Tampere University

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INTEGRATION AND TESTING OF AN ENERGY AUTONOMOUS, LOW-POWER, FLEXIBLE WIRELESS SENSOR NODE

Master of Science Thesis
Faculty of Information
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ABSTRACT

Lakshitha Pasan Geesara Ekanayake: Integration and Testing of an Energy Autonomous, Low Power, Flexible Wireless Sensor Node
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Internet of Things (IoT) and Internet of Everything (IoE) are becoming integral parts of our daily lives in this advanced society. With the rapid expansion of IoT and IoE, the number of smart devices that are connected is growing at a staggering pace. According to the regulations of the EU and other nations, the batteries of these IoE devices should also be recycled. Therefore, in the future, an increasing number of IoT and IoE devices will require alternative solutions to batteries. Energy harvesting from light and storage using supercapacitors is thought to be an excellent solution to this problem.

Lightning Sense, a research project funded by the Academy of Finland, aims to develop "energy autonomous wireless sensor node powered by light energy harvesting and storage" to resolve this issue. This thesis focuses mainly on the research that was conducted into the designing, fabricating, and testing of an antenna that is capable of to be utilized for the radio transmission of this specific IoT/IoE node. In addition to that, it dives into the topic of supercapacitors, among the components of the sensor node.

The research first fabricates and tests the laminated face-to-face supercapacitors in this wireless sensor node. Laminated face-to-face supercapacitors were made utilizing a graphite ink current collector, activated carbon electrodes, separator paper, and NaCl electrolyte, sealed with 3M adhesive paper. The Maccor 4300 test device was used to measure capacitance, leakage current, and equivalent series resistance (ESR), and the results were similar to those from the Lightening sense project.

The primary objective of this thesis was to design and test a printed flexible antenna that operates at 423 MHz and is compact enough to be integrated into a wireless sensor node. The antenna was developed using the " meander line" design principle and the CST Studio software for design and simulation. After extensive fine-tuning and parameter optimization, a miniature antenna design with acceptable performance at 432 MHz operation frequency was achieved. This design was fabricated using flexography and then measured. The similarity between test and simulation results confirms the functionality of this antenna design. This antenna and supercapacitor have been integrated into the final design of the sensor node.

This thesis demonstrated that it is possible to design a miniature flexible antenna with an operation frequency of 432 MHz and still achieve high performance. Finally, this Energy Autonomous, Low Power, Flexible Wireless Sensor Node can be viewed as a step toward the development of future IoT/ IoE devices that are environmentally friendly.

Keywords: Flexible Wireless Sensor Node, Antenna design, LightningSense Project, Supercapacitors

PREFACE

I was offered a full scholarship to Tampere University in Master of Science in Electrical Engineering, Wireless communications and RF Systems program. It goes without saying that I felt and still feel an overwhelming sense of gratitude for the opportunities that were provided to me as a direct result of such situation. Having the opportunity to take part in Tampere University's prestigious academic and research community has been a distinct honor.

This thesis was written as a part of the Academy of Finland funded project “LightningSense’ in collaboration between Tampere University and Aalto University. First and foremost, I would like to express my sincere gratitude to Prof. Donald Lupo, my supervisor, for giving me the opportunity to take part in this research study. I would also like to thank Dr. Behnam Khorramdel Vahed, Prof. Matti Mäntysalo, Dr. Maedeh Arvani and Dr. Jari Keskinen and all the other members of Laboratory for Future Electronics, Tampere University who supported and guided me throughout this research work. Special thanks to Dr. Jouko Heikkinen who has helped me immensely with the Antenna designing process.

I'd like to dedicate this thesis to the loving memory of my late father. This work is a testament to his unwavering encouragement, guidance, and inspiration throughout my academic pursuits. I would also like to express my gratitude to my mother, aunt, and friends for their love and support throughout this roller coaster ride. Receiving my master's degree has been a long journey with lots of up and downs, and I would not have accomplished that without all the encouragement I received.

Tampere, 28th of November 2023

Lakshitha Ekanayake

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LIST OF ABBREVIATIONS

2D	Two dimension
3D	Three dimension
1G	First generation of wireless communication technology
3G	Third generation of wireless communication technology
4G	Fourth generation of wireless communication technology
5G	Fifth generation of wireless communication technology
AC	Activated Carbon
AC	Alternating Current
ASIC	Application specific integrated circuits
DC	Direct Current
DSSC	Dye sensitized solar cells
ECG	Electrocardiogram
EDLC	Electric double layer capacitor
ESR	Equivalent series resistance
EU	European Union
FHE	Flexible hybrid electronics
FNBW	First-Null Beamwidth
Gbps	Gigabits per second
HPBW	Half power beamwidth
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IoE	Internet of everything
IoT	Internet of things
LCP	Liquid crystal polymers
M2M	Machine to machine communications
NaCl	Sodium chloride
PDMS	Polydimethylsiloxane
PET	Polyethylene
PP	Polypropylene
PV	Photovoltaics
OPV	organic bulk hetrojunction Photovoltaics
RF	Radio Frequency
RFID	Radio Frequency Identification
SC	Supercapacitor
UPS	Uninterrupted power supply
UV	Ultraviolet radiation
UAV	Unmanned aerial vehicle
VSWR	Voltage Standing Wave Ratio
WLAN	Wireless local area network
WSN	Wireless sensor network

LIST OF SYMBOLS AND VARIABLES

%	Percentage
A	Area of the conducting plates
a	acceleration
C	Capacitance
D	Directivity
D	Distance between the plates
dB	Decibel
dBi	Decibel isotropic
F	Farad
F	force
λ	Wavelength
Prad	Total radiated power
Pin	Total input power
U (θ, φ)	Radiation intensity in a given direction to E filed
Uo	Radiation intensity of an isotropic source
m	mass
mA	milliampere
mm	millimetre
P	Power
Q	Charge
R	Resistance
U	Radiation intensity
V	Voltage
W	Engery
µm	micrometre
ε_0	Dielectric constant of vacuum
ε_r	Relative dielectric constant of the insulating material
°C	Celsius
S_{11}	Return loss parameter

1. INTRODUCTION

1.1 Background

Since the beginning of this millennium, there has been a rapid advancement in the field of science and technology. As a result of this, communication has become a vital part of our lives. In the last two decades, communication technologies such as Wireless Communication, Satellite Communication, Optical fiber communications has shown unprecedented growth. Mobile communication technologies have transferred from a voice driven technology to a data driven technology from 1st generation (1G) to 5th generation (5G) of mobile networks. Higher data speeds became available as a result of 3rd generation (3G) and 4th generation (4G) of mobile networks in 2001 and 2006. By the end of 2020, 93% of the World population had access to a mobile network [1]. As shown in the figure 1, close to 85% of the World population had 4G network coverage by the end of 2020.

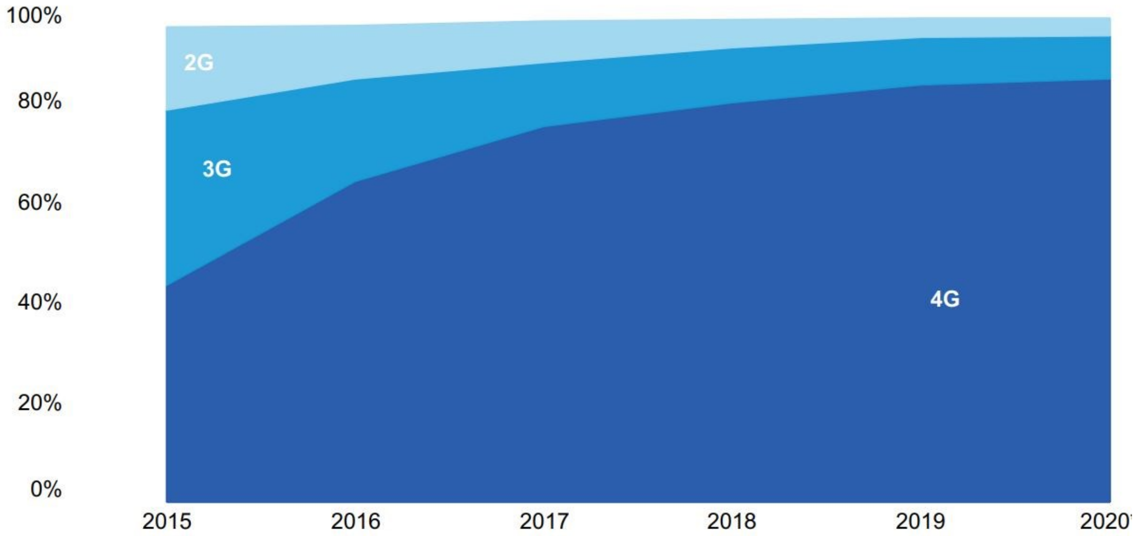


Figure 1. *Population Coverage by type of mobile networks between 2015 – 2020 [1]*

With this development, internet has become a significant part of our daily routines. This evolution enabled the possibility of providing higher data rates (up to 20 Gbps) with low latency for a higher number of users. As a result of this higher data rates and higher capacity, technologies like “Internet of Things” (IoT) and “Internet of Everything” (IoE) continues to grow at an exponential rate. Massive IoT connections are predicted to increase by 80% during 2021 and expected to reach close to 330 million connections [2]. As we can see from figure 2, this trend is supposed to increase even more in the upcoming years with an estimated number of active IoT device connections of 30.9 billion in 2025 [3]. As IoT and IoE continues to evolve, the number of connected smart objects will also increase in a rapid pace. One major issue of IoE is the energy supply. According to the law of EU and several other countries, batteries are required to be recycled due to environmental issues. Therefore, alternative solutions to batteries are required for increasing number of IoT and IoE devices in the future. It is believed that a combination of energy harvesting from the environment and storage in environmentally friendly supercapacitors is the most prominent way to tackle this issue moving forward.

