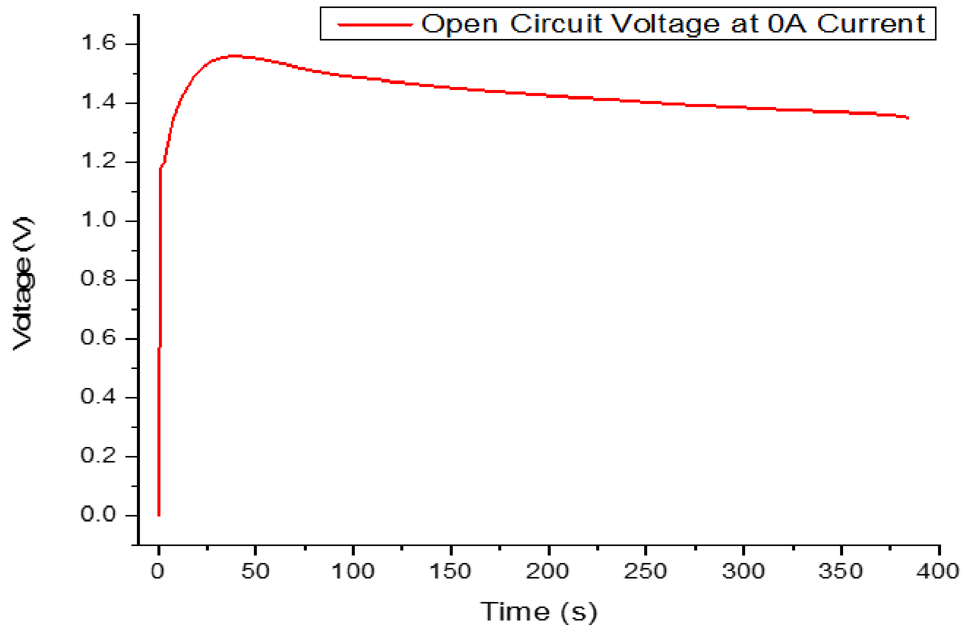

Figure 3.3: Output voltage of flexible wetness sensor.

3.3 Wetness Detector Unit

The wetness detector unit comprises of the wetness detector and the embedded BLE which sends out signal notification whenever wetness is detected.

The circuit diagram of the wetness detector implementation is as shown in Figure 3.4. It consists of two schematics. Schematic one represent the input source voltage from the flexible wetness sensor, why schematic two represent the wetness detector unit with the default off-the- shelf embedded In-play Nano-Beacon BLE Chipset.

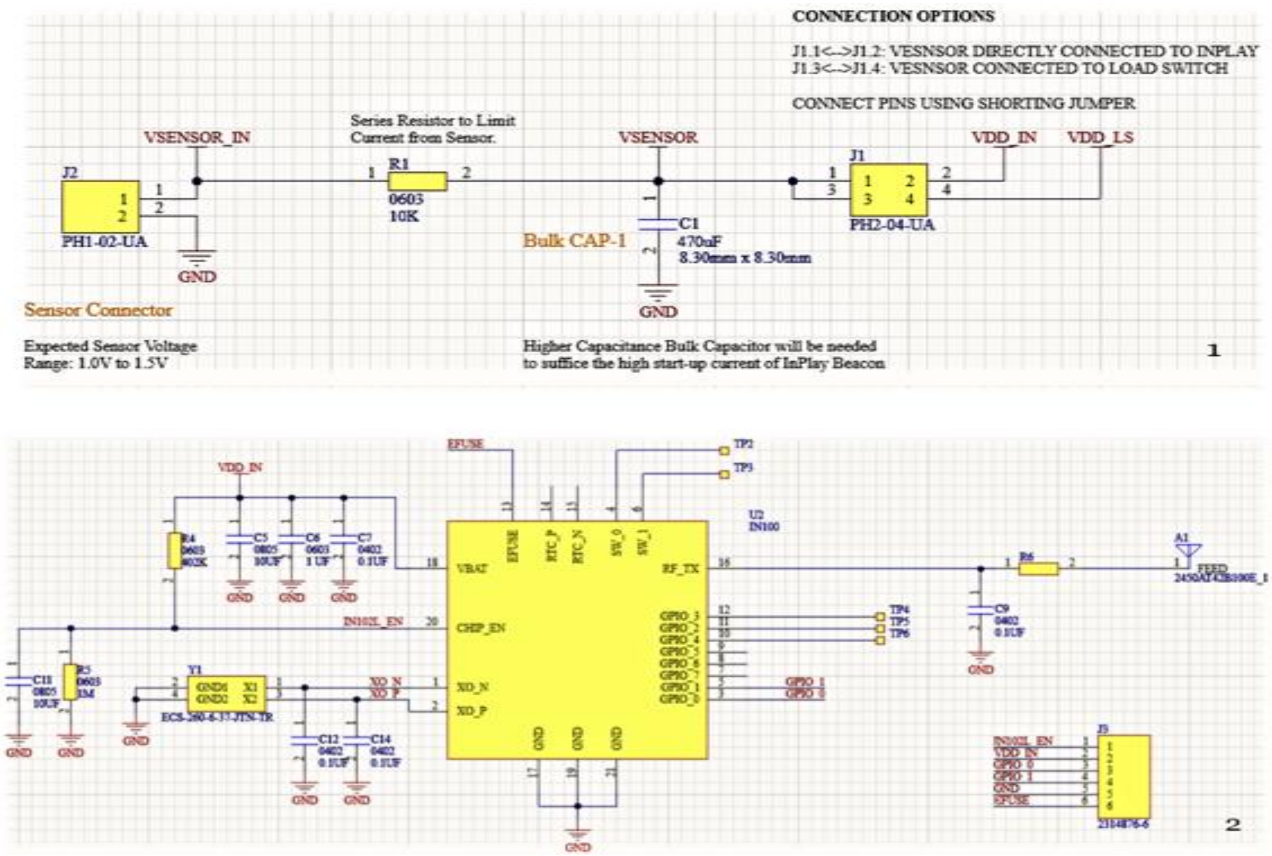

Figure 3.4: Complete Circuit Diagram of Wetness Detector Unit

The setup of the two schematics is used to analyze the behavior of the system before the construction of the wetness detector unit prototype. The wetness flexible sensor will be connected to the J2 pin (V_Sensor_IN).

3.4 Design and Selection of Circuit Component

3.4.1 Current Limiting Resistor (R1)

The essence of the current limiting resistor (R1) is to limit the current of the output signal from the wetness sensor. Basically, the current limiting resistors are chosen based on desired output voltage of the required system. Thus the purpose of the current limiting resistor meant be negligible if found that the input voltage from the wet sensor is just enough to charge the storage capacitor needed for the system functionality. However, a setup was carried out to evaluate the voltage from the wet sensor in connection with series resistor which is as shown in Figure 3.5.

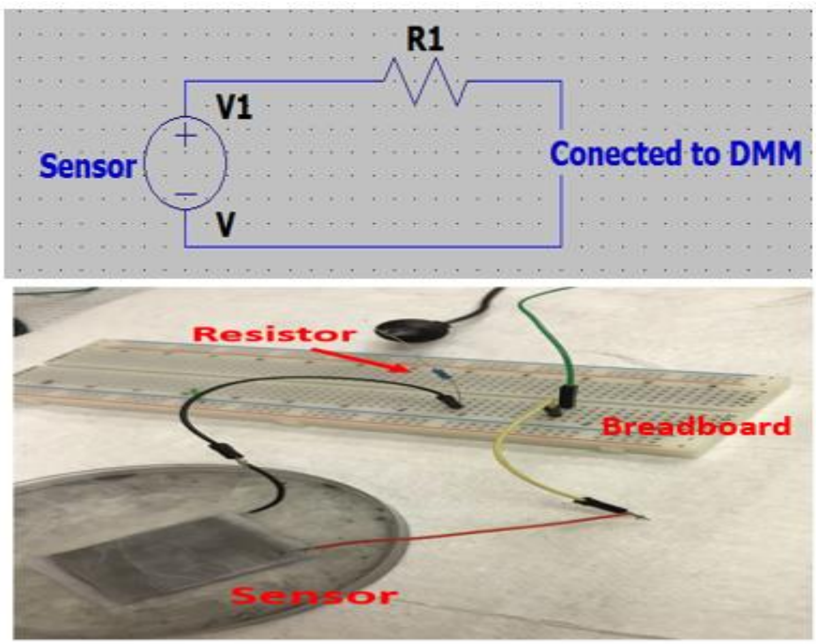

Figure 3.5: A setup to evaluate the behavior of the sensor in series with resistor

3.4.2 The Bulk Capacitor

The bulk capacitor is used to prevent the output of a supply voltage from dropping too far during the periods when current is not available. The essence of using a bulk capacitor for system storage is due to high pulse current from a given load to control an overshoot or undershoot requirement of transient response. Hence the capacitor selected for the system storage was 470uF. The energy harvester source impedance is dominated by capacitive behavior due to the opposition of an electric current to the energy flow when voltage is applied.

In other to solve such issue a higher capacitance values is selected. The analysis of the capacitor storage is presented as follows:

$$Q = CV \tag{3.1}$$

Where

- Q = quantity of charge
- C = Capacitance of capacitor
- V = voltage

Also,

$V = IR = IZ$, where Z is impedance (3.2)

$$Q = CIZ \tag{3.3}$$

Therefore, the higher the capacitance the higher the storage or quantity of charge required. These necessitate the requirement for high storage (470uF).

Also, Q is directly proportional to Z (impedance of the storage). Thus, if the impedance of the storage is high, Q (quantity of charge) must therefore be increased so as to achieve sufficient storage charged, knowing that the impulse current from the BLE is around 2mA and the voltage generated from the flexible wetness sensor is 1.6V.

$$V = IR = IZ$$

$$Z = \frac{V}{R} = \frac{1.6}{2mA} = 800\Omega$$

On comparing the capacitor values, using equation 3.3

$$Q = CIZ$$

$4.7uF\ x\ 2mA\ x\ \ 800\Omega$ = 7.52C

And

$470uF\ x\ 2mA\ x\ 800\Omega$ = 752C

Hence, from the current and voltage values known, the impedance of the storage element is computed as 800Ω using equation (3.2). Since the impedance is high, a higher values of capacitor is required to achieve higher storage.

The essence of capacitor (C1) as seen in Figure (3.4), Schematic 1 is to store energy generated from the wet sensor. Capacitor are passive devices used in electronic circuit to store energy in the form electric field. The type of capacitor selected for this project is the aluminum electrolytic capacitor which has a high capacitance value between the range of 1 to 47,000 μF. They also have high performance voltage up to 350V and capable of handling high ripple current [45]. However, a setup was carried out to evaluate voltage at the capacitor alongside with the flexible sensor so as to justify the prototype of the circuit which is as shown in Figure 3.6.

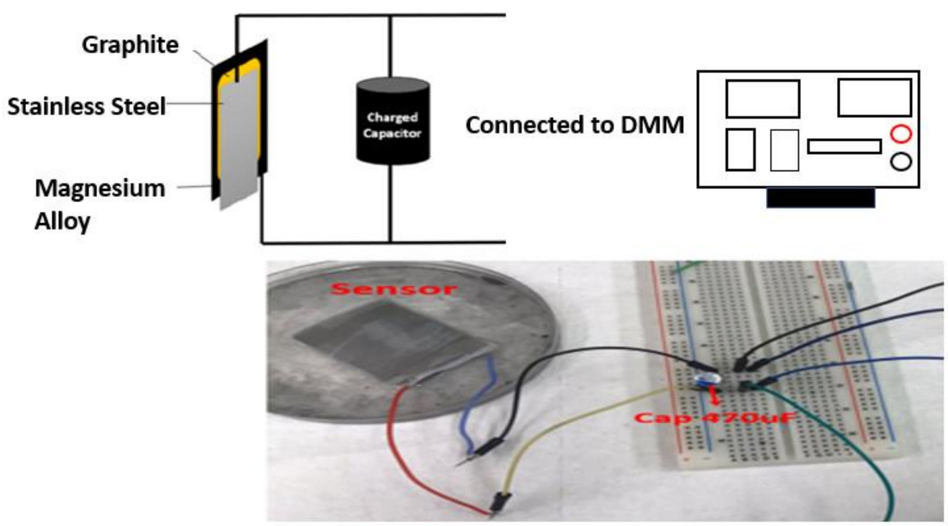

Figure 3.6: A setup to evaluate the behavior of the capacitor connected with the wet sensor.

3.4.3 Antenna

The antenna used for the design is chip antenna with a manufacturer part number of (2450AT42B100E) as stated in the data sheet [49]. It is an off-the-shelf-antenna for applications where the PCB size is extremely small and offer reasonable performance [48]. Chip antennas increases assembly expense, as it is an external component that need to purchased and assembled which has a dimension of 118 mils x 196 mils. The chip antenna performance depends on the ground plane. The minimum ground clearance is 0.8 mm from the antenna edge to the ground edge which 50 Ω transmission –line feed and good matching components. The guideline for mounting the antenna on wetness detector unit was follow from manufacturer (Johnson Technology Inc.) [49].

3.4.4 Voltage Divider Unit

A voltage divider involves applying a voltage source across a series of two resistors. This is usually very useful, when a lower voltage is required than the reference voltage in a circuit. The voltage divider equation assumes that the three values of the circuit below: the input voltage (V_{in}), and both resistor values (R_1 and R_2). The voltage divider circuit is as shown in Figure 3.7.

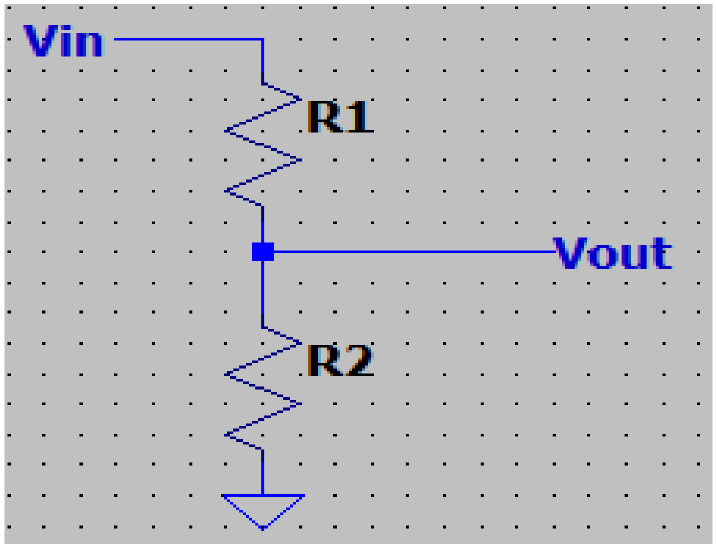

Figure 3.7: Voltage divider circuit for switch purpose integrated in the design

The voltage divider circuit consist of an important equation for calculating the resistors values when input and output voltages are known. The equation is as shown:

$$V_{OUT} = V_{in} \cdot \frac{R_2}{R_1 + R_2} \quad (3.4)$$

Where

V_{in} = is the source voltage, measured in volts (V)

R_1 = is the resistance of the first resistor, measured in Ohms (Ω)

R_2 = is the resistance of the second resistor, measures in Ohms (Ω)

V_{out} = is the output voltage, measured in volts (V)

The major importance of the voltage divider circuit implemented in this design is to enable the CHIP_EN_PIN 20 give a LOW(OFF) when the value is below threshold and a HIGH(ON) when the value reaches the threshold value of 1V.