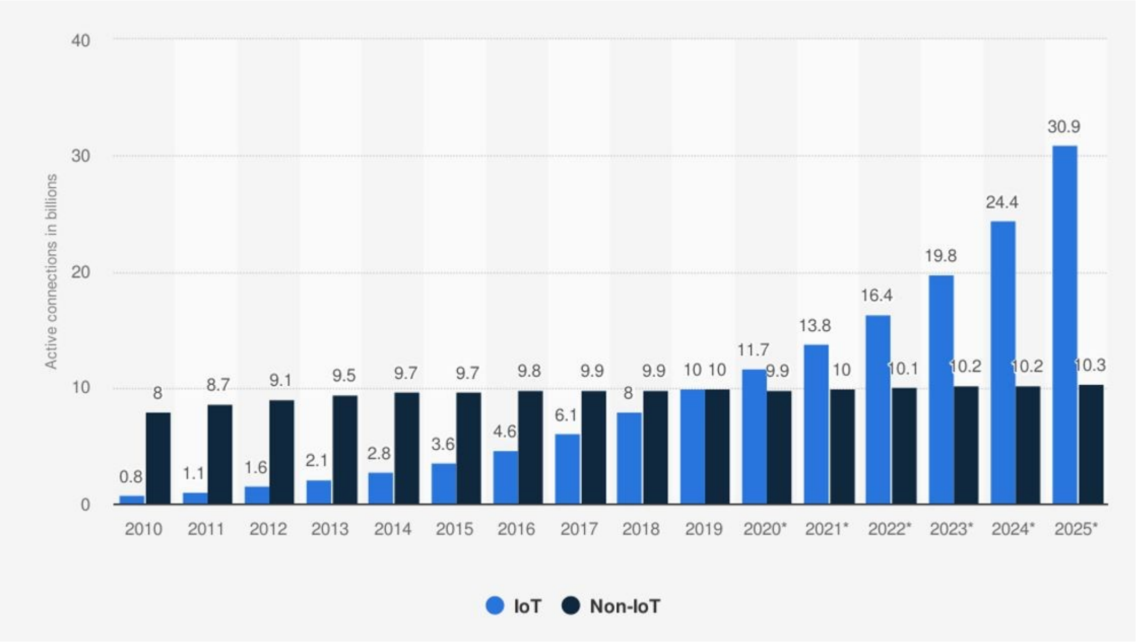


Figure 2. *Number of worldwide connections of active IoT and Non-IoT devices from 2010 to 2025 (in billions) [3]*

1.2 Motivation and Scope

Light is considered as one of the most efficient sources for energy harvesting in both indoor and outdoor environments. Photovoltaics (PV) is the 3rd renewable energy source in the world after hydro and wind powers in terms of global capacity. Third generation of PV technology such as organic bulk heterojunction PV (OPV) is a promising approach to light energy harvesting due to its characteristics, performance in indoor environment and cost effectiveness. A key feature of an energy harvesting systems is the ability to operate during the periods when there is no available energy.This requires an internal storage unit to store energy to operate during such scenarios. Printed Supercapacitors are considered as a feasible option for these IoE devices due to its better cycle life, low cost and environmental friendliness. Furthermore, this kind of IoE system requires several other technologies such as energy constrained power management, low energy radio communication system, Antenna etc.

The Academy of Finland research project “ LightningSense “ has been launched as an attempt to overcome the above-mentioned issues and develop an “energy autonomous wireless sensor systems powered by light energy harvesting and storage” [4]. The primary goal of this research project is to research on individual components of the future IoE systems and integrate those elements together into a wireless sensor node that is flexible, lightweight, compact, environmentally friendly and energy autonomous. Figure 3 illustrates the block diagram of the IoE node envisioned in the Lightning Sense project.

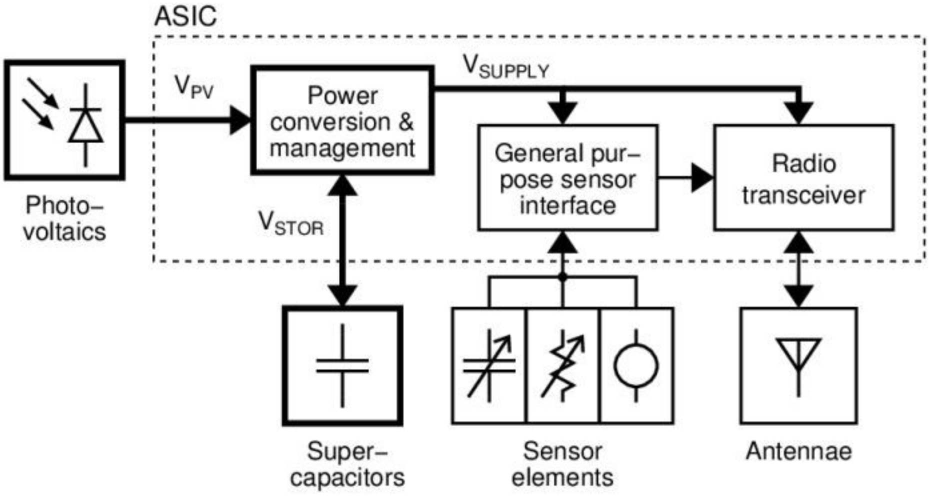


Figure 3. *System block diagram concept of the IoE node [4]*

This thesis discusses primarily the research done on designing, fabrication and testing of an antenna which can be used for the radio communication of this particular IoE node. It also discusses about the supercapacitors which are used in the sensor node.

1.3 Objectives

The main goals of this thesis are listed below

- Designing a printed miniaturised flexible antenna which can be integrated into the wireless sensor node
- Comparison of simulation results and the experimental results of the printed miniaturised flexible antenna
- Fabrication and testing of the laminated face to face supercapacitors.

1.4 Structure of the Thesis

Following the introduction chapter, the remaining four chapters of this thesis are organized as follows.

Chapter 2 is an overview of the theoretical background related to this thesis. It covers about overall concept of energy autonomous, low power, flexible wireless sensor nodes. Then, it addresses about the components of the sensor node such as energy module, supercapacitors, antenna. This chapter also presents the research process on system integration and testing of the sensor node.

Chapter 3 presents the experimental and modelling methods with sub chapters describing fabrication and testing of supercapacitors as well as designing, simulating, fabricating, and testing methods of the flexible antenna.

Chapter 4 is devoted to modelling and experimental results of the supercapacitors and antenna. It further discusses about the results and compare the experimental results of the antenna with the simulation results.

Chapter 5 is the conclusion chapter of this thesis which also discusses the possible further research work related to this thesis.

2. THEORETICAL BACKGROUND

2.1 Wireless Sensor Nodes

Sensors detect and record real-world events and convert them for processing, storage, and execution. Sensors, which are integrated into a wide variety of devices, equipment, and settings, give a significant societal benefit. They can help prevent disastrous infrastructure malfunctions, protect natural resources, enhance efficiency, improve safety and security, etc [5].

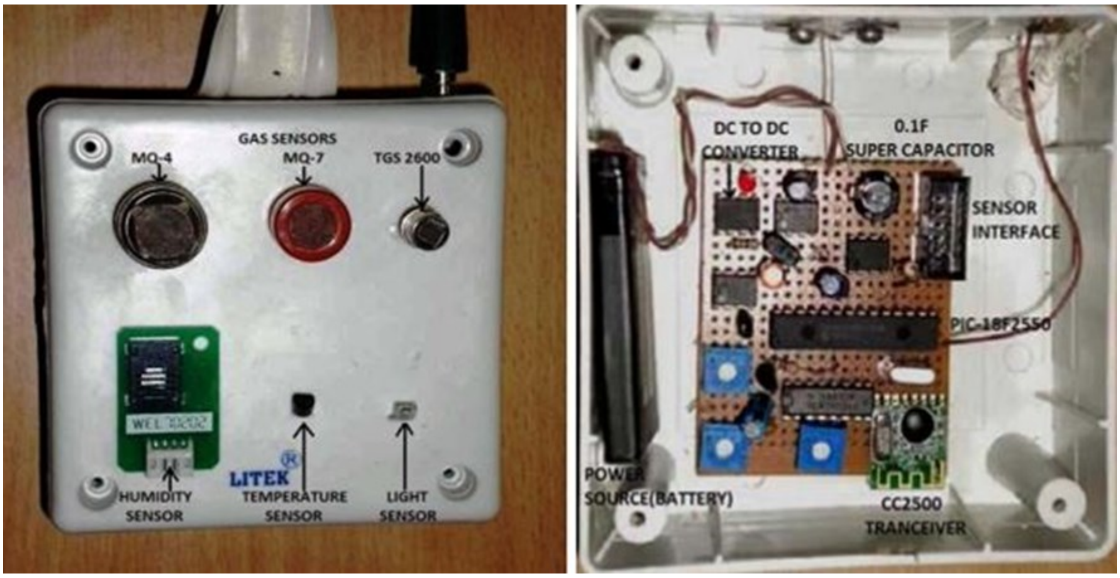

(a) (b)

Figure 4. *Wireless sensor node:(a) External appearance , (b) the detailed node architecture [6]*

Wireless sensor nodes serve as the brains of a wireless sensor network (WSN). Sensing, computing, networking, and energy all have their own dedicated subsystems within the node. A typical sensor node is comprised of several sensors that are processed and controlled by a centralized processing unit. A sensor node may be used to execute a variety of tasks, based on the node's resources available [6]. Sensor nodes in a WSN can monitor a single physical phenomenon or integrate many sensing approaches. Also, their data rates and latencies can vary depending on whether they communicate utilizing ultrasound, infrared, or radio frequency technologies. While simple sensors just gather and transmit data about their surroundings, more complex devices may also process and aggregate data [5]. The figure 4 above depicts a typical wireless sensor node with temperature, humidity, light, and three gas sensors [6].

2.1.1 Applications of Wireless Sensor Networks

There are numerous applications for wireless sensor networks. Some are futuristic, while the majority are practical. This section will discuss some of these applications.

Healthcare Applications

The Internet of Things is transforming the healthcare business through its unique devices and human-to-human interaction, which enables the implementation of seamless healthcare solutions. Health and fitness bands and other IoT devices like blood pressure and heart rate monitors enable personalized assistance. This is especially true for senior people, who now have the option of continuous health monitoring. The Internet of Things has allowed doctors to better track their patients' health and historical data. They can keep track of patients' commitment to treatment plans as well as potential medical emergencies. IoT in healthcare enables healthcare professionals to be more prepared and responsive. IoT in healthcare allows medical professionals to be more proactive and attentive. Doctors can use information collected through IoT devices to enhance care for their patients.[5].