The voltage divider formula is used to calculate the threshold value needed for activation. Since the sensor voltage generates a voltage of 1.5 volts at maximum and the threshold voltage given at the In-play Nano-beacon is 0.3V(LOW) and 0.7(HIGH). The threshold value for activation (1.05V) was obtained by multiplying the sensor voltage (1.5V) by the threshold voltage of the In-play (0.7V). With this threshold value for activation, the value of resistor R1 is obtain as followed.

$$(1.05)V = \frac{1.5 * (1M\Omega)}{R1 + (1M\Omega)}$$

$$(1.05)(R1 + 1M\Omega) = 1.5 * 1M\Omega$$

$$R1 + 1M\Omega = \frac{1.5 * (1M\Omega)}{1.05}$$

$$R1 = \frac{1.5 * (1M\Omega)}{1.05} - 1M\Omega$$

$$R1 = 428.6K$$

Hence, for a threshold voltage of 1V, 402K was selected for resistor R1.

3.4.5 The Bluetooth Low Energy (BLE) Unit

Although the In-play BLE requires no software programming, it has to be configured before it can be used. For testing purpose, the In-play BLE has a Beacon-Config tool which is a window platform software programmer for testing and writing configuration for the Nano-Beacon BLE Tag. The Graphical user interface (GUI) of the software is show in Figure 3.8 [54] The Nano-Beacon BLE configuration tool selected for this project consists of five main parts.

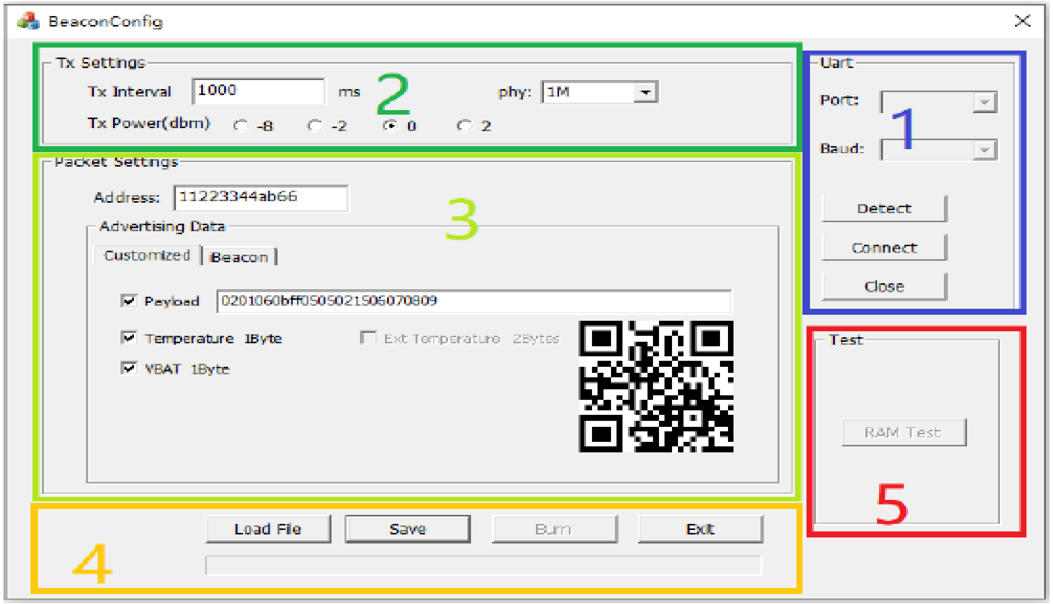

Figure 3.8 The Beacon-Config tool programmer software interface.

1) The PC UART port selection: Here, the Beacon-Config application communicates with the OTP memory programmer board through a UART serial port. The default baud rate is 115200 and according to the In-play it should not be change.

Once the PC and programmer board is connected via USB cable, then click the Detection button to refresh the port list. Select the port selection drop-down box to select the corresponding UART COM port and click on the connect button to execute action.

2) The Tx setting: The Beacon broadcast interval, radio transmit power level and data rate can be configured at column 2. The TX interval is the broadcast interval which broadcast in milliseconds, the TX Power (dBm) is the radio transmit power level, why PHY is the transmit data rate with option of 1Mbps and 125Kbps. The 125kps is a proprietary mode and will rely on using a chip from the In-play.

3) The Packet settings: The settings consist of two broadcast format at the moment which are the User-defined(customized) data format and iBeacon data format and when configuring the broadcast data, you can choose either customized or iBeacon.

4) The OTP Memory Burn and Save/Load: Save: save the configuration content filled in by the user in the directory where the tool is located as Beacon-Config. In the configuration file. Also updates the QR code with latest configuration settings.

- **Load File:** load the beacon profile previous saved by user
- **Burn**: burn the settings currently configured into the IN100 OTP memory. Once OTP memory is burned, it is permanent and cannot be changed again.

5) Testing Beacon for activation/broadcasting: After the payload has been selected by changing the default one to a customize one which denotes a user-defined broadcast data format with a total length of no more than 31 bytes. The broadcast data shall comply with the Bluetooth broadcast frame format which will be display on the phone. To run the test after the settings, click on RAM and after with 1-2 seconds by using a scanning device like an Android phone it begins to transmit the received the BLE beacon. The transmitted beacon and broadcast data was seen on the phone with an input voltage of 1.2V from the Agilent B2911A Precision Source Machine after burning in the code which is as shown in Figure 3.9 and the power captured on the system by the waveform is as shown in Figure 3.10.

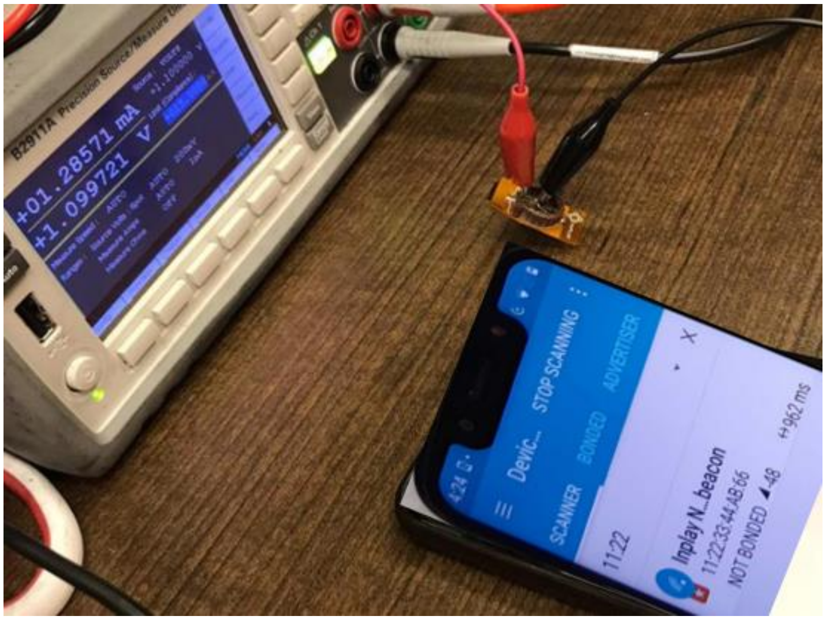

Figure 3.9 Displayed of transmitted beacon on android smart phone indicated with red showing (In-play Nanobeacon)

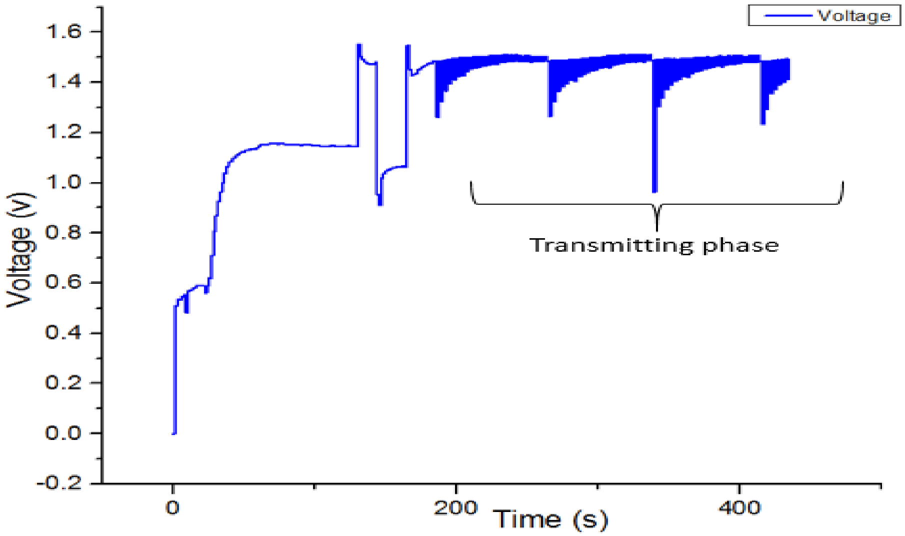

Figure 3.10: Transmitting phase of the beacon BLE

3.5 The Construction of the Wetness Detector Prototype

The construction of this project was achieved with the aid of the printed circuit board. The design followed an approach where all the components were interconnected to the printed circuit board with a soldering iron and soldering lead. The lead-free rosin core solder was used which is made up of a Tin/Copper (60% tin, 40% lead). The designed circuit diagram shown in (Figure 3.4) was used as a guide and all the components were made available. The components were firstly connected on a breadboard temporarily to observe the workability of the design before permanently transferring them to the printed circuit board. The construction was in two stages; the soldering of components and assembling of the entire system with the embedded In-play Nano-Beacon BLE Chipset, the circuit was soldered in a number of pattern at different stages on the printed circuit board from the voltage divider stage.

The circuit diagram of the wetness detector (Figure 3.4) was fabricated on a PCB. The PCB designed was done in a mixed design automation environment, where PCB layout is characterized by full functionality using Altium designer software. Figure 3.11 shows the PCB layout in Altium software designer. it is constructed to practically mimic the conformation and material properties of the PCB for fabrication. 0.8mm thick FR4 (fiberglass) was used as a substrate. The routing traces are used to connect component from one point to another. In the PCB the connector pin J2 is connected to the flexible sensor while J3 consists of the CHIP_EN, VBAT, and GND for programming the In-play BLE IC chipset.

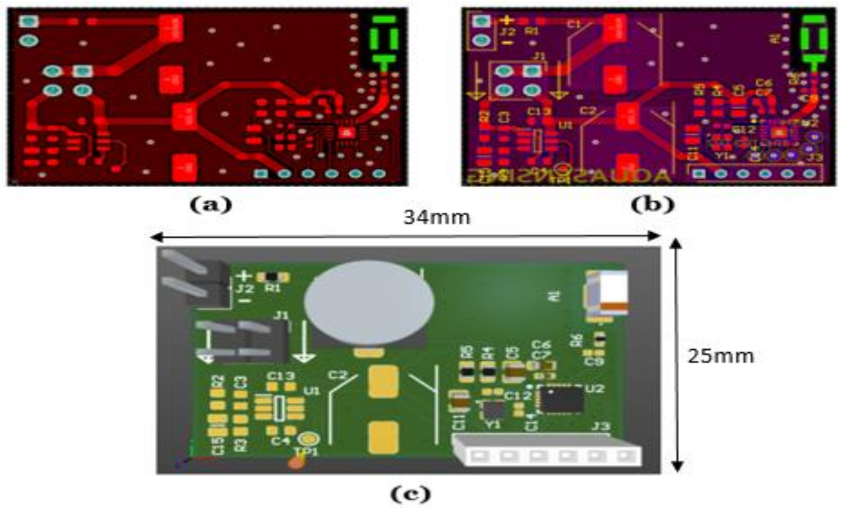

Figure 3.11: (a) circuit layout; 34mm x 25mm (b) mesh density distribution; (c) 3D layout of wetness detector circuit with In-play Nano-beacon BLE for transmission.

3.6 Assembling of Component

The assembling of the component was done through careful soldering. the QFN (Quad Flat No-Lead) IC chipset from In-play was carefully soldered. It also uses an on-board chip default antenna with a feed line matched of 50 Ohms impedance. A continuity test was carried out the circuit board. The soldering and assembling process is as showed in Figure 3.12.

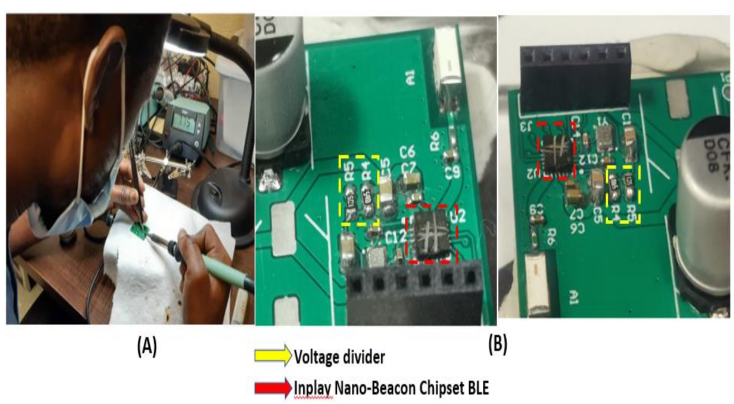

Figure 3.12: a) Soldering of fabricated board: (b) Output product after soldering

3.7 Working Principle of Smart-Diaper Based Wetness Detector

The flexible wetness sensor is designed using nanomaterials [53] such as graphite solution deposition and a filter paper to absorb wetness. When place inside the diaper it absorbs wetness and thus a signal is generated which is a form of voltage. This voltage signal is sent to the wetness detector which in turn analysis the voltage signal which ranges from 1.1 to 1.6V. The BLE senses the signal which operates within the range of 1.1 to 3.6V and sends a wireless signal to the smart-phone which then notifies the user of the wet diaper and needed for change. The pictorial view of the mode of operation of the wetness detector is shown in Figure 3.13.

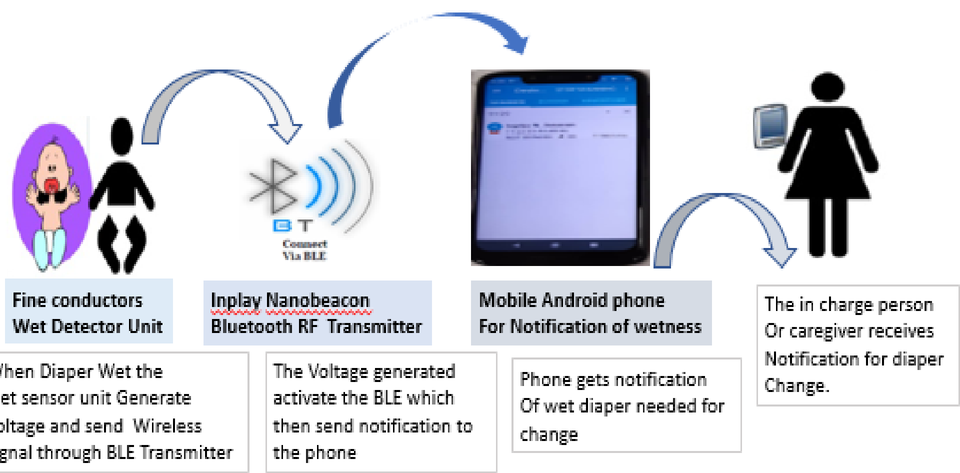

Figure 3.13: Pictorial block diagram of mode of operation

3.8 Summary

The methodology adopted in this project as discussed in this section showed that the successful implementation of the low-cost wet detector system involved three basic stages; the wet sensor, wetness detector, and the BLE. The sensor is made of nanomaterials such as carbon. The wetness detector sensor was designed using the Altium Designer Software. It detects wetness inside the diaper and sends a notification to the caregiver's phone. It generates a voltage signal ranging from 1.1V to 1.5V. The wet detector unit consists of the wetness detector and the embedded BLE unit. The wetness detector unit was designed with a voltage divider circuit to act as a switch for the ON and OFF of the BLE enable pin. Also, a buck capacitor was incorporated for energy storage. This became necessary to avoid delay in switching on the BLE when connected to the sensor directly. The In-play BLE has a Beacon-Config tool which is a windows platform software programmer for testing and writing configuration for the Nano-Beacon BLE Tag. Once the In-play BLE is activated, it sends a notification to the caregiver's smartphone for appropriate action.

Chapter 4

RESULT AND DISCUSSION

4.1 Introduction

In this project, a prototype of a battery-free smart diaper wetness detection system has been designed and constructed according to the design specification. Repetitive testing was carried out to identify and ascertain the performance of the system and to ensure that the system performs as predicted. During the experimentation phase of the project, all the sections and units of the system were tested and the result obtain are presented and discussed in this section. The major test carried out include component testing, continuity and short circuit test on the PCB, software current consumption testing, and transmission range testing. The rest of this section will be devoted to discussing the various results and finding obtained from each test and their corresponding analysis.

4.2 The Printed Circuit Board (PCBs) Performance Analysis

The complete implementation of the wetness detector unit with embedded In-play Nano-Beacon BLE is as shown in Figure 4.1. A functional test was carried out on the PCB to check for tiny whiskers between pads. A multi-meter with milliohm sensitivity was used to check for short circuit after component soldering. To determine the voltage at CHIP_ENABLE and VBAT, the PCB was power from the DMM machine. The voltage divider was able to turn on the CHIP_ENABLE when it is high above the threshold of 1.0V and VBAT at 1.45V. The observed waveforms are as shown in Figure 4.2.

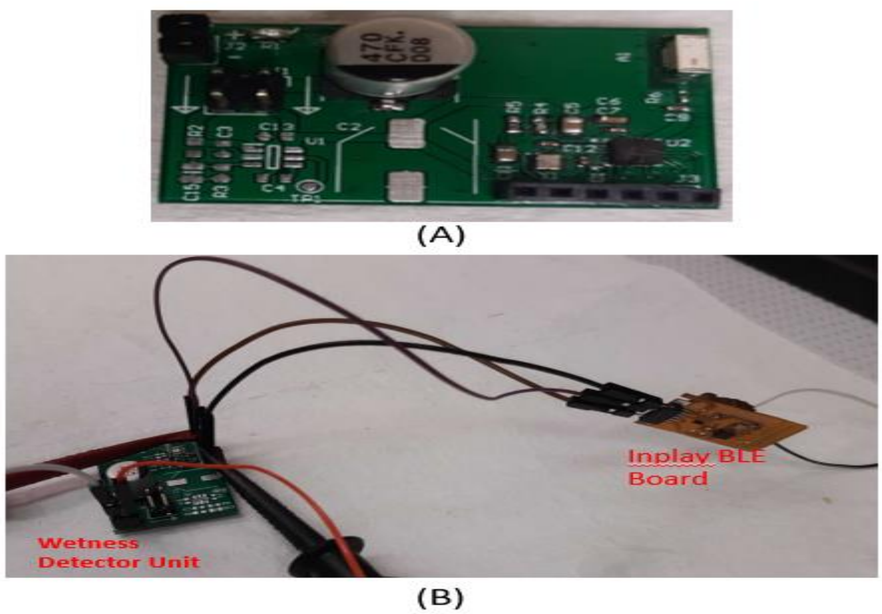

Figure 4.1: a) Complete soldered wetness detector PCB; b) Detector connected with external In-play BLE to Digital Multi-Meter Machine.

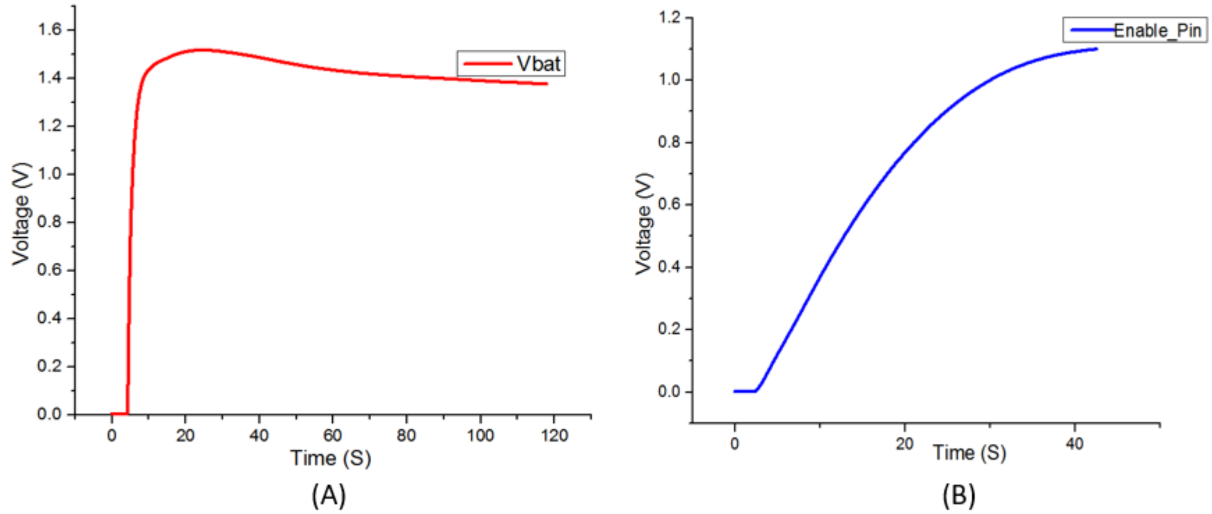

Figure 4.2: The waveform of the voltage a) voltage at VBAT; b) voltage at Chip Enable Pin.

4.3 Components Evaluation for System Implementation

Selection and evaluation of the components for the system implementation is necessary to produce an efficient design of the system. To select the best component for the system each component was tested and the result analyzed to determine the overall performance of the system.

4.3.1 Current Limiting Resistor

The essence of this resistor R1 is to limit the current from the output signal of the wetness sensor. Basically the current limiting resistor was chosen based on our desired output voltage. While selecting the resistor, several resistance values were tested to determine the effect on the output voltage. The waveform of Figure 4.3 shows the effect of different resistance value on the output voltage.

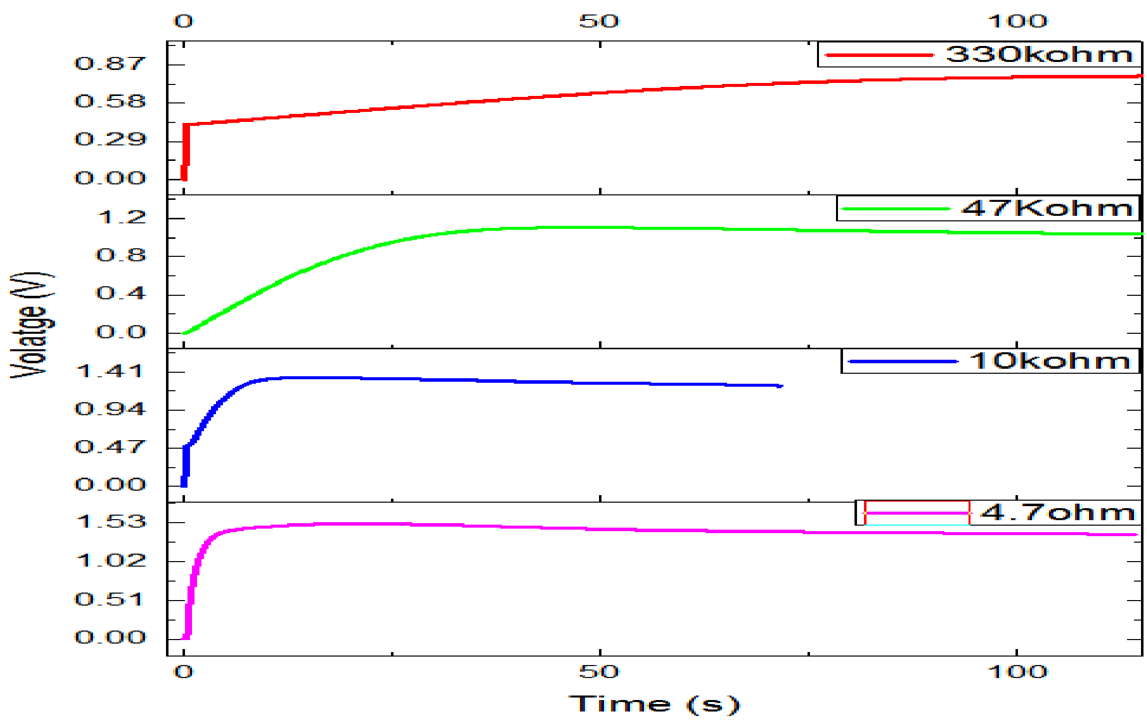

Figure 4.3. Output obtain from different resistors values used.

Figure 4.3 shows the output voltage obtained from different resistance values. it was observed that higher resistance value (330kohms) reduce the voltage generated from the sensor (1.5V to 0.7V) which is below the voltage requirement of the system. A small resistance value of 10kohms was selected because it produced the same output voltage (1.5V) as required for the system operation. As shown in Figure 4.4 the current limiting resistor also have effect on the storage capacitor. It limits the capacitor from charging fast, which reduces the voltage on VBAT and CHIP_EN as seen in Figure 4.3, from 0.7V and 0.5V respectively. This resulted in the delay of the BLE from transmitting on time. Hence the R1 resistor was remove from the circuit. The waveform of the output current from BLE with R1 in place as observed using an RGOL oscilloscope is as shown in Figure 4.4.

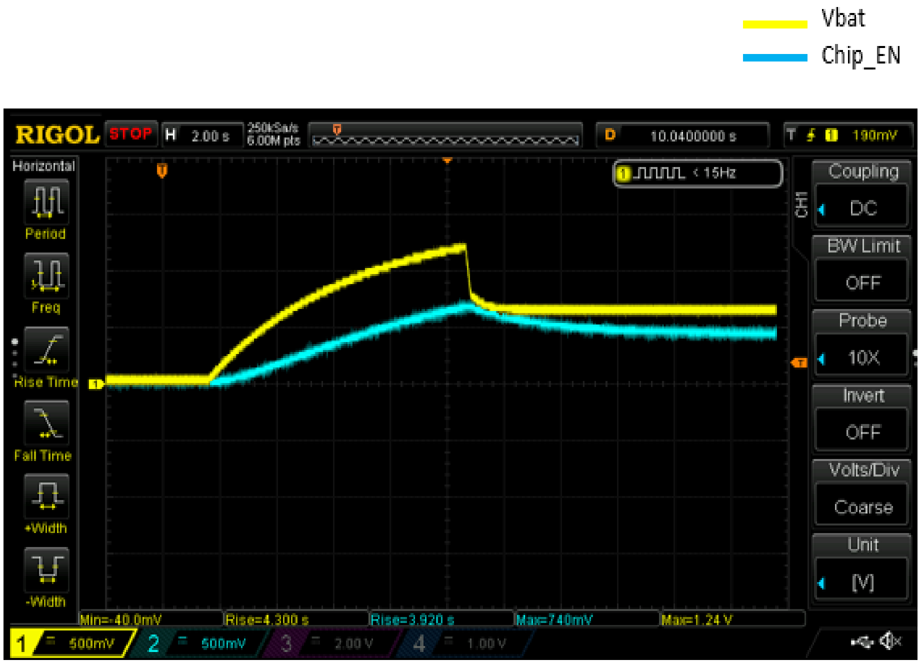

Figure 4.4: Output current waveform of the BLE with current limiting resistor.

4.3.2 Storage Capacitor

The capacitor used in the project serves as a storage capacitor. The bulk capacitor becomes necessary because with the In-play BLE connected directly to the wetness sensor there was a delay in activating the BLE. Hence the capacitor was incorporated to store energy from the sensor and immediate availability to the BLE when it is powered. In selecting the storage capacitor for the design, a comparison between a 680uF and 470uF was carried out. The essence of this comparison is to determine which among this capacitor charges faster for the same source voltage generated by the sensor. The waveform of performance comparison of the capacitors is as shown in Figure 4.5.