Smart Agriculture Applications

Smart agriculture maximizes the usage of resources to enhance the productivity of farms. The use of sensors to collect environmental and machine data and providing them to farmers in order for them to make smart decisions about all aspects of their operation, whether it be livestock or crop farming. The ultimate goal is to maximize crop quality and yield while minimizing waste and optimizing the use of human labour. In addition to enhanced cost management, waste reduction and water conservation, increased production control will assist farmers thrive their agriculture business and result in greater income [5].

Military Applications

Military applications utilize wireless sensor networks. Data gathering, enemy tracking, combat monitoring, and target classification are military applications. [7][8]. A wide range of sensors are available for detecting Chemical, Biological, Radiological, Nuclear and Explosive materials. WSNs' architectural flexibility also allows them to adapt to different requirements. For example, large-scale WSNs with thousands of nodes are utilized in warfare operations [9].

Environmental Monitoring Applications

WSNs can be used to improve environmental applications that require constant monitoring in hostile and isolated places. Water, air, and emergency alerts are the main environmental applications of WSNs [9]. These developments usually utilize several field sensors to continuously measure meteorological & hydrological parameters such as wind speed and direction. The majority of them change slowly over time, allowing for sparse sampling. Deployments, on the other hand, must survive long enough to catch fascinating phenomena, like as rock slides or avalanches, which are rare and difficult to forecast [10].

WSN are also used in emergency services and indoor environmental monitoring. Most countries mandate fire and smoke detection in buildings. Large buildings must also have exit light signals. In a fire, these two systems do not work together. Sensor networks in buildings can properly integrate these two systems. Temperature, light, air streams, and indoor air pollution may all be monitored to provide optimal control of the indoor environment. Overheating or cooling buildings waste electricity. WSNs are able to help homeowners effectively and economically use necessary equipment, improving resident health and well-being [11].

2.1.2 Architecture of Wireless Sensor Nodes

Within the node, there are specific subsystems for sensing, computing, networking, and energy. The designer has plenty of options for integrating these subsystems into a centralized and configurable node. The processor subsystem of the node determines the trade-off between flexibility and energy and performance efficiency. Microcontrollers, DSPs, ASICs, and FPGAs are just a few examples of the numerous processor types currently on the market. Figure 5 shows an integrated wireless sensor node subsystem. Power subsystem interconnections are not displayed.

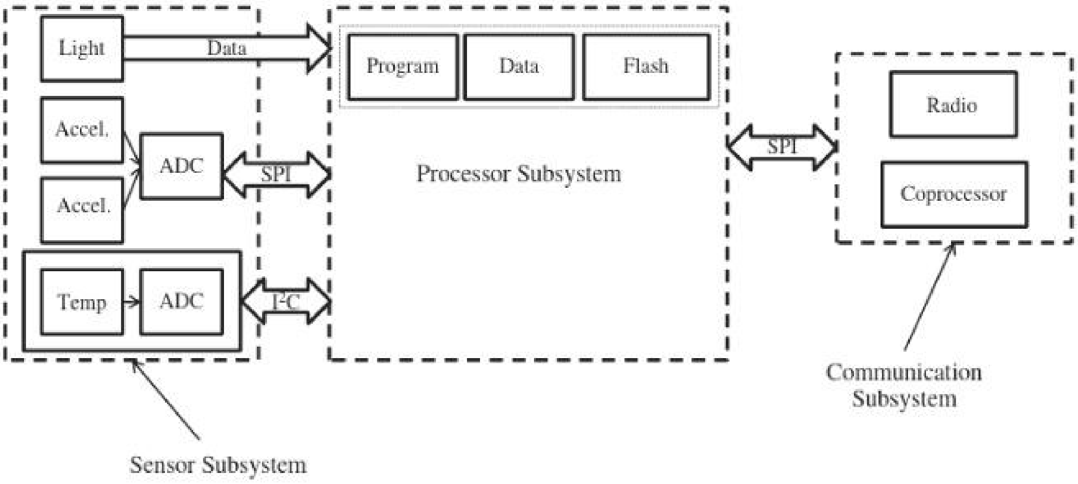


Figure 5. *An overview of wireless sensor node architecture [5]*

The sensing module includes a number of physical sensors and an analog to digital converters. The sensors establish a link between the virtual and physical worlds. The sensing subsystem can be connected to the processer in a variety of ways. The communication and multiprocessor modules can be connected in a number of ways. The communication module is the most energy intensive. Most industrial transceiver devices are capable of switching between active, idle, & sleep states. The processor module links all other modules and some devices. It performs sensing, communication, and self-organizing commands. It includes a Processor, memory, and an internal clock. The power subsystem is responsible for supplying power to all other subsystems [9][5].

2.1.3 Printed Flexible Wireless Sensor Nodes

Wireless sensor network applications require low-power and efficient communication protocols. Additionally, sensor nodes should be miniaturized and deployed in huge quantities, requiring cost-effective and environmentally friendly substrates for industrial manufacturing [12][13] [14]. These devices must be extremely compact and compatible with a wide range of surface contours. These problems demand technological sequences and remedies that challenge contemporary design principles. IoT envisions data being sensed in every application and location [15]. The required devices must be compact, power-efficient, and flexible or bendable. This is the point where the concept of flexible electronics comes in. The global market for flexible designs in consumer electronics, medical and healthcare, automotive, aerospace, and defence is expected to surpass 42.48 billion USD by 2027 [16][17].

"Flexible hybrid electronic" (FHE) is an emerging method that aims to integrate the best aspects of flexible and traditional electronics, bringing advantages as well as challenges. Printed electronics are a type of electronics that are characterized by their ability to be printed on flexible substrates. The printing process is similar to that used in graphical art, in that electrically functioning electronic or optical inks are printed on the substrate, resulting in passive or active circuit elements. Printed Electronics are cheaper than standard Silicon integrated circuits (ICs) which is important for many applications like Radio Frequency Identification (RFID) [18].

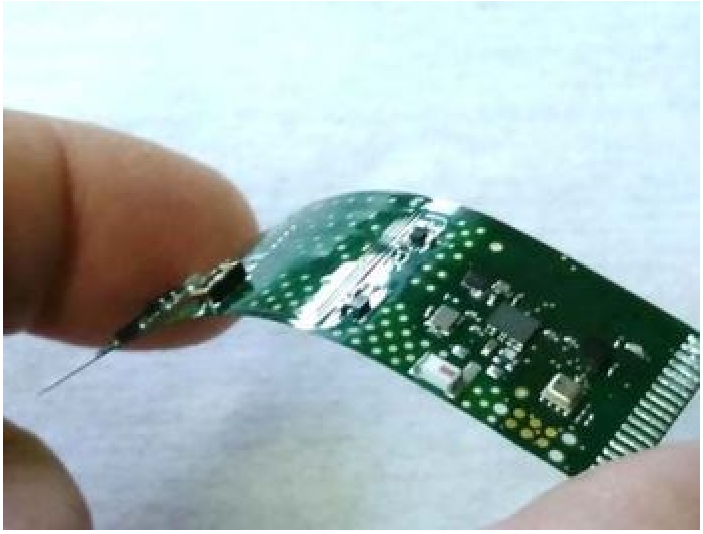


Figure 6. *A fabricated printed flexible wireless sensor node [17]*

Thus, printed flexible wireless sensor nodes are in high demand for future IoT/IoE applications. The thickness, size, and flexibility of the physical platform are critical in these applications. Figure 6 depicts such a sensor node. The sensor node was designed for flexibility and versatility. The hardware is mounted on a thin polyimide substrate for physical and mechanical flexibility [17]. Similarly, a research on fully integrated wireless modules on organic substrates demonstrates the integration of a two dimensional sensor and a RFID tag on paper [19].

2.2 Energy Harvesting and Storage

Advancements in science and technology have enabled the implementation of wireless sensor network (WSN)-based automation systems at a minimal cost. WSNs, as described in 2.1.2, can be used for a number of applications. Sensor nodes gather information and transfer it to a receiver, who could be an end user, a central control unit, or one of the operators. Operational lifespan of the sensor nodes are restricted since they are often battery-powered devices [20][21].

Energy harvesting has emerged as an ideal energy source for these kinds of purposes. Replaceable or rechargeable batteries are not always ideal given the huge number of devices and dangerous components contained in batteries. Renewable energy harvesting is also a crucial strategy for preserving the environment. For instance, energy can be harvested from light, changes in temperature, motion, and radio waves. Photovoltaic cells, antennas, thermocouples, and piezoelectric harvesters can capture light, radio frequency, thermal, and motion energy. Energy harvesters should be regulated by a circuit to convert DC to AC or vice versa and stored in supercapacitors or batteries. Supercapacitors provide greater advantages than batteries for long-term operation due to its cyclability [22][23].

When it comes to outdoor environments, light harvesting has the largest power output of any technology. Light is also used on a large scale in the grid-scale production of energy. [24][25]. A solar cell transforms sunlight into electricity. To compete with conventional sources, it must be affordable and reliable. To enhance solar cells, numerous technologies and materials, such as thin-film solar cells, organic solar cells, dye-sensitized solar cells (DSSC), and crystalline silicon solar cells, are explored [26][27]. PV cells have been researched since 1950, and they are now widely used in commercial applications [28]. Figure below illustrates an example of an energy harvesting system. As indicated, solar cells can harvest energy from light. The harvested energy is utilized to power a transceiver for communications. A communication link can be formed between the transceiver (TCVR A) and the distant transceiver (TCVR B). Generally, the transceiver stores excess energy harvested to ensure smooth operation in the event of a power failure or similar situation [20].

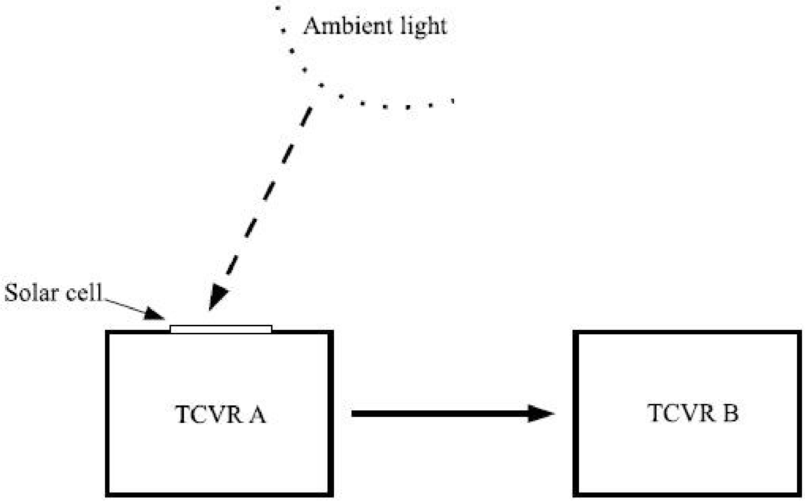


Figure 7. *A solar energy harvesting system that contains a harvesting link & a communication link [20]*

2.3 Supercapacitors

This chapter covers the basic principles of supercapacitors, which are necessary to grasp the supercapacitor design and testing achieved in this thesis.

2.3.1 Introduction to Supercapacitors

To fulfil the world's expanding energy requirements, we must pursue alternate, renewable energy sources to combat climate change, fossil fuel depletion, and unequal energy distribution. To adapt to this shifting energy paradigm, accessible, cost-effective, and reliable energy storage methods that enable energy harvesting from renewable energy sources like wind power, tides, and sunshine must be developed and implemented. Supercapacitors, often known as SCs, are a type of energy storage device that, in terms of performance, falls somewhere between capacitors and batteries. Due to their unique qualities, such as high power densities at reasonably high energy densities and long cycle life, supercapacitors have grown rapidly as electrochemical energy storage devices [29]. A comparison between supercapacitors and lithium batteries reveals that extremely high-power lithium batteries are a very beneficial choice for applications requiring high energy density and peak powers that can be provided without the usage of extra storage systems. Their shortcomings include a short life cycle and a rapid rise in system temperature during performance. Supercapacitors outperform high-power lithium batteries in terms of power density and life cycle. Their limitation is their energy density [30]. Thus, supercapacitors can be utilized in applications needing large power peaks along with lengthy cycle times.

2.3.2 Supercapacitor Fundamentals

A capacitor stores energy in the form of an electric field. A conventional capacitor consists of two conductor plates separated by an insulating substance. Electrochemical capacitors store energy as an electric field between electrodes and electrolyte. The diagram below depicts the fundamental layout of a supercapacitor.

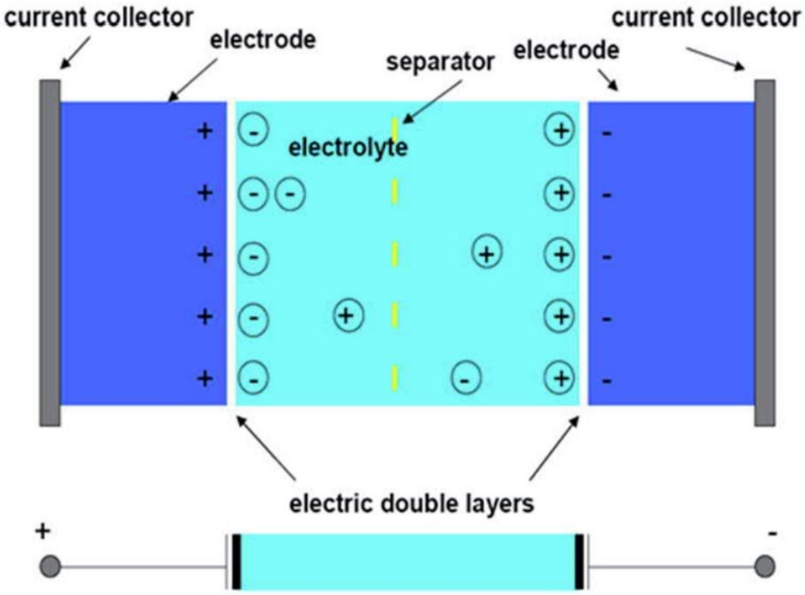


Figure 8. *Structure of a Supercapacitor [31]*

The preceding figure illustrates two capacitors between each electrode and electrolyte. The following equation can be used to determine the value of a capacitor.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

ε_0 - Dielectric constant of vacuum

ε_r - Relative dielectric constant of the insulating material

C – Capacitance

A - Area of the conducting plates

d - Distance between the plates

When a voltage is applied between the electrodes, the electrolyte's ions migrate and create electric double layers, which balance the electrode's charge with a layer of oppositely charged ions. Electrochemical processes require a voltage below the limit to allow ions to accumulate electrostatically on the electrode surface. The double layer of each electrode acts as a plate capacitor with molecular dimensions between the charged layers. Distance between plates inversely affects plate capacitor capacitance. It indicates that the capacitance is really high. The capacitance is even higher because the porous electrode material has a lot of surface area, which makes it even bigger [32][33][23]. In a supercapacitor, two "capacitors" comprising double layer electrodes are connected in series, with the electrolyte acting as an ionic conductor between them. The equation below calculates total capacitance C from electrode capacitances C1 and C2.

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

C1 and C2 can theoretically be determined utilizing electric double layer models. The total capacitance is half the sum of C1 and C2 if they are equal. If there is a large disparity, the total capacitance will be close to the smaller value. Anions are often larger than cations. As a result, even though the electrodes are the same and symmetric, C1 and C2 are typically different because smaller ions can be positioned closer to the electrode surface [32][22].

2.3.3 Types of Supercapacitors

There are three distinct types of supercapacitors, each with a unique mechanism for storing energy [29]. They are,

1. Electrochemical double-layer capacitors (EDLC)
2. Pseudocapacitors
3. Hybrid supercapacitors.

Electrochemical double layer capacitor (EDLC)

EDLCs have an electrolyte, separator, and two carbon-based electrodes. EDLCs are capable of storing charge via either an electrostatic approach or a non-Faradic method.

In the non-Faradic method, no charge is transferred between the electrode and the electrolyte [29]. EDLCs store energy using electrochemical double layer concept. When a voltage is applied, charge accumulates on the electrode surfaces, and the attraction of opposite charges occurs due to the difference in potential, resulting in ions in the electrolyte diffusing over the separator and into the pores of the opposite charged electrode [34][35]. A second layer of charge is produced to prevent ion recombination at the electrode. Energy density in EDLCs is improved by the double layer, the larger specific surface area, and the shorter distances between the electrodes. In addition to enhanced power performance, the EDLCs' unique technique for storing energy permits exceptionally fast energy intake and delivery. [36].

Pseudocapacitors

Pseudocapacitors store charge using the Faradic process, resulting in a transfer charge between the electrode and electrolyte [37]. Pseudocapacitors have an advantage over EDLCs because of the Faradic method, which enables them to attain larger specific capacitance as well as higher energy densities. Metal oxides, conducting polymers, and others are examples of materials that have generated interest. But, as a result of the Faradic nature, it entails a reduction–oxidation cycle similar to that of batteries; resulting in low power density and instability [38].

Hybrid supercapacitors

Hybrid supercapacitors combines EDLC and Pseudocapacitors by combining a battery-like electrode with a capacitor-like electrode in the same cell[39][40]. Energy and power densities can be increased by increasing cell voltage with the right electrode combination. There have been many experiments with various positive and negative electrode combinations in both aqueous and inorganic electrolytes. At the moment, researchers are focusing the majority of their attention on three different types of hybrid supercapacitors. These hybrid supercapacitors can be distinguished from one another by the designs of their electrodes [41].

2.3.4 Applications of Supercapacitors

When designing an electrical energy storage system, the decision between supercapacitors and rechargeable batteries is determined by the application's demands. Supercapacitors are utilized when their characteristics are superior to those of regular capacitors or batteries [31]. A number of research projects have been carried out in the field of supercapacitors to produce potential electrode and electrolyte materials, as well as device fabrications, in order to accomplish a significant advancement in energy storage systems with numerous electronic applications. They are capable of numerous applications since they can deliver a lot of power rapidly. [42]. We will examine some of the primary applications of supercapacitors in this section.

Flexible and Portable Electronics

Smart technological devices have now become an integral part of our daily lives. However, smart energy storage devices are required to power these smart electronics. Batteries and supercapacitors both serve vital roles in modern energy storage technologies. Supercapacitors are capable of providing high output power, making them a valuable complement to battery systems in situations where high power requirements exist. Thus, battery life can be extended, and smaller, cheaper batteries can be used. Supercapacitors can power portable electronics with minimal energy needs [31]. The ideal power solution for contemporary mobile electronic devices comprises a hybrid configuration of batteries and supercapacitors. This allows small electronic devices like phones, watches, and headphones to use lightweight battery devices. In today's sophisticated flexible and wearable electronic systems, flexible supercapacitors can be used for a range of different applications. They can be seamlessly incorporated into wearable clothing, serving as power sources for various electrical devices [42]. The diagram below depicts some of the smart applications that use supercapacitors as an energy source [43].

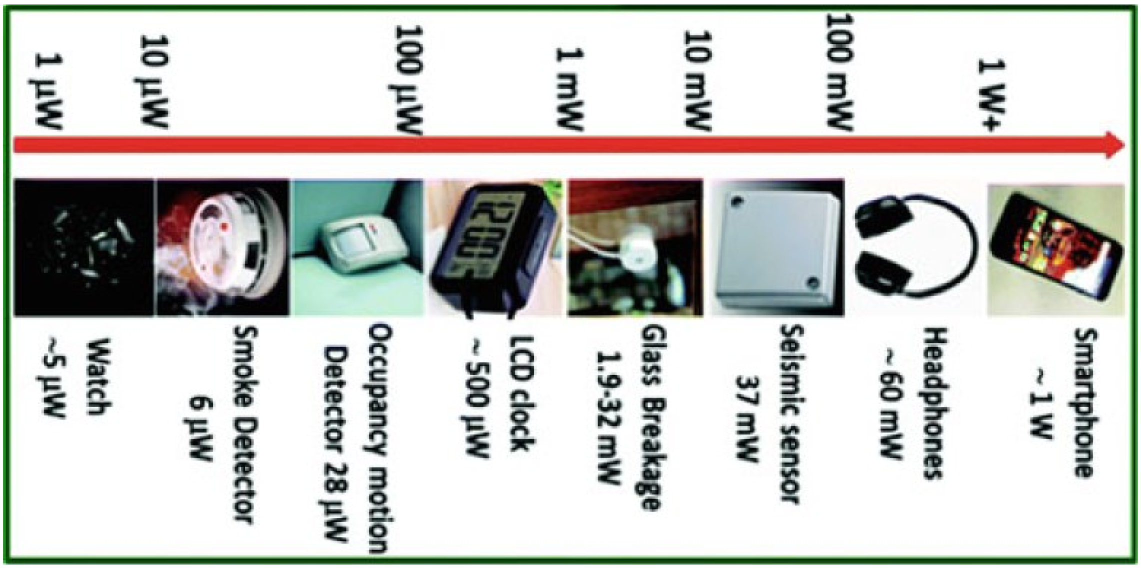


Figure 9. *Various smart, portable electronic energy equipments that are powered by supercapacitors [43]*

Hybrid Vehicles

Hybrid electric vehicles utilize a combination of supercapacitors, batteries, and fuel cells to supply power for acceleration and recover braking energy. Hybrids of supercapacitors and batteries can be used to power electric vehicles, vessels, and public transportation [33]. Unlike diesel and gasoline engines, these energy sources are environmentally friendly and pollution free. Hybrid supercapacitors charge and discharge rapidly and reliably, extremely efficient and dependable batteries. Such a system converts the vehicle's braking kinetic energy into electricity that powers the alternator during restart [44].