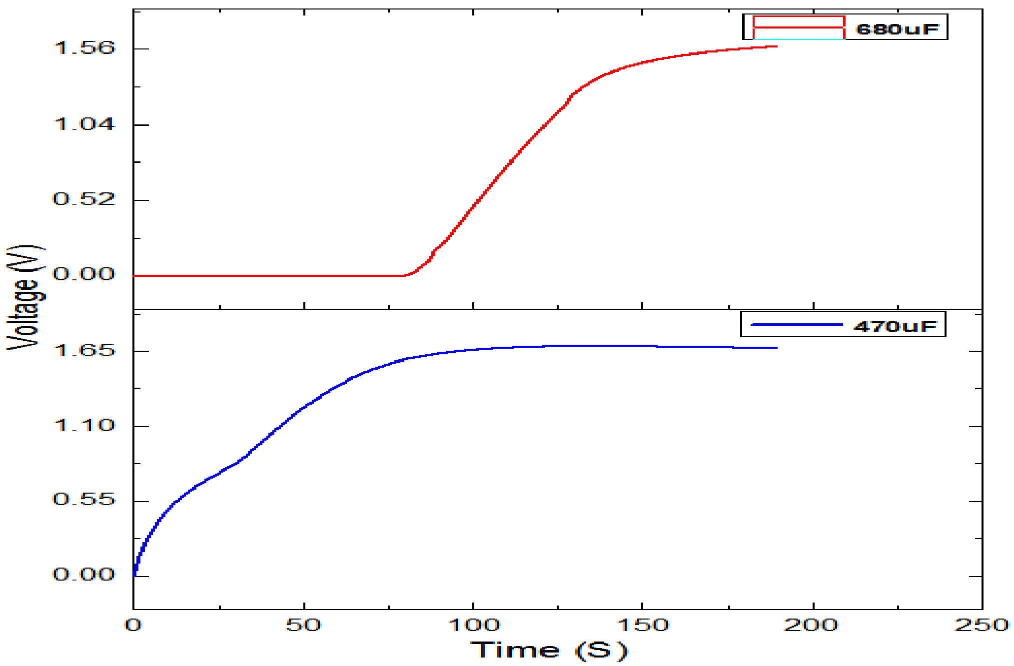

Figure 4.5: Measurement Performance comparison of storage capacitor.

As seen from the graph, there is a delay of about 40 seconds before the 680uF capacitor starts charging and such delay is not needed for the purpose of the design. However, the 470uF capacitor starts charging immediately it senses the voltage from the sensor. In other to achieve a shorter response time for the wetness detector system, the 470uF storage capacitor was selected. The activation point of the BLE is as shown in Figure 4.6, as soon as the capacitor is charge and exceed the threshold.

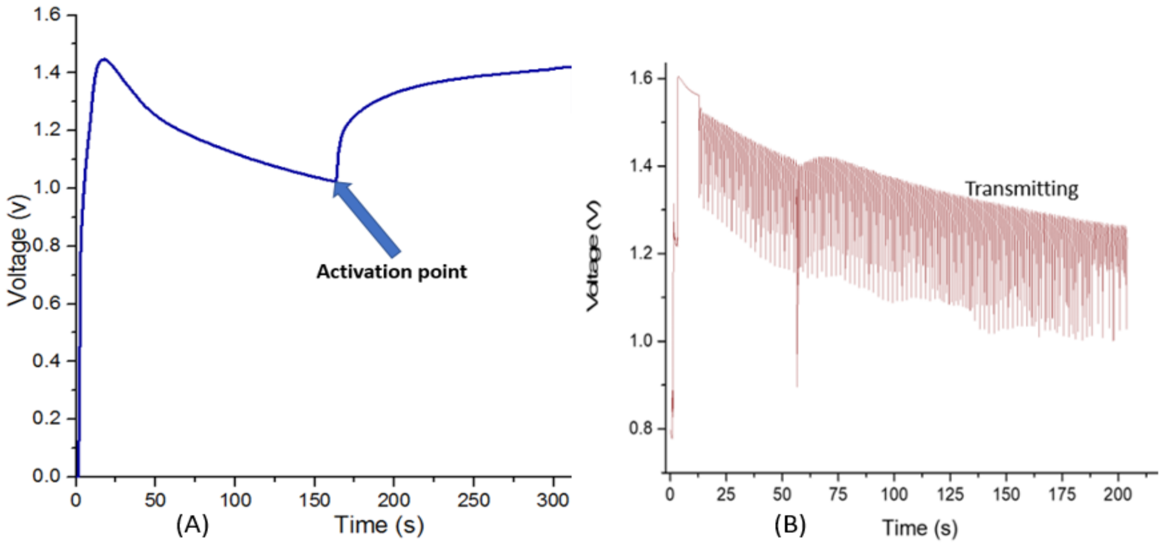

Figure 4.6 a) activated BLE when capacitor is charged; b) Transmitting phase of the BLE.

4.4 Performance Analysis of Nordic nRF52832 Bluetooth Low Energy (BLE)

The Nordic nRF52832 [55] Bluetooth was programmed using Aqua-Sensing data payload at 0dBm. It has an input operating voltage range of 1.8V to 3.6V for the BLE to transmit properly. A setup was implemented using the Agilent B2911A precision power source machine to power the BLE as shown in Figure 4.7. The Nordic custom Bluetooth board was powered at different constant voltages (1.8V, 2.2V,2.5V,2.9V, and 3.3V) to ascertain its functionality and checking the current consumptions.

Figure 4.7: The Nordic Nrf52832 BLE Module

The average current for each voltage was taken into consideration. The voltage at 1.8V, which is the actual starting voltage, resulted in a current consumption of 3.5mA at the starting point at different intervals. The other voltages resulted in a lesser current of uA for some seconds before picking up at mA. Thus all the voltages activated the Bluetooth and stayed for long period. The analysis showed the current consumption of the Nordic Nrf52832 BLE at different voltage levels from 1.8V to 3.3V and the usable voltage range of the BLE is from 1.8V to 3.6V. However due to the high startup current and the operating voltage range of 1.8V to 3.6V, the BLE module cannot be used for the design as the wet sensor can only generates a maximum voltage of 1.5V and a current of uA. Key-Sight Bench-UVE software was used to study the different waveforms obtained as shown in Figure 4.8.

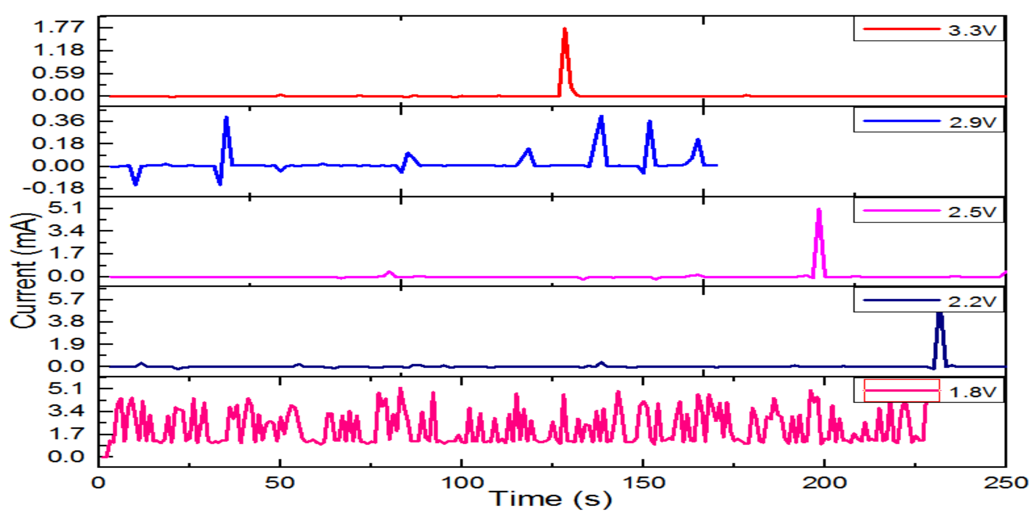

Figure: 4.8: Results of current waveforms at different voltage range on the Nordic Bluetooth.

4.5 Sensor Performance with Nordic Nrf52832 Bluetooth Low Energy (BLE)

To ascertain the performance of the Nordic Nrf52832 BLE, the wet sensor was connected to it. The sensor was not able to activate the BLE because the voltage generated from the wet sensor at 1.5V is not enough to power the BLE for activation, since it needs 1.8V to 3.6V for its operation. Thus the wet sensor needed a device to boost its voltage so as reach the voltage level for the BLE to operate. The sensor was connected along with an energy harvester circuitry boost converter. The sensor was placed inside a petri dish with 75mL of water poured on it. It generated a voltage of 1.5V, which was boosted up to 2V and 1.8V on two different testing and the BLE was activated since it reaches its starting voltage. The output waveform of the boosted voltage is as shown in Figure 4.9.

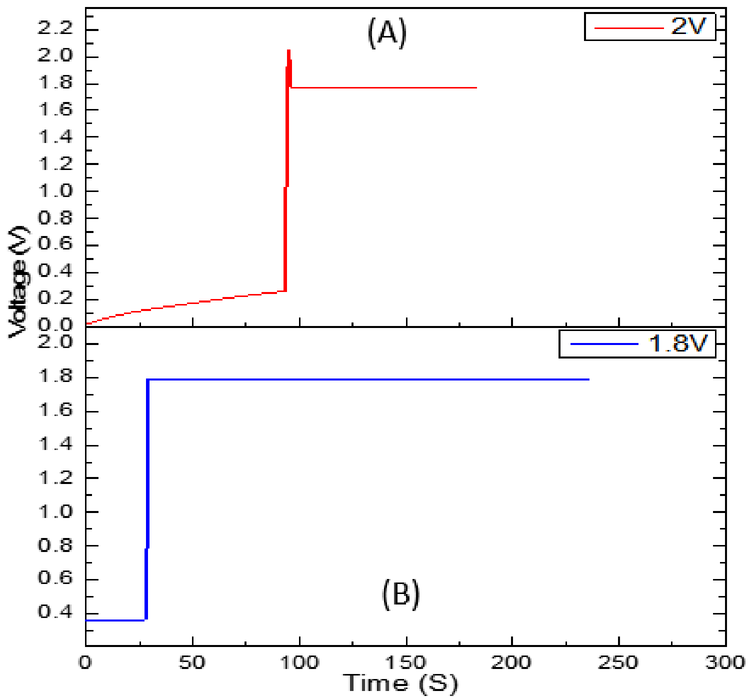

Figure 4.9: Measured voltage rise of flexible sensor; (A) 1.5V to 2V. (B)1.5V to 1.8V

The sensor was seen to have a voltage rise at two different phases using the boost converter. The boosted voltages were able to trigger on the Nordic BLE since it was up to its operating range of 1.8V. The major challenge was that, using a boost converter for the wet detector system will incur more cost. Thus, knowing that the sensor cannot activate the Nordic BLE without a boost converter, an alternative measure was taken to search for a Bluetooth with low energy consumption and low startup voltage for operation. The In-play Nano-Beacon

BLE was considered a better option with a voltage operating range of 1.1V to 3.6V. Thus the boost converter was eliminated and that of Nordic Bluetooth making the design simpler, using fewer component and cost reduction.

4.6 Performance Analysis of the In-play Nano-Beacon (BLE)

The In-play Nano-Beacon Bluetooth Low Energy (BLE) was programmed using the Aqua-Sensing data payload at 0dBm and at 3 seconds transmitting interval. It has input voltage range of 1.1V to 3.6V as expected for the BLE to work correctly. The sensor and the In-play Bluetooth board were connected from starting and a 75mL of water was poured on the sensor. The sensor voltage starts increasing and at same time the In-play BLE also starts taking power from the sensor. The sensor voltage increased to just 0.6V-0.8V as shown in Figure 4.10. It was observed that the BLE did not worked because it does allow the sensor to reach its maximum voltage since it was taking powering directing from the sensor. At this point it necessary to have a storage capacitor so that the voltage generated from the sensor can be stored in the capacitor and readily available for the In-play BLE for activation.

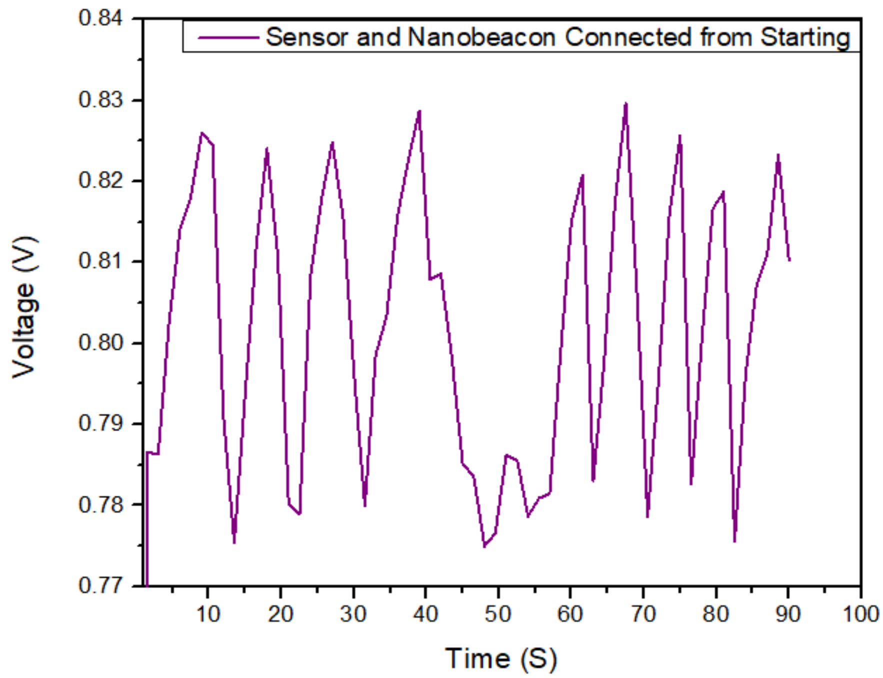

Figure 4.10: Result of the sensor and In-play BLE connected from start.

However, after observing and resolving the issue as stated in Fig 4.10, it was later observed that the In-play BLE board did not work at 1.1V as stated in the datasheet [54]. After trouble shooting, it was discovered that, the resistor R2 on the design circuit was acting as pull-up resistor with a resistance value of 500Mohm. These prevented the CHIP_EN pin on the BLE board from getting a valid "HI" signal to activate at 1.1V. The measurement set up was carried out on removing the R2 resistor and replacing it with a smaller resistor of 0 ohms, which then became active. The activation at 1.1V is as shown in Figure 4.11.

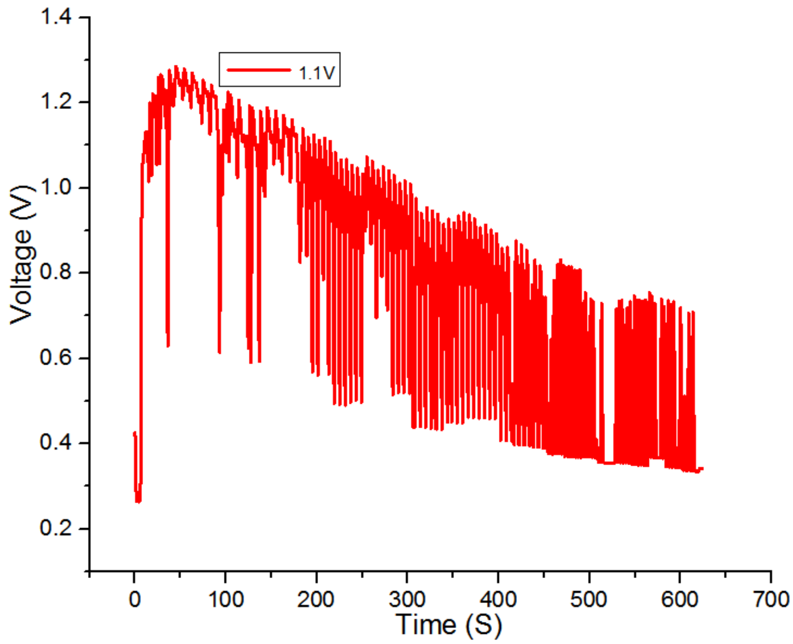

Figure 4.11 Results of activation of 1.1V applied on the BLE shows.

After successfully implementing the voltage ranges, experimental setup was conducted using different range of values to evaluate the performance of the BLE. Table 1 presents the results obtained after conducting several tests on the BLE. The waveforms obtained from the different voltages applied to the BLE is as shown in Figure 4.12.

Table 1 Presents the Results Obtained after Conducting Several Tests on the BLE

Test Setup	
Power Source	B2900 Series
Source Voltage	3.0V to 1.2V
Current Limit	1A
Display Mode	Average
Auto Mode	ON
Power Input on Beacon	P1.2 VBAT/SUPPLY P1.5 GND

Input Voltage (V)	Connected R1. Power cycle the device between voltage changes						Connected R1. Don't power cycle the device between voltage changes.					
	Beacon turned on (Yes/No)	Startup current	Average current after startup	Current Peaks	Time	End current consumption	Beacon turned on (Yes/No)	Startup current	Average current after startup	Current Peaks	Time	End current consumption
1.2	Yes	1.3mA	1.4uA-2.4uA.	618uA	10min	2.2uA	Yes	1.3mA	800nA-2.7uA	604uA	5min	1.8uA
1.5	Yes	1.3mA	1.7uA-2.8uA	100.9uA	10min	2.1uA	Yes	1.6uA	1.6uA-2.9uA	1.3mA	5min	1.6uA
1.8	Yes	1.4mA	800nA-2.1uA	992.6uA	10min	2.4uA	Yes	2.2uA	2.1uA-2.5uA	______	5min	1.5uA
2	Yes	1.4mA	1.7uA-2.3uA	2.6mA	10min	2.2uA	Yes	1.5uA	1.3uA-2.3uA	2.0mA	5min	1.6uA
2.5	Yes	1.4mA	1.9uA-2.0uA	251.1uA	10min	1.9uA	Yes	1.7uA	2.0uA-2.6uA	______	5min	2.0uA
3	Yes	2mA	1.3uA-2.5uA	516uA	10min	1.4uA	Yes	2.0uA	1.4uA-2.0uA	2.7mA	5min	1.5uA

The average current for each voltage from initial to final was also taken into consideration as shown in the table and the time taken for the voltages to activate the BLE and how long each stayed. Thus all the voltages activated the BLE, at this point the functionality of the BLE was implemented.

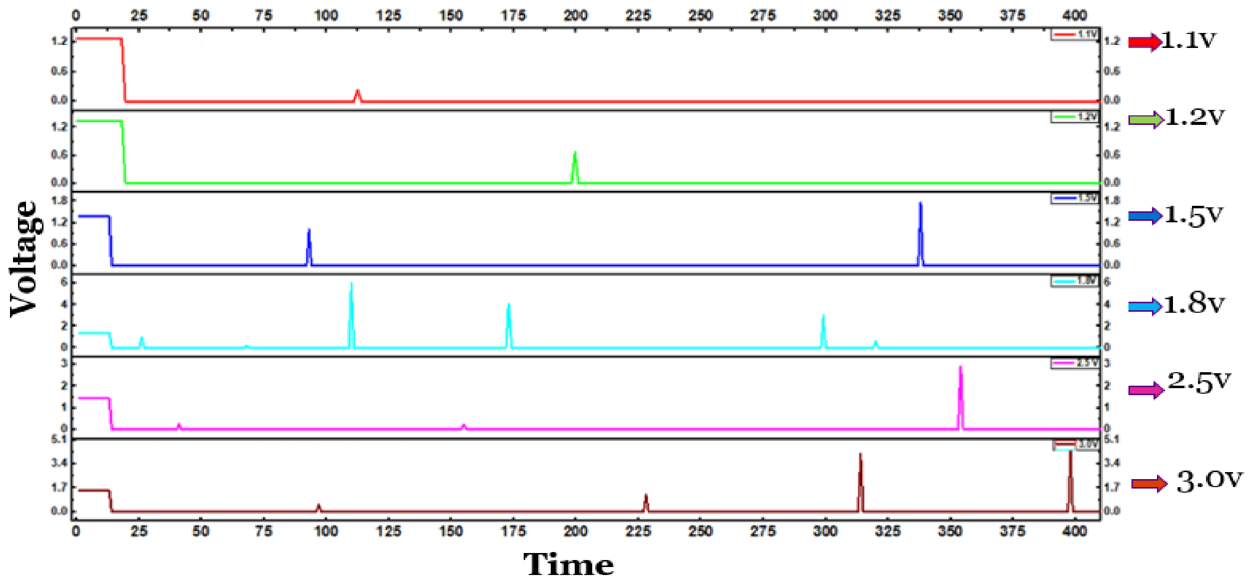

Figure 4.12: Results of waveform applying different voltage range on the BLE.

4.7 Software Current Consumption

The Beacon-Config software was used to burn the codes into the Nano-beacon In-play BLE. Different test was carried out to determine the most suitable version of the software to use. The old software version (V1.8_2021022/V1.11) was selected because it has the lowest start up current of 2mA compare to the new software version (V1.12_20210324) with a startup current of 3mA-4mA. Figure 4.13 show the waveforms of the startup currents for the old and new software versions. [54].

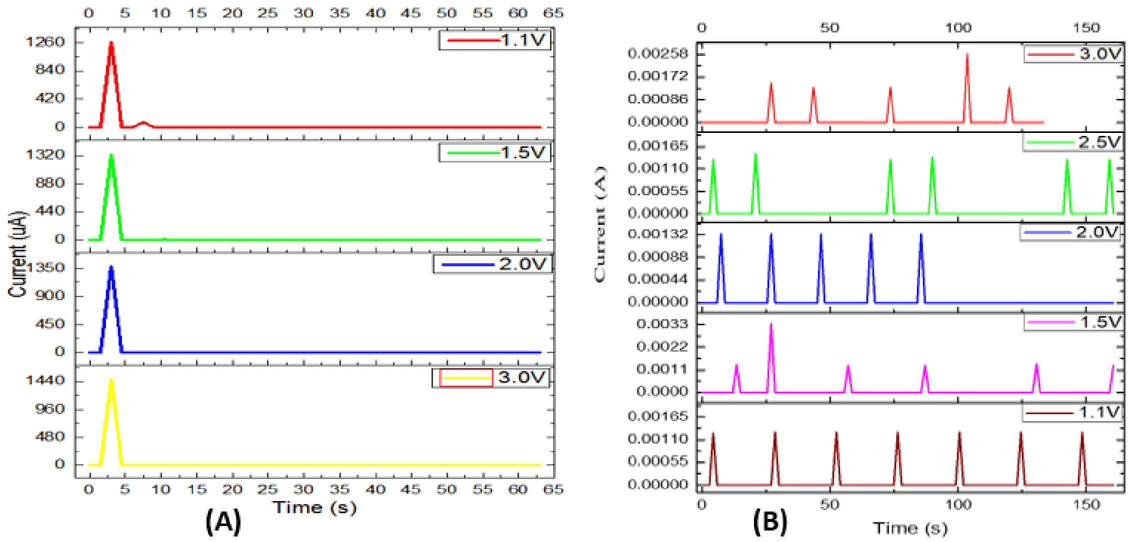

Figure 4.13: Result comparison of current consumption; a) old software V1.8_2021022; b) new software V1.12_20210324.

4.8 Load Testing of the Sensor

The essence of load testing of the sensor is to ascertain the internal resistance of the sensor, alongside the charge capacity of the sensor and to know the optimal current and time it will last for the senor to work along with the wetness detector system. The experimental setup is schematically shown in Figure 4.14.

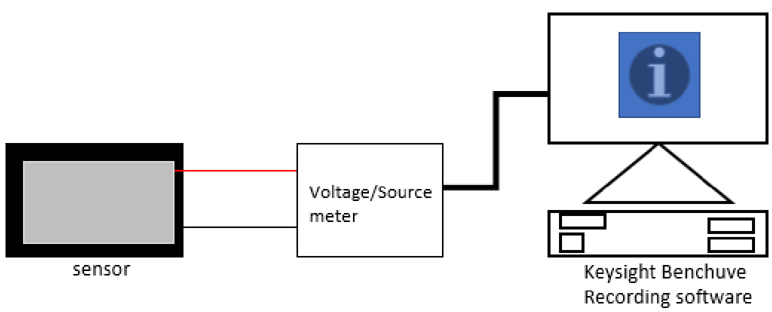

Figure 4.14: Schematic of Load Test Setup

The sensor was placed in water of 75mL and allowed to reach its maximum voltage level of 1.6V using the digital multi-meter. It was allowed to stay for 6 seconds for the reaction to start properly. The power source machine was turned on and the current was set to negative in order to draw current at a particular value. Different current values of -10mA, -5mA, -1mA, -100uA, were used to carry out the measurement. It was observed that the amount of current drawn affected the sensor. At mA levels (-10mA, -5mA, and -1mA) it stayed for 16mins maximum, while at low current (-100uA) it stayed for two to three days before it became fully drained. A few notable observations during the test were recognized. The higher the current value the quicker the voltage is drained; while the lesser current values kept the sensor for longer periods of time before it gets fully drained. The output waveforms of the measured resistances are as shown in Figure 4.15 and the charge capacity by averaging of sensor which is determine by (Area x Current) after the current is drawn from the source machine is shown in Table 2

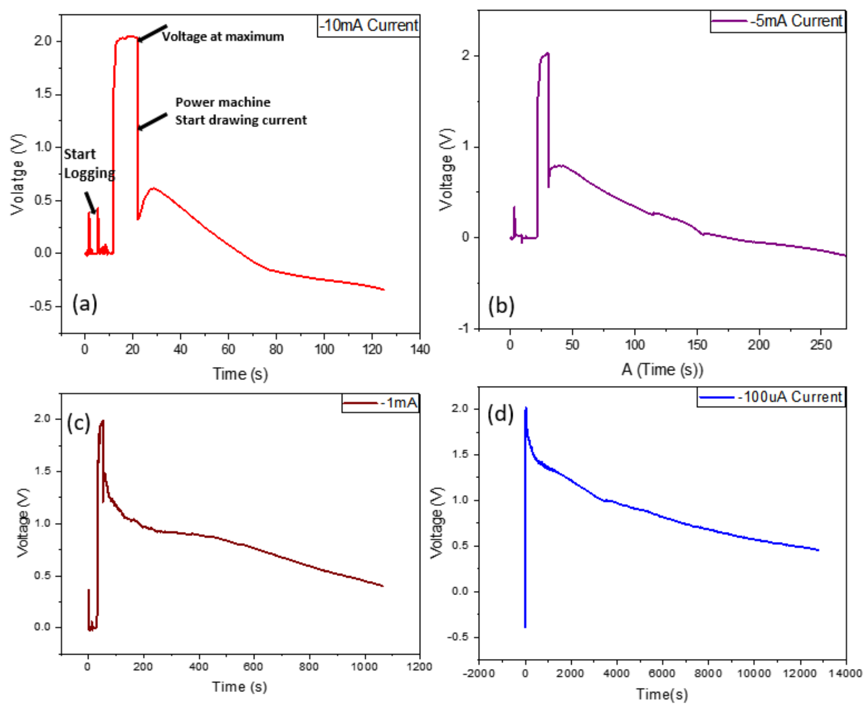

Figure 4.15: (a) Resistance measurements showing resistance at -10mA. (b) at -5mA, (c) at -1mA, (d) at -100uA.

Table 2 : Sensor Charged Capacity by Averaging.

Sensor	Drawing Current	Charge Capacity by Averaging
Flex sensor	10mA	0.079mWhour
	5mA	0.0575mWhour
	1mA	0.0365mWhour
	100uA	57.54uWhour

4.9 Performance Analysis of Wetness Sensor with Wet Detector System

An important decision on the flexible sensor suitable for implementation of the smart-diaper was informed by the performance analysis of the flexible wetness sensor in comparison with the wet sensor for leaks. The sensors were fabricated using nanomaterials such as carbon material solution deposition. From the results obtained the sensors worked correctly with the voltage divider implemented in this prototype of the wetness detector. The waveforms of both sensors are as shown in Figure 4.16.

(A) (B)

Figure 4.16: Waveforms of both sensors; a) flexible wetness sensor, b) water leak sensor

In Figure 4.16 (a) the voltage increase as the wetness sensor absorbed water and started charging the capacitor. The capacitor charged up to 1.7V within 5s and the enable pin got to its threshold of 1V. The voltage divider switched to enable pin "HI", the point at which the In-play BLE started transmitting. As shown in Figure 4.16(a) there was a voltage drop at V_{bat} (Sensor Voltage) due to the high startup current consumed by the BLE when it is activated. However, the BLE consume less current after 2-3s of activation and maintained this low current for the rest of the period of operation. While the voltage at Figure 4.16 (b) increase as the sensor absorbed water and started charging the capacitor. The capacitor charged up to 2V within 3s and the enable pin got to its threshold of 1V. The voltage divider switched to enable pin "HI", the point at which the In-play BLE started transmitting. As shown in Figure 4.16(b) there was a voltage drop at V_{bat} due to the high star up current consume by the BLE when it is activated. However, the BLE consume less current after 1-2s of activation and maintained this low current for the rest of the period of operation.

4.10 The System Workability

The workability of the system was demonstrated so as to validate the proof of concept and system functionality. The system setup is as shown in Figure 4.17.