Implantable Healthcare

Wearable microsystems that monitor heart rate, electrocardiogram (ECG), and activity level are increasingly attracting customer base [45][46]. Supercapacitors are commonly used in a variety of implantable healthcare devices that require microwatts to milliwatts of power. Power solutions based on supercapacitors show great potential for future portable and wearable technologies, especially those that interface with the skin due to their high power density and rapid recharging times [47][48][49]. The figure below illustrates the implantable medical applications utilizing supercapacitors.

Figure 10. *Implantable medical devices that use supercapacitors for power [42].*

Power Supply

Supercapacitors are utilized in uninterruptible power supply (UPS) systems.These systems are beneficial since they can be utilized in an emergency, provide surge protection, and give portable charging options. The UPS supplies fast backup to highly sensitive equipment during generator initiation [42].

Internet of Things (IoT) Applications

The architecture of the Internet of Things will influence the energy system that will be used by smart applications such as the smart grid, smart homes, and intelligent modes of transportation. The rapid expansion of IoT networks has posed significant challenges to energy storage and management. Therefore, Internet of Things is an invaluable asset in the field of smart energy [50].

Supercapacitors provide temporary power storage in IoT sensor and actuator systems [51]. It is possible to power autonomous sensor systems as well as applications for the internet of things by combining solar cells and supercapacitors [52][53]. Other applications include keeping an eye on the temperature of food to make sure it's safe, and using wearable devices to store energy from motion to power user interfaces like screens or low-power data transfer [54]. These applications prioritize supercapacitors with long cycle life, low cost, and reuse over high power density [51].

2.3.5 Components of a Supercapacitor

Supercapacitors are made up of four basic components: electrodes, electrolyte, collectors, and separators, as depicted in Figure 8. Every component of a supercapacitor is responsible for a specific function during operation. It is possible to implement supercapacitors in a variety of shapes and sizes.

Electrodes

The electrode is the supercapacitor's active component, as the charge storage depends on the the materials that are used in the electrode. Electrodes need to be electrically conductive, have a wide surface area, and be porous [42].

Electrolytes

Supercapacitors' power density relies on electrolyte resistance. The term "electrochemical series resistance" is used to describe the total resistance of a supercapacitor system [42].

Separators

Separators are required in Supercapacitors with liquid electrolytes to prevent short circuit between electrodes. It should be porous to facilitate the flow of electrolyte ions [22].

Current Collectors

The purpose of the current collector is to collect electrons from the electrode-active material and direct them to the external circuit so that the current can be collected. On supercapacitors, it is common practice to use a pair of current collectors. There is a correlation between the thickness of the current collector and the properties of the supercapacitor [42][22].

2.3.6 Supercapacitor Materials

Supercapacitors are made of electrodes, electrolytes, separators, and current collectors. The electrode material and electrolyte type influence the SC's properties as the energy is stored at the electrode-electrolyte interface [22].

Electrodes

The selection of electrode-active materials is vital for optimal performance of a SC. Carbon is commonly utilized in SC electrodes. Carbon nanotubes, graphene, activated carbon (AC) are some of the manifestations of carbon [55]. ”Activated carbon ” (AC) is the most frequently utilized electrode material in supercapacitors since it has a large specific surface area (1000-2500 m2/g), chemical and thermal stability, and electrical conductivity [56][57]. AC can be manufactured from a variety of natural sources, notably coconut shells, and it is cost - effective, making it an excellent material for supercapacitor electrodes [31].

Electrolytes

The electrolyte used in supercapacitors has an effect on a number of critical variables, most notably the voltage and temperature range and specific capacitance. Various electrolytes yield varying equivalent series resistance (ESR) readings. In SCs, liquid electrolytes are classified as ”aqueous” and ”non-aqueous” (Organic). Many of the supercapacitors available in the market are made with organic electrolytes, which allow charging to maximum voltage of 2.2-3 V. The maximum voltage is critical since the maximum energy stored in a SC is related to the maximum voltage . Organic electrolytes are favored by commercial SC companies due to maximum storage. According to the number of publications, scientific study focuses primarily on aqueous electrolytes. An aqueous electrolyte limits the SC's maximum voltage to 1 V or 1.2 V, but it also improves safety, non-flammability, environmental friendliness, and cost. In identical devices, aqueous electrolytes have lower ESRs than organic ones [29][31] [22][58].

Separators

The separator needs to be strong mechanically and able to resist the supercapacitor's operational temperature range, as well as being chemically and electrochemically stable. The separator is a passive component of the SC. As a result, it should be thin. Main objective of the Seperator is to the prevent short circuit between electrodes. Typically, cellulose-based paper separators with a thickness of 15–50 µm are utilized. Additionally, the utilization of glass fiber and different polymer-based separators like polyethylene (PE) and polypropylene (PP) has been reported [31][59][60].

Current Collectors

The current collector connects the electrode to the supercapacitor's external junction. Aqueous and organic electrolytes have different current collector requirements due to electrochemical stability issues. Aluminum is the most often used current collector material with organic electrolytes. To avoid corrosion, carbon paper current collectors are utilized with aqueous electrolytes [31][59] .

2.3.7 Properties of Supercapacitors

Capacitance

Capacitance is a key parameter of supercapacitors. Capacitance (C) is defined as the ratio of charge (Q) on each electrode to the voltage differential (V) across them. Farad (F) is the unit of measurement for capacitance. Capacitance is determined using the following equation[32][61].

$$C = \frac{Q}{v}$$

The ”specific capacitance” is the capacitance to mass or volume ratio. It should be stated clearly which mass or volume is being utilized, as the mass or volume can relate to one electrode, two electrodes, or the overall mass or volume of the supercapacitor. The amount of energy stored in a capacitor can be determined using the equation below, where C represents capacitance and V represents voltage [33][22].

$$w = \frac{1}{2cv^2}$$

Equivalent series resistance (ESR) and Power

A supercapacitor's ”equivalent series resistance” (ESR) includes the current collectors, electrodes, and electrolyte's ionic resistance. Contact resistances between layers or materials also affect ESR. The ESR has a significant impact on the power available from the supercapacitor [62]. The maximum power is

$$P = \frac{v^2}{4R}$$

where V represents the voltage across the supercapacitor and R represents the ESR. As a result, if the voltage is limited by the electrolyte used, the ESR is the most important parameter to consider in order to maximize output power. ESR can be reduced by using low resistivity current collectors, electrodes, and electrolytes. The shape of the supercapacitor must also be optimized. To optimize the ESR, the electrode and ion paths can be made shorter and wider. Despite the fact that the porous separator between the electrodes is comprised of insulating material, the configuration of its pores influences the ionic resistance of the electrolyte layer. Similarly, the pore structure of the electrodes influences ionic resistance. Specific power or power density can be defined relative to supercapacitor mass or volume in the same manner that specific energy can [33][23].

Self-discharge and leakage current

Self-discharge is the process by which the voltage of a charged supercapacitor decreases even when it is not linked to a load electrically. The origins of this phenomenon can be traced back to either chemical reactions or physical events. A relatively low current is necessary to keep the supercapacitor voltage stable. This phenomenon is referred to as ”leakage current” [23].

Efficiency

Supercapacitors' efficiency determines how much charged energy it can recover after charging. Efficiency can be broken down into two categories: energy efficiency and charge efficiency, often known as the Coulombic efficiency. ESR and leakage current are two factors that influence efficiency levels. Some energy is always wasted during the charging and discharging of a battery because of the series resistance. As a result, reducing ESR is important as it not only boosts maximum power but also reduces losses. Self-discharge affects energy and charge efficiency since it depletes the supercapacitor's charge [23].

Cycle life

The primary reason for supercapacitors' extended life is that they do not require chemical or electrochemical processes to operate. Ions and electrons migrate within the electrolyte and electrodes during charging and discharging. Thus, in contrast to batteries, neither the dimensions nor the materials undergo changes as a result of electrochemical reactions [23]. Supercapacitors degrade slowly, especially at high temperatures and voltages. A parasitic electrochemical reaction can limit the lifetime of supercapacitors even though they are not dependent on the Faradaic reactions. Temperature and voltage increase ageing dramatically. With time, capacitance diminishes and ESR increases [63][64]. As the supercapacitor ages, side reactions cause electrolyte loss, electrode pore blockage, and the production of volatile by-products that might cause gas bubble formation and hence increased pressure. Surface functional groups and contaminants in activated carbon electrodes may cause loss of electrical characteristics. The encapsulation of a supercapacitor may affect its lifetime. Lack of electrolyte or oxygen barrier characteristics might cause rapid deterioration [64][65].

2.3.8 Printed Supercapacitors

Supercapacitors, like batteries, are manufactured by rolling the electrode layers and separator between the current collector films and packing the device in a rigid metal or plastic casing. On the other hand, printing on plastic substrates has made it possible to create flexible devices that use supercapacitors [23].

The vast majority of published research on printed supercapacitors discusses systems in which electrodes are printed on various substrates and then sandwiched together with separator paper to form the device [66][67]. Demonstrations of gel electrolytes, which do not require a separator layer, have also been performed [68]. Also, It has been reported that all layers can be printed on the same substrate [69]. A printed supercapacitor is shown in the figure below.