The sensor is placed at the bottom which is 3mm x 3mm, towards the frontal part of the diaper where it is mostly likely to be in contact with urine coming from the genital part of the diaper wearer. The quantity of water poured on the diaper towards the sensor was 75mL of water, the moment the sensor starts absorbing the water the voltage began to increase as the electrical resistance between the wires connected to the flexible sensor falls when the conductors come in contact with water or other wetness in the diaper.

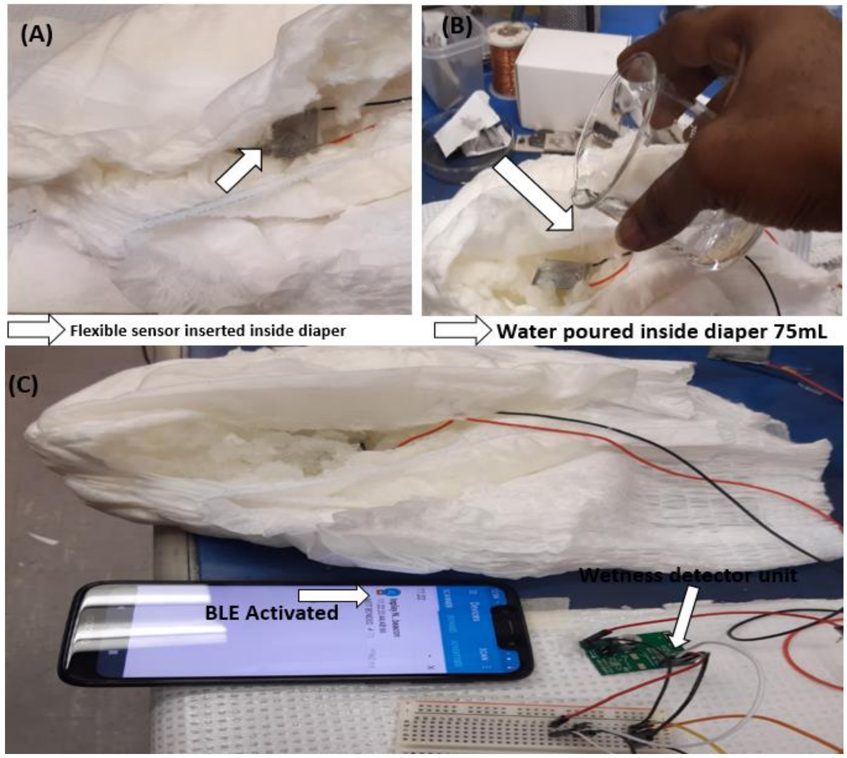

Figure 4.17: System workability setup: a) The wetness sensor inserted inside the diaper; b) water poured inside the diaper; c) notification of BLE on the smart-phone.

The output waveform is as shown in Figure 4.18. The voltage can be seen rising the moment the flexible sensor absorbs the water, and start charging the capacitor immediately. The voltage drops as seen in the waveform is the startup current of the BLE at which the enable pin exceeds the threshold, a forward bias is initiated by the voltage divider for activation, and the Nano-Beacon at this point is sending BLE advertisements which is seen on the smart phone.

(A) (B)

Figure 4.18: a) Output characterization of the system; b) Continuous transmitting phase up to 4minutes.

Further experiment was carried out using different amount of water level to ascertain the reliability of the wetness detector system. The volumes of water used were 1mL, 4mL, 6mL, and 8mL. The five volumes were added at different stages. After performing the tests, it took approximately 90 seconds for the capacitor to fully charge. The wet detector gave a good response by activating with the voltage divider on reaching above threshold of 1V of the In-play Nano-Beacon BLE. The results of the waveforms of the five different volumes of water used are as shown in Figure 4.19.

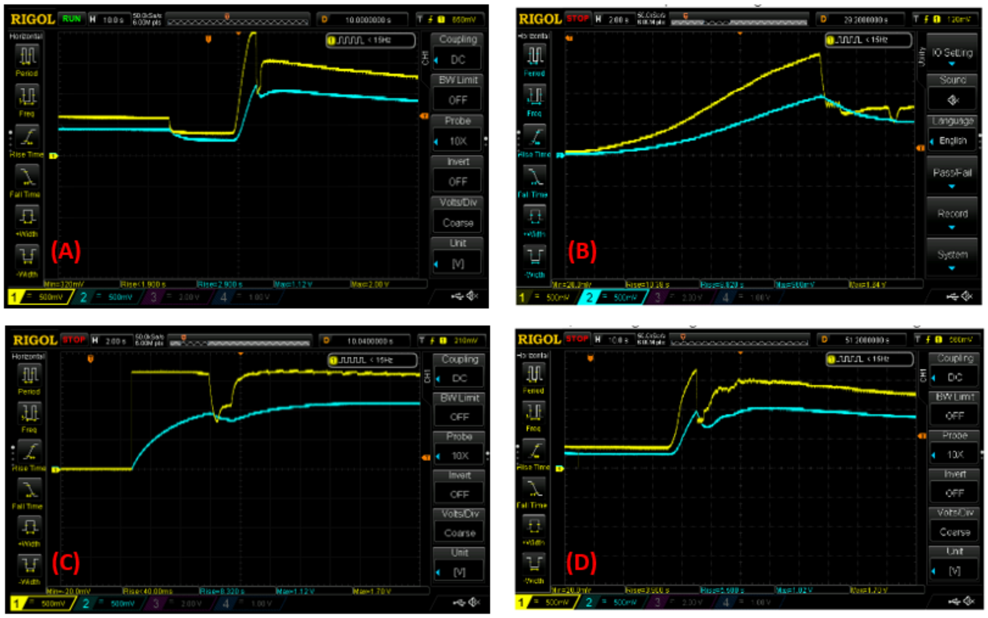

Figure 4.19: Output response for different water volumes; (A) 1mL of water. (B) 4mL of water. (C) 6mL of water. (D) 8mL of water.

The moment the wetness sensor detects fluid starts charging the capacitor as indicated by the yellow color called the V_{bat}. As seen from the waveform of the V_{bat}, there is a voltage drop and consequent startup current of the In-play BLE at which the enable pin exceeds the threshold. A forward bias is initiated by the voltage divider for activating the Nano-Beacon to start sending BLE advertisement to the smartphone. As seen in Figure 4.19 (a), (c) and (d) there was a delay in startup charging of the capacitor. This was as a result of packing and non-uniform deposition of nanomaterial mixture. This can be resolved by properly depositing a uniform mixture solution for proper startup charging rate on detection of wetness by the sensor. The tests results showed that the wet detector sensor can be adjusted to detect any required wetness level. This is a very useful feature that can be used to adjust the diaper to specific wetness levels depending on its use, such as reducing severe diaper rash infection and as the situation requires. The battery-free system of the detection unit is going to be fixed on the upper front portion of the diaper using contact pins.

4.11 System Sensitivity

The sensitivity of the wetness detector system depends on the quantity of water. As seen in [56] the output rate of urine of children is about 1mL/kg/hour which is almost the same as adult. An experiment was carried out using 0.5mL of water as in [56] it was observed that, the sensor was able sense wetness a little but could not generate the maximum voltage of 1.5V to activate the BLE as seen in Figure 4.19. However, when the wetness detector system sense a volume of water above 1mL it generates the maximum voltage of 1.5V which is above the BLE threshold to active. Most of the high output rates of urine occurs early in the night, around the time of transition from activity to inactivity. The waveform of the system sensitivity using 0.5mL volume of water is shown in Figure 4.20.

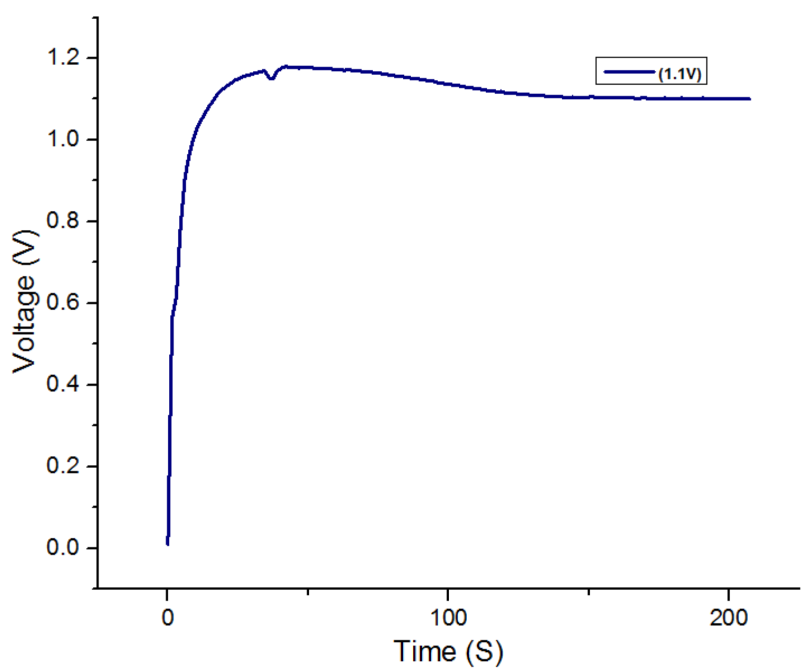

Figure 4.20: Measured Output response of 0.5mL volume of water for wetness detector sensitivity.

4.12 Wet-Detector Delay Analysis

The design wet-detector device is further analyzed to understand the delay functionality in activating the In-play Nano-Beacon BLE. From the schematic shown in Figure 3.4, resistor R4, R5 and capacitor C11 make up the RC circuit to delay the Enable pin of the In-play BLE chipset. The position of resistor R4, R5 and capacitor C11 which make up the RC circuit is shown in Figure 4.21.

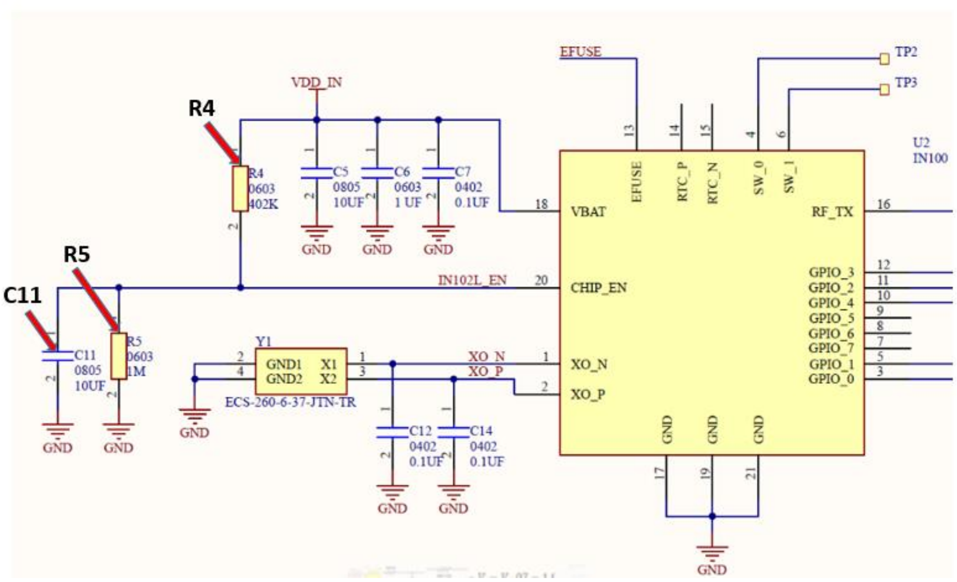

Figure 4.21: Position of RC circuit components to delay the enable pin

The RC circuit of the components in position is drawn from Figure 4.21 which is shown in Figure 4.22.

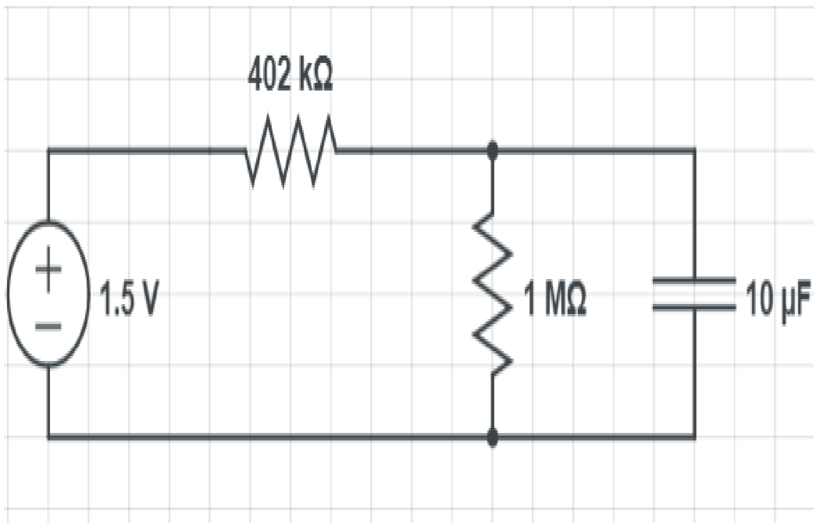

Figure 4.22: RC circuit of resistor R4(402kΩ), R5(1MΩ) and C11(10uF) and Vs (1.5V)

The voltage divider produces a voltage of 1.07V when powered by a 1.5V supply voltage.

Which is deduced using equation 3.4.

$V_{OUT} = 1.5. \frac{402k\Omega}{402k\Omega + 1M\Omega} = 1.07\text{V}.$

However, the circuit can be further simplified using circuit theory as seen in Figure 4.23.

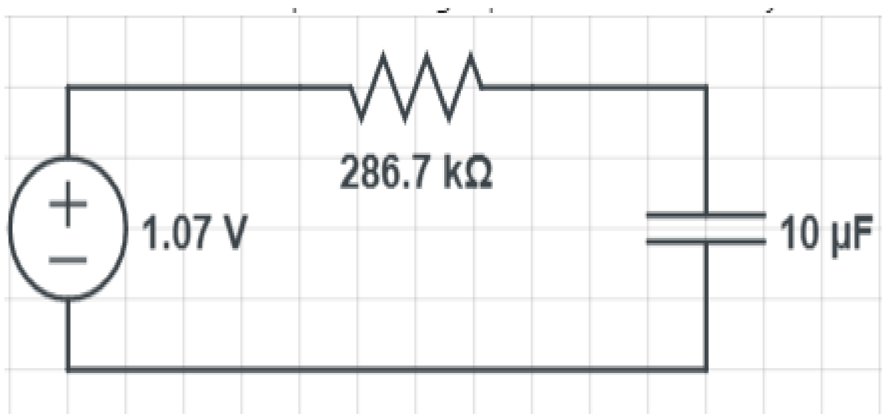

Figure 4.23: Simplified equivalent circuit

This allow us to use a simple RC equation, where the voltage cross the capacitor is equivalent to the Enable pin voltage.