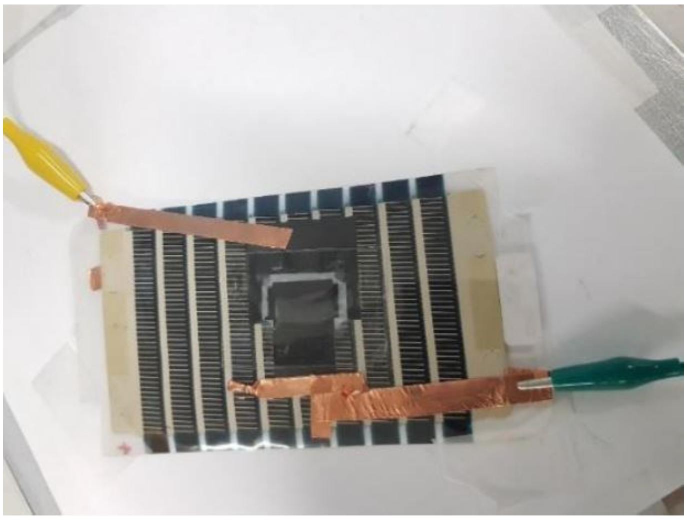


Figure 11. *The single supercapacitor that is printed on the back of the OPV [70]*

The thickness of the film is the most important factor when selecting a printing method. Supercapacitors require thicker active material films than ordinary printed electronics devices [23]. Aside from the general benefits of printing technologies such as low cost, large area, flexibility, and ease of integration, printing presents special benefits for the fabrication of SCs such as enhancing performance , maximizing of energy density, and so on. Different fabrication methods of printed supercapacitors are shown in the figure below [71].

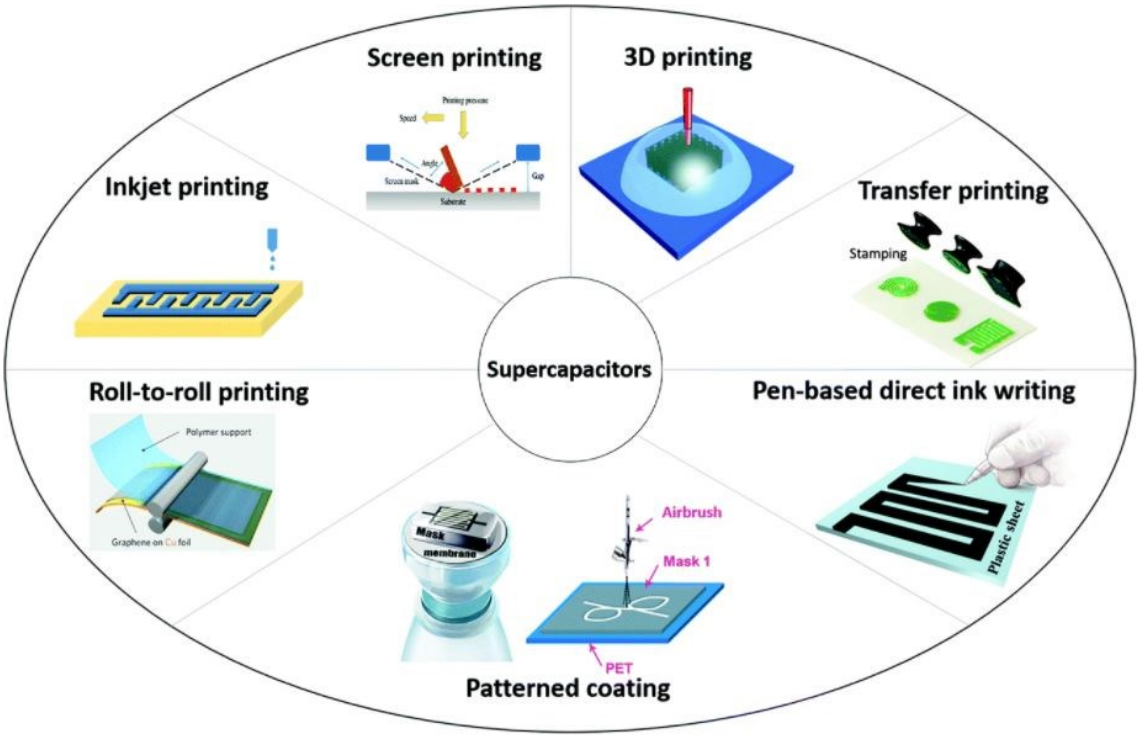


Figure 12. *Different fabrication methods of printed supercapacitors [71]*

2.4 Antenna

An antenna is a device that converts a radio frequency signal passing through a conductor into an electromagnetic wave in free space. Comprehending the fundamental antenna characteristics and antenna fundamentals is critical for understanding antenna design demonstrated in this thesis. This sub-chapter will examine some of the fundamental antenna characteristics

2.4.1 Introduction to Antennas

Radiation is the transformation of an electric signal into electro-magnetic waves and any object containing an electric charge has been proven to be capable of radiating to some degree [72]. An antenna is essentially a device that has been deliberately constructed to be an efficient radiator [73]. Antenna is a reciprocal device, meaning it can take electromagnetic radiation from another device and convert it to an electrical signal [74]. According to the standard definition, an antenna is, "That part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves" [75]. When it comes to wireless communication, an antenna is one of the most important components. An antenna in a radio communication system can perform either the role of a transmitter or a receiver. The antenna is inextricably linked to electricity and magnetism. According to Maxwell's equations, a changing magnetic field results in a changing electric field and vice versa. A constant current provides a constant magnetic field but not radiation. To generate radiation, current must constantly fluctuate. Charges accumulate as a result of a time-varying alternating current, resulting in a fluctuating electric field. Radiation is produced by both the accumulation of charges and time-varying current [74] .

2.4.2 Types of Antennas

It is necessary to classify antennas in order to have an understanding of both their physical structure and their functionalities. Antennas are available in a wide number of designs, each of which is tailored primarily to a specific usage. We'll take a look at a few different types of antennas to get a sense of their diversity.

Wire Antennas

The most frequent form of antenna in the field is the wire type antenna. Linear or curved antennas are other names for wire antennas. These antennas are inexpensive, simple, and versatile [74]. Wire antennas come in a wide variety of forms, including the dipole, loop, and monopole. Wire antennas have a wide range of use cases and can be found in a number of places, including on buildings, ships, spacecraft, and even home electronic devices [76]. A diploe antenna is shown in Figure 13.

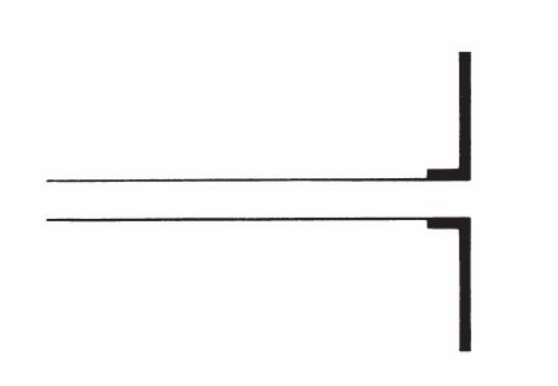


Figure 13. *Dipole Antenna [74]*

Microstrip Antennas

Microstrip antennas have a low profile and are compatible with both planar and non-planar surfaces. They are easy and affordable to construct, physically durable when mounted on hard surfaces, and extremely adaptable in terms of resonant frequency, polarization, pattern, and impedance. In the 1970s, microstrip antennas were quite popular, mainly for spaceborne applications. These antennas are formed by a metallic patch attached to a grounded substrate. The metallic patch is available in a variety of forms [74][77]. These microstrip antennas are utilized in applications such as Satellites, Aircrafts , Cars , Mobile devices [76]. The figure 14 illustrates the fundamental structure of a microstrip patch antenna.

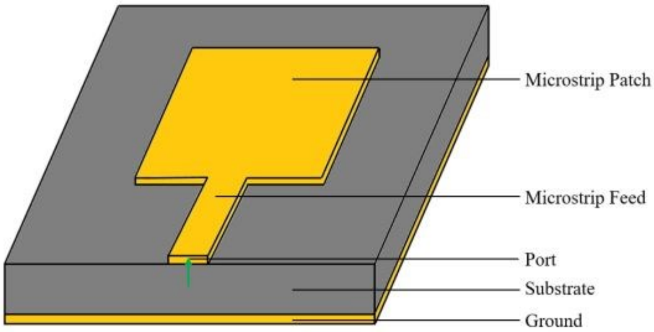


Figure 14. *Fundamental structure of a microstrip patch antenna [78]*

Aperture Antennas

Aperture antennas are antennas that have an aperture at the end. The edge of a transmission line radiates energy when it is terminated by an opening. This aperture-like opening is what distinguishes it as an aperture antenna [79]. Aperture antennas include waveguide antennas and horn antennas. These aperture antennas are utilized in spacecraft, airplanes, and flush-mounted applications [74] [76]. A horn type of aperture antenna is shown in the figure below.

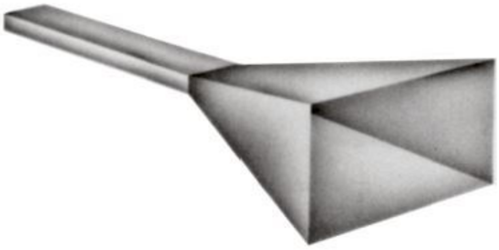


Figure 15. *Horn antenna [74]*

Reflector Antennas

The reflector antenna is the most common satellite antenna because of its relatively simple design and light weight. A reflector antenna is composed of many reflectors with parabolic, hyperbolic, ellipsoid, or spheroid surfaces. The most common reflector antenna is parabolic. The most significant drawback is that the reflector needs to be adjusted so that it does not block the feed point. This offset destroys the optical aperture's rotational symmetry, limiting the scan range to a few bandwidths [80]. Reflector antennas are also utilized in microwave communication systems [76]. A typical configuration of a Parabolic reflector antenna is shown in the figure.