Where

$$V_C = V_S - V_s e^{\frac{-t}{RC}} \quad (4.1)$$

$$V_C = 1.07 - 1.07 e^{\frac{-t}{2.87}}$$

The plotted waveform of the enable pin voltage (Voltage at the capacitor) as expected is shown in Figure 4.24.

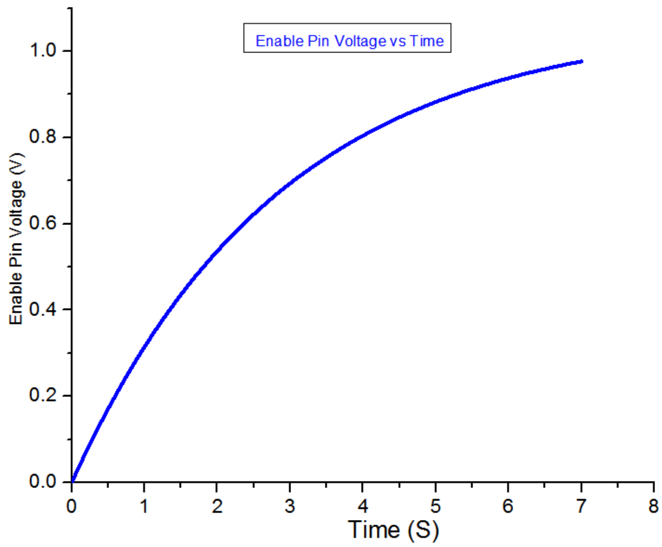

Figure 4.24: Measured Enable Pin Voltage vs Time

Figure 4.24 shows the measure enable pin voltage, which is voltage of the capacitor over time. As expected, the voltage rises, approaching the level of the voltage divider output voltage of 1.07V which is the voltage threshold for activation. This gives very similar results to what was observed when testing with the power source supply voltage at 1.5V.

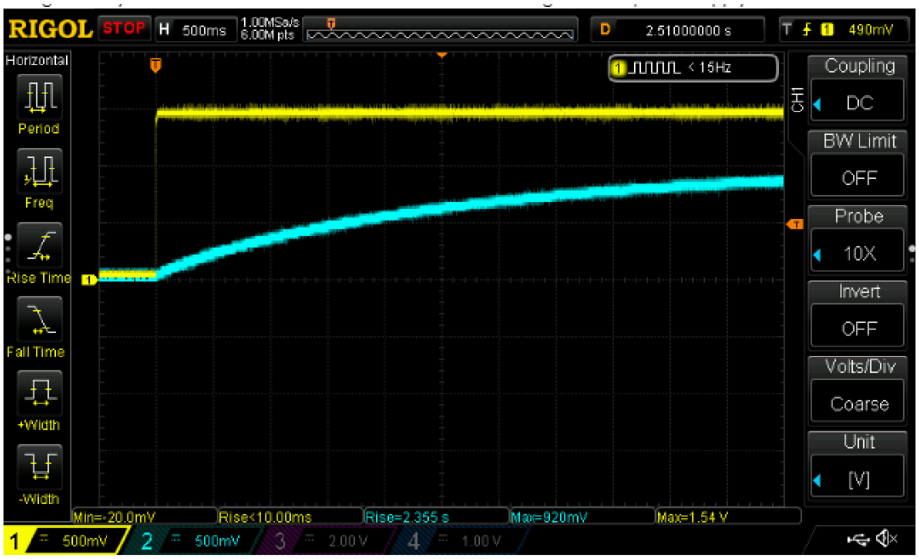

Figure 4.25: Measure similar result waveform of supply voltage.

Figure 4.25 shows the measured similar results of voltage at enable pin as seen in Figure 4.24 using the RC circuit equation for evaluation. Where yellow is equals “Supply voltage/V_{bat} and blue equals voltage at enable pin. After 5s the voltage seen in both the calculations and oscilloscope plot is around 900mV, thus there was consistency with the theory.

When powered with the wet sensor, it does not immediately rise to 1.5V as the way a power source supply does as shown in Figure 4.25. As a result, the delay is longer since the delay of the capacitor (C11) charging is combined with the delay of the sensor increasing in Voltage as seen in Figure 4.19. The delay in this case is close to 15s, due to the time it takes the sensor voltage to increase.

The idea behind the delay was to allow the sensor voltage to increase before turning on the BLE. Without the delay there was issues with activating the BLE, as it would power up, but the voltage of the wet sensor would drop fast as seen in Figure 4.26 and not be able to keep it BLE powered.

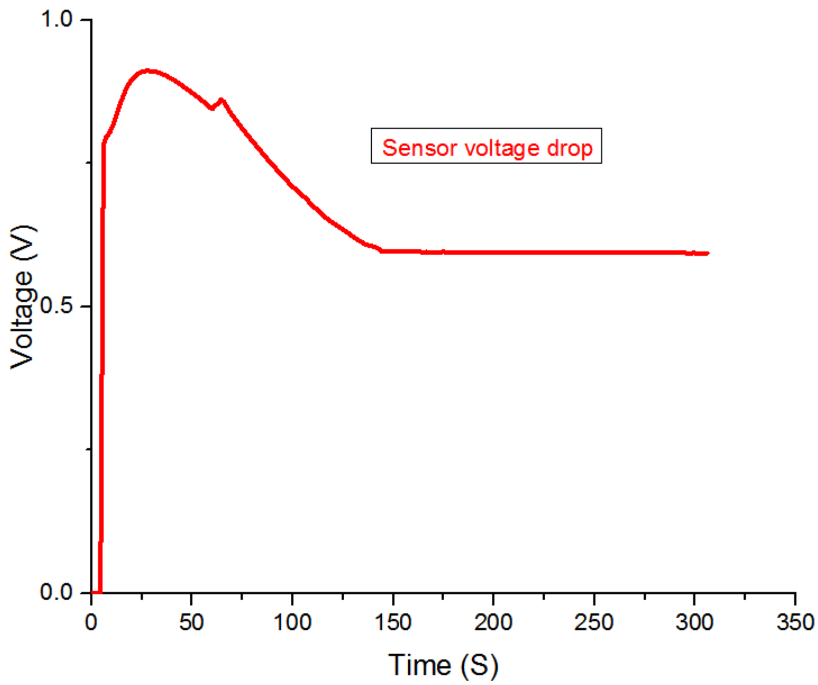

Figure 4.26: Measure Sensor voltage drop vs Time

This was the original challenge faced due to the starting current of the BLE, so to solve that challenge we added the delay. If it was found that the delay was still too short, we could use a larger capacitor value as to the 10uF which will take longer to charge and increase the delay. However, using the 10uF was good enough for the delay as the sensor was able to power the BLE on testing.

4.13 The In-play BLE Module Versus Nordic Nrf52832 BLE Module

Bluetooth Low Energy (BLE) is a wireless technology for exchanging data, over short distances, designed for Internet -of- Things era. As widely supported by wearable devices, BLE has the potential to become an alternative for indoor-tracking and proximity sensing.

An experiment using line of sight was conducted to compare the transmission performance of the In-play BLE module and the Nordic nrf52832 module. To achieved required ranged to test the signal strength of both BLEs, the E3 hall way showed in Figure 4.27 was adopted and the result of the experiments are presented in Table 2. From Table 2 (a and b) both BLE transmitted efficiently up to 43meters. Beyond 43m there was a signal lost from the Nordic BLE while the In-play BLE transmitted at the same signal strength up to 100m. The difference in transmitted signal strength was due to the difference in the antenna use in the design. The waveform of the received strength indicator (RSSI) over a range of 43m is shown in figure 4.28. Hence the In-play BLE became a better option for our application. It is cost effective, simpler in design integration and requires no programming.

Table 3: Transmission Performance of Nordic BLE and the In-play BLE

Nordic BLE

Distance (Meters)	Status for Beacon Activation	RSSI Value		Distance (Meters)	Status for Beacon Activation	RSSI Value
0	✓	-65, -67		24	✓	-93, -84
1	✓	-63, -71		25	✓	-91, -89
2	✓	-76, -79		26	✓	-88, -81
3	✓	-70, -76		27	✓	-88, -87
4	✓	-84, -79		28	✓	-94, -81
5	✓	-82, -92		29	✓	-81, -83
6	✓	-80, -87		30	✓	-93, -88
7	✓	-84, -80		31	✓	-88, -95
8	✓	-87, -90		32	✓	-92, -93
9	✓	-85, -86		33	✓	-97, -96
10	✓	-84, -77		34	✓	-91, -95
11	✓	-83, -76		35	✓	-94, -100
12	✓	-88, -81		36	✓	-97
13	✓	-85, -88		37	✓	-93
14	✓	-75, -78		38	✓	-96
15	✓	-85, -86		39	✓	-79, -84
16	✓	-91, -83		40	✓	-97
17	✓	-85, -83		41	✓	-94, -99
18	✓	-82, -85		42	✓	-98, -99
19	✓	-84, -92		43	X	----------
20	✓	-86, -80		44	X	----------
21	✓	-84, -86		45	X	----------
22	✓	-81, -85		46	X	----------
23		-85, -93		47	X	----------

(a)

Nanobeacon BLE

Distance (Meters)	Status for Beacon Activation	RSSI Value		Distance (Meters)	Status for Beacon Activation	RSSI Value
0	✓	-54, -60		24	✓	-98, -85
1	✓	-73		25	✓	-92, -88
2	✓	-70, -77		26	✓	-87, -86
3	✓	-76, -80		27	✓	-94, -92
4	✓	-76, -82		28	✓	-94, -98
5	✓	-76		29	✓	-92
6	✓	-72		30	✓	-102, -96
7	✓	-73, -75		31	✓	-96, -97
8	✓	-80, -85		32	✓	-90, -86
9	✓	-76, -80		33	✓	-97, -95
10	✓	-84, -91		34	✓	-92, -93
11	✓	-82, -90		35	✓	-98, -97
12	✓	-91, -83		36	✓	-92, -95
13	✓	-90, -87		37	✓	-97, -94
14	✓	-86, -79		38	✓	-100, -94
15	✓	-88, -79		39	✓	-98, -100
16	✓	-87, -91		40	✓	-93, -94
17	✓	-78, -85		41	✓	-98, -97
18	✓	-88, 90		42	✓	----------
19	✓	-85, -82		43	✓	----------
20	✓	-88, -85		44	✓	----------
21	✓	-87, -88		45	✓	----------
22	✓	-90, -88		46	✓	----------
23	✓	-90, -93		47	✓	----------

(b)

Figure 4.27: E3 hall way for range testing of Nordic BLE versus In-play BLE.

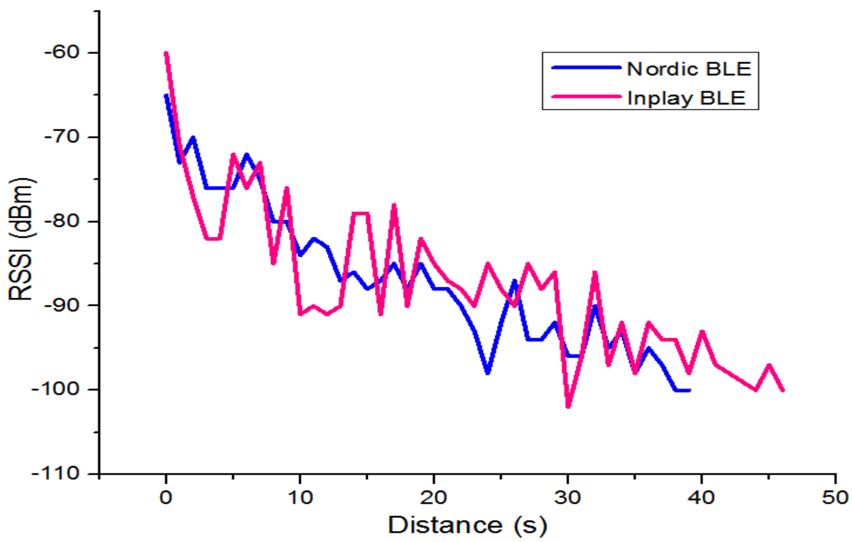

Figure 4.28: RSSI trend of the In-play BLE up to 100m

The maximum range obtained from In-play Nano-Beacon BLE up to 100m is dependent on the class of the antenna used for the design [49]. An important feature of BLE technology is that the Received Signal Strength Indicator (RSSI), defined as the ratio between power of the transmitter and that of the receiver, is available to the users (IEEE 802.11 standard). However, the BLE signal strength can be highly unstable and its strength is influenced by a number of experimental factors such as, the output power of the transmitter, the sensitivity of the receiver and the physical obstacles in transmission paths which meant have affected the performance of the Nordic Nrf52832 BLE.

The distance estimate based on the RSSI measurement is the relationship between the RSSI and the distance d is usually described by an exponential model [57]

$$RSSI_{dBm} = -10 \,.n.\, Log_{10\,(d)+A} \quad (4.1)$$

Where n is a real number between 2 and 4, which depends on the specific environmental conditions; A is the RSSI value reads at an arbitrary selected distance.

4.14 Summary

From the test analysis, when the PCB was powered from the DMM machine, the voltage divider was able to turn the V_{bat} and Chip-enable when it is high above the threshold. The components were selected to meet the design requirement. Although the current limiting resistor required to limit the generated from 1.5V to 0.7V below the voltage required for the system. However, it was removed because it prevented the proper charging of the storage capacitor and which resulted in immediate availability of voltage to the BLE.

The performance comparison between the Nordic Nrf52832 BLE and the In-play BLE informed the choice of In-play BLE over the former. The voltage range of the In-play is from 1.1V to 3.6V which correspond to the voltage generated by the sensor. This helped to further reduced cost by eliminating the boost converter to have a more simplified and cost effective design. The test result also showed the In-play BLE has a longer transmission range of 100m compared to the Nordic Nrf52832 BLE which is only able to transmit up to only 43m. However, the effective performance of the developed wetness detector system was achieved.

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The design and implementation of a low-cost wet diaper detector based on smart phone and In-play BLE has been presented in this thesis. A simple fabricated printed circuit board (PCBs) with selected embedded BLE IC (In-play Nano-beacon) chipset to transmit signal once wetness is detected is also presented. The BLE was tested with the proposed wetness detector sensor and the result showed that the wetness detector is capable of wirelessly sending notification to a smart-phone immediately wetness is detected.

The input to the BLE IC chipset is a voltage flexible wet sensor that generates 1.5V at some micro-amps (200uA) to the BLE chipset which consumes a voltage range of 1.1V to 3.6V and a current of 2mA at 0dBm. To avoid a delay in supplying generated power to the BLE chipset when connected to the voltage sensor directly, a 470uF capacitor storage capacitor was connected across the BLE to store the generated voltage energy for instant availability to the BLE chipset for activation when threshold is exceeded.