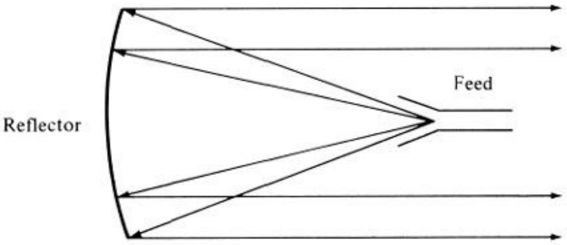


Figure 16. *Parabolic reflector antenna with a front feed [74]*

Array Antennas

In radio frequency communication, an array antenna is a group of antennas that work together [81]. The array may be configured in such a way that the radiation from the components adds up to produce a radiation maximum in one or more directions, a radiation minimum in others, or any combination thereof [74]. Antenna arrays are used in situations requiring extremely high gain. Usually, we need to control the radiation pattern. Yagi-Uda antenna, Micro strip patch array, Aperture array, Slotted wave guide array are some types of array antennas. Microstrip patch array is shown in the figure below.

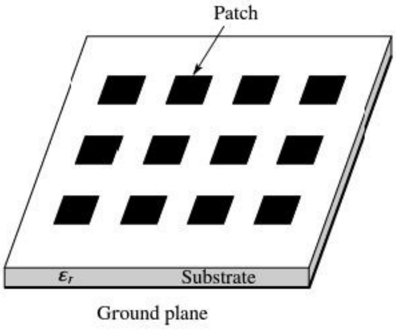


Figure 17. *Microstrip patch antenna array [81]*

2.4.3 Field regions of an Antenna

Generally, the area surrounding an antenna is segmented (classified) into three distinct regions: the reactive near field, the radiating near field, and the far field [74] .These regions are essential for determining the field structure and evaluating which simplifications can be used, but there is no obvious boundary or drastic change in the field configuration. There three regions can be identified as shown in the figure 18 below.

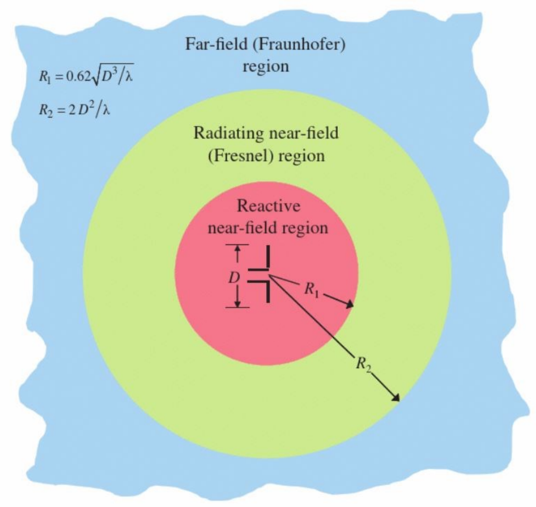


Figure 18. *Field Regions surrounding an antenna [74]*

The region that is immediately surrounding the antenna and is dominated by the reactive field is referred to as the reactive near field. Electric and magnetic fields are not always in phase with one another, and the angular field distribution is significantly dependent on the antenna's distance and orientation. This field does not radiate in its whole region. Radiating near field is the region around the reactive near field. Electric and magnetic fields work in tandem here. Yet, the angular field distribution is still influenced by the distance from the antenna. However, as we're still close to the antenna, the contributions of the various antenna components create a complex field structure. The far field region encompasses the area connected to the reactive and radiating near-field zones. It is infinite in range and encompasses the large bulk of the space through which the wave typically travels. The angular field distribution is independent of antenna distance since the entire field radiates. Electric and magnetic fields are in phase and perpendicular to each other and the propagation direction [74]. The boundaries between these three zones are shown in the table below, D is the maximum extent of any finite antenna and λ is the Wavelength [73].

Table 1*.* *Distance to field region from the antenna.*

Antenna Field Region	**Distance from the Antenna**
Reactive near field region	$0\ to\ 0.62 * \sqrt{\frac{D^3}{\lambda}}$

Radiating near field region	$0.62 * \sqrt{\frac{D^3}{\lambda}}\ to\ \frac{2D^2}{\lambda}$
Far field region	$\frac{2D^2}{\lambda}\ to\ \infty$

2.4.4 Radiation Pattern of an Antenna

A radiation pattern of an antenna is used to represent the variation in the power radiated by an antenna as a function of the direction away from it [75]. Directional coordinates are used to validate the far field radiation pattern. The parameters of the radiation pattern include the power fluctuation, field strength, polarization, and density [73]. Radiation patterns can be represented in 2D (two dimensions) or 3D (three dimensions). Radiation patterns can be used to describe various antenna features, such as field or power patterns, on a linear or decibel scale (dB). Figure illustrates the 3D and 3D radiation pattern of an antenna [82].

Isotropic, directional, and omnidirectional radiation patterns are three of the most frequent types of antenna radiation patterns. Isotropic antennas are theoretically lossless antennas that produce the same amount of radiation in all directions. The radiation pattern of an omnidirectional antenna is isotropic in a single plane. The radiation patterns of directional antennas typically have a singular peak in one direction. The major portion of radiated power is directed in this direction [83]. Lobes are used to characterize the various parts of a radiation pattern; these parts can be further broken down into main, minor, side, and rear lobes. "a portion of the radiation pattern that is bounded by regions of relatively low radiation intensity" is how scientists characterize a radiation lobe [74].

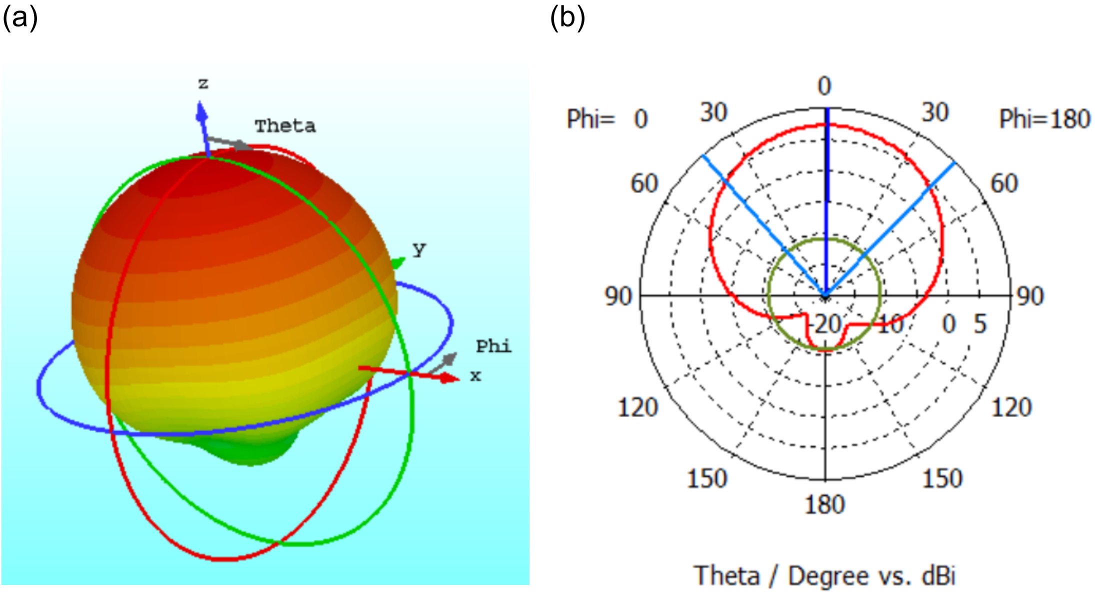


Figure 19. *Radiation emitted by a directional patch antenna. (a) 3D representation of the radiation pattern. (b) 2D representation of the radiation pattern [82].*

2.4.5 Antenna Beamwidth

Beamwidth represents the antenna's radiation pattern and defines the antenna's operating frequency range. The beamwidth of an antenna varies depending on its type. The most commonly used phrase for beamwidth is half power beamwidth (HPBW) which is defined as “In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam” [75]. The First-Null Beamwidth (FNBW) is another essential beamwidth. It is the angle between the pattern's first nulls. The beamwidth of an antenna is a critical figure of merit and is commonly utilized in conjunction with the side lobe level. Thus, as beamwidth narrows, side lobe expands, and vice versa. Representation of lobes, half power beamwidth and first null beamwidth can be seen from the figure below [74].

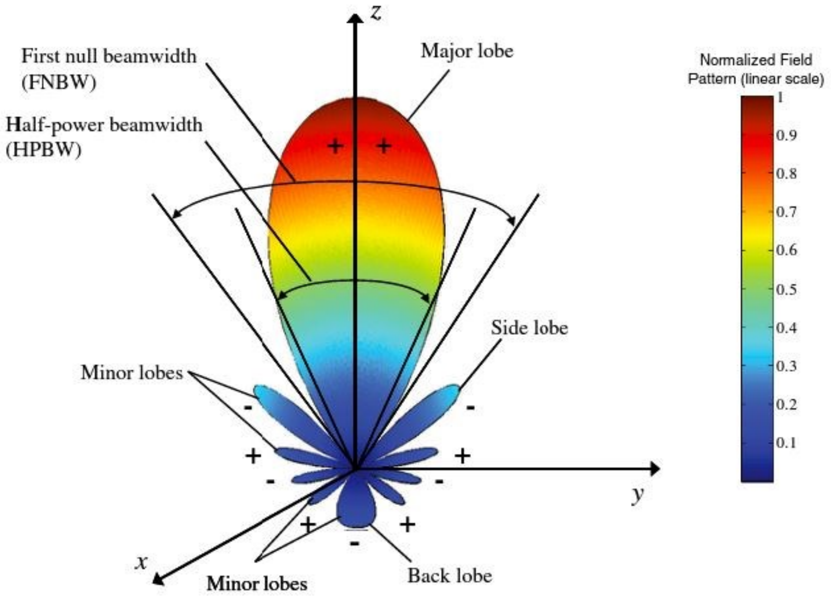


Figure 20. *Representation of lobes ,HPBW and FNBW [74]*

2.4.6 Directivity, Gain, Realized gain and Efficiency of an Antenna

Directivity

Directivity of an antenna is defined as “The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions” [75]. Directivity is a dimensionless quantity denoted by dBi (Decibel isotropic). The following mathematical formula is used to express directivity [74].

$$\mathrm{D} = \frac{\mathrm{u}}{\mathrm{u}_0} = \frac{4\pi\mathrm{u}}{\mathrm{P}_{\mathrm{rad}}}$$

where, D is the directivity, u is the Radiation intensity of an isotropic source, u_0 is Radiation intensity and $\mathrm{P}_{\mathrm{rad}}$ is the total radiated power.