A unique feature of the proposed diaper's wetness detector is a voltage-divider circuit that is developed and assembled with the BLE IC chipset for chip-enable of digital logic on Field Programmable Gate Array (FPGA) on the UART (Universal Asynchronous Receiver-

Transmitter) interface of BLE at the PCB frontend. It enables the BLE to transmit and send wetness notification directly to the smart-phone using line of sight over a distance of 43m.

An important consideration while designing the wet diaper detector unit was cost – effectiveness. The detector unit can be decoupled from the connector pin and reused. The detector unit can also be fabricated on a very small reusable PCB to further minimize cost. The concept of the prototype was implemented as the wetness detector transmit functionality by sending notification to the smart- phone.

5.2 Recommendation for Future Work

This project has been design and tested on an external PCB wetness detector circuit. It can further be developed by burning the code on to the In-play BLE IC CHIPSET embedded on the fabricated PCB. This can be an interesting area for future work. Another interesting area of the project in which the design can be improved upon is reduce the size and use fewer components to make it more cost effective.

References

[1] Y. E Simik, Feng Chi, Randa S. I Saleh and Abdeldime M. S. Abdelgader, "A Design of Smart Diaper Wet Detector using Wireless and Computer," *Proceedings of the World Congress on Engineering and Computer Science San Francisco,* pp. pp. 1-5, October 2015.

[2] H. Prasad, P. Srivastava, and K. K. Verma, "Diapers and Skin Care," *Merits and Demerits. The Indian Journal of Pediatrics* , vol. Volume 71, pp. pp. 907-908, October 2014.

[3] W. A. Jabbar, S. Hamid, A. A. Almohammedi, R. M Ramli, M. Ali, "IoT-BBMS Internal of Things-Based Baby Monitoring System for Smart Cradle," *IEEE Access,* vol. Volume 9, no. issue 7, pp. pp. 64-76, July 2020.

[4] D. Pamela. K.Gerard, K. Stanley, "Wet Diaper Alert System for Bedside Patients with Wireless Communication to Nursing Station Via Smart Diaper Mobile Application," *International Journal of Pure and Applied Mathematics,* Vols. Volume 118 No. 20,, pp. pp. 3681-3685, July 2018.

[5] M. Y. E Simik, F. Chi and C. Li Wei, "Design and Implemenatation of a Bluetooth Based MCU and GSM for Wetness Detection," *IEEE Access,* vol. Volume 7, pp. pp. 21851-21851, July 2019.

[6] X. Nie, Z. Song, J. Yang, Z. Dengyun, M. Yin, X. Duan, B. Jiao, "Design and Implementation of a Real Time Wireless Monitor System for Uninary Incontinence," *International Journals of Communications, Network and System Science,* vol. Volume. 10 , pp. pp. 252-263, May 2017.

[7] L. M. Ang, S.H. Ow, K.P.Seng, Z.H.Tee, B.W.Lee, M.K.Thong, P.J.H.Poi,S.Kunanayag, "Wireless Intelligent Incontinence Management System Using Smart Diapers," *2008 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology,* pp. 69-72, May 208.

[8] M. Falk, S. Cirovic, P. Falkman, J. Sjoholm, O. Hydbom, S. Shleev, "Wireless Biosensing of Analytes in Human Urine: Towards Smart Electronics Diapers," *Journal of Biosensors, Biomarkers and Diagnostics* , pp. pp. 1-6, September 2019.

[9] D. S . Driver, "Perineal Dermatitis in Critical Care Patients," *Critical Care Nurse,* pp. pp 42-46, August 2007.

[10] N. Scheinfeld, "Diapr Derimatitis," *American Journal of Clinical Dermatology,* vol. Volume 6, no. Issue 5, pp. 273-281, October 2005 .

[11] L. b. P. "Shop the Lumi by Pampers Connected Care System", " [Online]. Available: http://www.pampers.com/en-us/lumi/connected-care-system.," [Accessed: 23-June-2021].

[12] S. P. S. M.M.Loranty, "Tundra vegetation effects on pan-Arctic albedo," *Enivronmental Research Letters,* May 2011.

[13] "BLE Advertising Channels-BLE Data Channels List," *[Online]. Available: https://www.rfwireless-world.com/Terminology/BLE-Advertising-channels-and-Data-channels-list.html.*

[14] J. Abraham., "Understanding Bluetooth Advertising Packets," *[Online]. Available:http://j2abro.blogspot.ca/2014/06/understanding-bluetooth-advertising.html,* 2014.

[15] M. Waters, ""The smart diaper is coming. Who actually wants it"," *[Online]. Available: https://www.vox.com/the-goods/2019/5/18525487/smart-diaper-huggies-monit-pampers-alert-poop-pee.,* [Accessed: 23-June-2021].

[16] S. Rahman, C. Choi, Y. Pil Kim, S. Kim, and J. Choi, "A Low-Cost Wet Dipaer Detector Based on Smart phone and BLE Sensor," *International Journal of Applied Engineering Research,* vol. Volume 12, pp. pp. 9074 - 9077, 2017.

[17] ""CVICLOUD. "[Online].Available:https://www.cvicloud.com/en/solution/opro9-accessories/smart-diaper.," [Accessed: 25-June-2021.

[18] M.Y Simik, F.chi, A.M Abdelgader, R.S Saleh,, "Automated Alarm System for Diaper Wet using GSM," *IEEE 17th International Conference on Computational Science and Engineering,,* pp. pp 1799-1803, 2014.

[19] W. Yu, W. Seo, T. Tan, B Jung, B. Ziaie,, "A Diaper -Embedded Disposable Nitrite Sensor with Integrated on-board Urine-Activated Battery for UTI Screening,," *in , 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC),* pp. PP. 303 - 306, 2016.

[20] S. Pankhuri, Sai Nithin, R. Kantareddy, R. Bhattacharyya, S.E. Sarma, Joshua E. Siegel,, "Low-Cost Diaper Wetness Detection using Hydrogel-Based RFID Tags," *IEEE Sensors Journal,* 2019.

[21] H.E Nilsson, J. Siden, M. Gulliksson, , "An incontinence alarm solution utilizing RFID based sensor technology in:," *2011 IEEE International Conference on RFID-Technology and Application,* pp. pp. 359 - 363, September 2011.

[22] M. A. Ziai, John C. Batchelor , "Smart Radio-Frequency Identification Tag for Diaper Moisture Detection," *Healthcare Technology Letters,* vol. Volume 2, no. 1, pp. pp. 18-21, February 2015.

[23] J. Siden, A.koptioug, and M. Gulliksson,, "The Smart Diaper Moisture Detection System,," *IEEE MIT-S International Microwave Symposium Digest Sundsvall, Sweden Mid-Sweden University, Electronics Department,* vol. Volume 2, pp. pp. 1-4, July 2004.

[24] S. H Lin, Kaimi Kajiyama, Tien Hsiang Wu,, "The difference of a smart diaper for special needs adults," *Journal of Textile Engineering and Fashion Technology,* vol. Volume 3, no. Issue 4, pp. pp. 674 - 677, November 2017.

[25] F. Chi, R.S.I. Salah, M.Y.E. Simik, Abdeldime.M.S. and Abdelgadar, "Smart Diaper Wet Detector using Wireless and Computer," *Proceedings of the world congress on Engineering, San Francisco, USA,* pp. pp. 1-5, 2015.

[26] S. Z. Sajal, Y. Atanasov, B. D. Braaten, "A low cost flexible passive UHF RFID tag for sensing moisture base on antenna polarization," *2014 International Conference on Electro/Information Technology (EIT),* pp. pp.542-545, June 2014.

[27] "Smart Diaper Nappy Technology," *[Online]. Available:https://www.dezeen.com/2020/03/23/mit-smart-diaper-nappy-technology*.

[28] B. Sup Shim, W. Chen, C. Doty, C. Xu, and N. A.Kotov, "Smart electronic yarns and wearable fabrics for human biomonitoring made by carbon nanotube coating," *2008 American Chemical Society,* pp. pp. 4151-4157, November 2008.

[29] N. Anindya, S. Chandra, Mukhopadhyay and J. Kosel,, "Wearable flexible sensors," *A Review IEEE Sensors Journal* , pp. pp. 1-14, 2017.

[30] A. Nag, A. I. Zia, X. Li, S.C. Mukhopadhyay and J.Kosel,, "Novel sensing approach for LPG leakage detection: Part I- Operating mechanism and preliminary results,," *IEEE Sensors Journal,* vol. Volume 16, no. Issue 4, pp. pp. 996-1003 , February 2016.

[31] A. Nag, A.I.Zia, X.Li, S.C. Mukhopadhyay and J.Kosel,, "" Novel sensing approach for LPG leakage detection : Part II: Effect of particle size, composition and coating layer thickness",," *IEEE Sensors Journal* , vol. Volume. 16, no. Issue 4, pp. pp. 1088-1094, February 2016.

[32] S. Han, H. Peng, O. Sun, S. Venkatesh, K. Chung, S. C. Lau, Y. Zhou, and V. A. L. Roy , "Sensors," *Overview of the Development of Flexible Advanced Materials* , pp. pp. 1-22, July 2017.

[33] W. Y. Chang, T. H. Fang, H. J. Lin, Y. T. Shen and Y. C. Lin, , ""A large area flexible array sensors using screen printing technology"," *Journal Display Technology,* vol. Volume 5, no. Issue 6, pp. pp. 178- 183, June 2009.

[34] S. Patel, H. Park, and P. Bonato, "A review of wearable sensors and system with application in rehabilitation," *Journal of Neuro-Engineering and Rehabilitation,* vol. Volume 9, no. Issue 1, pp. pp. 1 - 7, November 2012.

[35] J. C. Costa, F. Spina, P. Lugoda, L. G. Garcia, "Flexible Sensors From Material to Applications," *Wearable Technologies, Sensor Technology Research Centre,,* February 2019.

[36] D, Guyomar, A. Badel, E. Lefeuvre, C. Richard,, "Towards energy harvesting using active materials and conversion improvement by non-linear processng,," *IEEE Transactions on ultrasonic ferroelectric and frequency control,* vol. Volume 52, no. Issue 4, pp. pp. 584-595, 2005.

[37] W. D. P. M. J. L. G. Y. D. Shen, "Moisture Enabled Electricity Generation: From Physics, Materials to Self-Powered Applications," *Adv. Mater,3,,* 2020, 2003722.

[38] C. Ju, and J. Liu,, "The basic principles of PCB wiring layout for switching power," *8th International Conference on Management and Computer Science (ICMCS) Atlantis,* vol. Volume 77, pp. pp. 624-627, January 2018.

[39] P. Chancerel, S. Rotter, "Recycling -oriented characterization of small waste electrical and electronic equipment," *Journal Waste Management,* vol. Volume 29, pp. pp. 2336-52, 2009.

[40] B. Willis, "Reflow soldering processes and troubleshooting SMT, BGA, CSP, and Flip Chip technologies solder," *Surface Management Technology,* p. https://doi.org/10.1108/ssmt.2003.21915aae.003., 2003.

[41] V. Fung and K. C. Yung, "An intelligent approach for improving printed circuit board assembly process performance in smart manufacturing," *International Journal of Engineering Business Management,* July 2020.

[42] C. F. Coombs , "Printed circuit handbook sixth edition McGraw-Hill Handbook," *[Online]. Available: https://openlibrary.org/books/OL7301368M/Printed_Circuits_Handbook.*

[43] A. C. Marques, J. M . Cabrera, and C. D. F. Malfatti, "Printed circuit boards: A review on the perspective of sustainability," *[Online] : Available: https://www.scribd.com/document/248850069/Printed-Circuit-Boards,* October 2013.

[44] M. V. Dongen and W. Serdijin, "Design of efficient and safe neural stimulators a multidisciplinary approach," 2016.

[45] J. Teel, "Linear and switching voltage regulators," *[Online]. Available: https://predictabledesigns.com/ linear-and-switching-voltage-regulators-introduction/.*

[46] Kaiser, "Resistor handbook," *[Online] . , www.analog.com/library/analogDialogue/archives/322/Ask Engineer.html..*

[47] "Resistor term glossary," *[Online]. Resistor Term Glossary at www.prpinc.com/pdf/Glossaryof Terms.pdf.*

[48] D. Su, S. Xie, F. Dai, Y. Liu and Y. Jia, "Theory and method of quantification design on system level electromagnetic compatibility," *[Online]. Available :https://www.vitalsource.com/products/theory-and-methods-of-quantification-design-on-donglin-su-shuguo-xie-fei-v9789811336904,* pp. pp. 54-55, 2019.

[49] "Antenna Design and RF layout Guidelines," *[Online]. Available: "https://www.cypress.com/file/136236/download".*

[50] D. Basu, "Dictionary of pure and applied physics," *[Online]. Available: https://www.routledge.com/Dictionary-of-Pure-and-Applied-Physics/Basu/p/book/9780849328909,* p. 382, 2000.

[51] "Wireless communications systems," *[Online]. Available: http://www.physicsandradioelectronics.com/blog/elements-of-a-communication-system/.*

[52] M. H. Rashid, "Power electronics,circuits, devices and applications, Third Edition, Pearson Education, Inc, 2004," *[Online]. Available: https://easyengineering.net/power-electronics-circuits-devices-applications-by-rashid/.*

[53] J. Feng, M. Xiao, M. Hui, Z. Shen, D. Tian, Y. Hang, C. Duley, W. W. Zhou and N.Y, "High Performance Magnesium-Carbon Nanofiber Hygroelectric Generator Based on Interface-Mediation-Enhanced Capacitive Discharge Effect.," *ACS Applied Materials and Interfaces,* 2020,12,24289-24297.

[54] Inplay Nano-Beacon, "[Online]. Available: https://inplay-launches-worlds-smallest-software BLE".

[55] Nordic_Semiconductor-NRF52832-CIAA-R-datasheet.pdf, "[Online]. Available: https://www.nordicsemi.com/products/low-power-short-range-wireless/nRF52832/GetStarted.," [Access 25 June 2021]..

[56] A. .. B. M. H. .. L. C. H. .. H. M. E. .. V. D. M. D. .. V. R. M. J. .. D. .. G. K . Van Hoeck MD, "Urine Output Rate and Maximum Volume Voided in School-Age Children with and without Nocturnal Enuresis," *The Journal of Pediatrics,*, vol. 151, no. 6, pp. 575-580, December 2007,.

[57] B. L. S. L. a. W. C. E. Lau, ""Enhanced RSSI-based high accuracy real-time user location tracking system for indoor and outdoor environment"," vol. 1, no. No. 2, June 2008.