Gain, Realized Gain

The term "antenna gain" refers to the amount of energy transmitted in the direction of peak radiation from an isotropic source. Despite the fact that gain is inextricably tied to directivity, it is a measurement that takes into account both the efficiency and directional capabilities of the antenna. The following mathematical formula is used to express directivity [74].

$$\text{Gain} = 4\pi \frac{\text{radiation intensity}}{\text{total input (accepted) power}} = 4\pi \frac{U(\theta, \phi)}{P_{in}}$$

where Pin is the total input power and U (θ, φ) is the Radiation intensity in a given direction to E-filed. Multiplying the directivity by the radiation efficiency and the return loss factor yields the realized gain [81].

Efficiency

The efficiency of an antenna is defined as the ratio of the power provided to it to the power radiated by it. High-efficiency antennas radiate most of their input energy. Low-efficiency antennas lose most power to internal losses or impedance mismatch [73][74].

2.4.7 Antenna Bandwidth

"Bandwidth" refers to an antenna's frequency range for transmitting and receiving energy. When picking an antenna, bandwidth always becomes an important factor. Many antenna types cannot be used for wideband operation due to their extremely narrow bandwidths. The correlation between bandwidth and antenna characteristics varies depending on the antenna parameters, thus there is no bandwidth standard [74]. There are two types of bandwidths: pattern bandwidth and impedance bandwidth. Antenna gain, polarization, directivity, and beamwidth determine pattern bandwidth. Antenna impedance and radiation efficiency affect impedance bandwidth [73][77].

2.4.8 Printed Flexible Antennas

As previously discussed, the past few years have seen a tremendous enthusiasm in flexible electronics from both academic and business communities. These systems are now possible due to miniature and flexible energy storage and self-powered wireless components [84]. Flexible electronic systems require flexible antennas operating in specific frequency bands to enable wireless connectivity in today's information-centric world. The performance of these systems is mostly influenced by the integrated antenna's characteristics. Flexible wireless technologies necessitate the use of antennas that are lightweight, relatively small, and low-profile. Simultaneously , these antennas has to be mechanically robust, efficient, have an acceptable bandwidth, and also have appropriate radiation properties [85]. Hence, throughout the design phase, consideration must be given to selecting appropriate materials for the fabrication of the flexible antenna [86].

Substrate thickness and dielectric constant affect an antenna's efficiency and bandwidth [87][88]. Figure 21 depicts a graphene-based flexible antenna utilized in consumer electronic devices [89].

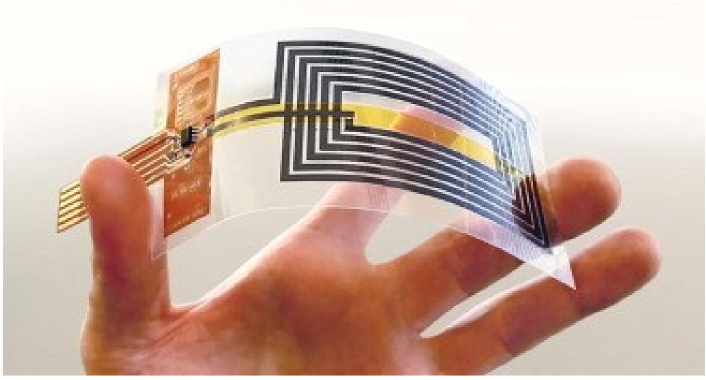


Figure 21. *Graphine based printed flexible antenna [89]*

In the literature, some of the most frequent flexible substrates are Kapton polyimide film, Polydimethylsiloxane (PDMS), and polyethylene (PET) [90]. There are studies of antennas fabricated on flexible substrates such as papers, liquid crystal polymers (LCP), and PET films [91][92]. Flexible bow-tie antennas based on synthetic flexible substrates are proposed in another study [93][94]. The integration of a flexible single-band antenna printed on a miniaturized paper-based substrate with flexible displays for WLAN applications was presented [95]. There are a variety of fabrication processes for flexible antennas. We shall examine these techniques in the following chapter.

2.4.9 Flexible Antenna Fabrication Methods

This section examines the various ways for fabricating flexible antennas that are currently available.

Chemical Etching

Chemical etching, which is frequently used in conjunction with photolithography, is the technique of producing metallic patterns by corrosively milling off a specified area with a photoresist and etchants. Chemical etching has achieved widespread popularity due to its ability to precisely make highly intricate patterns with a high resolution [96]. Organic polymers used in photoresist materials undergo chemical changes when exposed to ultraviolet light. Photoresist becomes positive when the developer dissolves the exposed area. A negative resist occurs when a chemical becomes less soluble. Negative resists' exposed sections increase when the developer dissolves the counter-part, endangering resolution [97]. As a result, positive resists are used more frequently in photolithography-based antenna and (RF circuits since they have a greater resolution than negative resists. While this approach is capable of producing patterns with a high degree of complexity and fine detail, the lengthy procedure, poor throughput, use of hazardous chemicals, clean room needs, as well as by product and waste residues, are significant disadvantages of this technology. The process of chemical etching is indicated in the figure below [85].

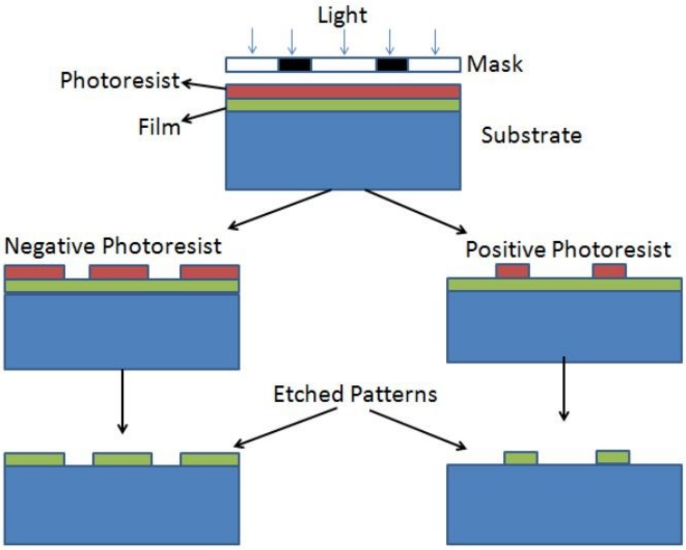


Figure 22. *Chemical etching process flow diagram [85]*

Screen Printing

Screen printing is a cost effective, basic fabrication procedure. This approach utilizes a woven screen with varying thicknesses and densities of threads. A squeegee blade is pushed into the screen to generate a printed pattern. The required pattern is created when ink is ejected through the screen's exposed areas on the substrate [98]. Polyester and stainless steel are two components that are frequently utilized in the production of these technologies. Present screen-printing technologies include the flat bed, cylinder, and rotary methods. Screen printing is affordable and more sustainable than chemical etching. The substrate is thermally cured with the patterned mask instead of masking a screen. This approach has been used effectively to prototype several RFIDs and flexible antennas [99], [100]. This method lacks control over thickness, Layer Consistency, and design quality [98]. Screen printing process is indicated in the figure below [85].

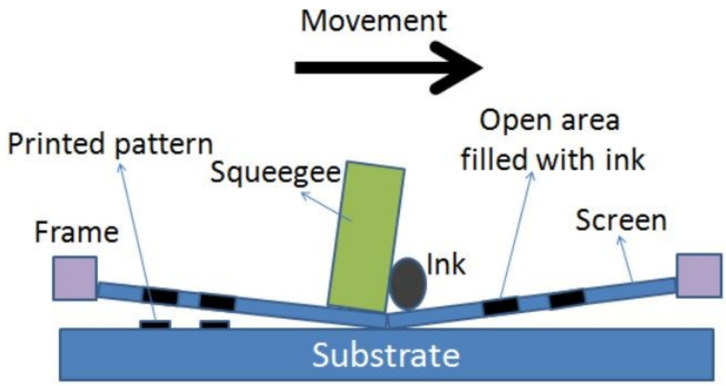


Figure 23. *Screen Printing Process [85]*

Dispenser Printing

The ink is deposited on the substrate using an ink syringe that is part of a dispenser printing system. Printing can be done with a wide variety of ink viscosities when using the dispenser printing method. By changing the pressure within the ink barrel, the ink is printed as filaments or drops [101][102][103]. The needle can be anywhere between 0.5 and 400 millimeters long. Stainless steel is used for the larger needles, whereas drawn glass capillaries are used for the tiny needles. Pressure needed to drive ink through a needle depends on its diameter and viscoelasticity. The ink's shear-thinning property permits printing at very lower pressures. Figure 24 depicts dispenser printing [104].

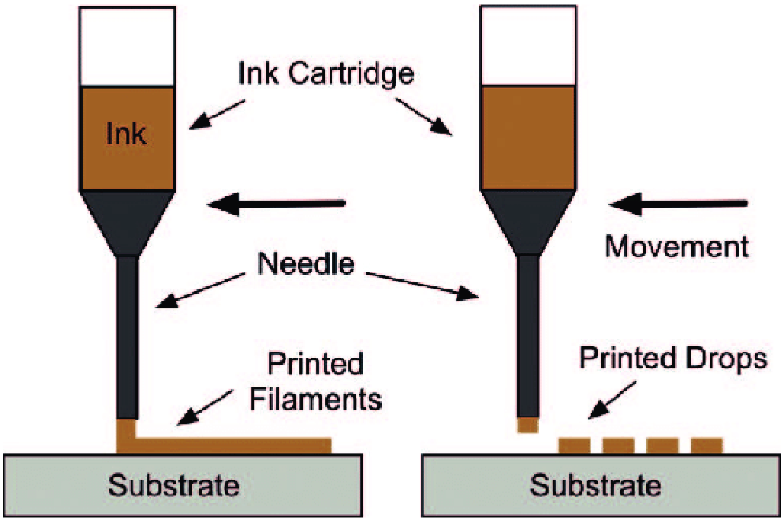


Figure 24. *Dispenser printing process* [104]

The ink preparation process for dispenser printing could be challenging. Ink can quickly clog the printing needle due to differences in particle densities and particle size distribution. To prevent sedimentation, the ink's solvent fraction is kept low and active particles are ball milled to reduce particle size. Dispenser printing uses repeating lines or droplets to print ink on 100 mm^2 to 1 m^2 surfaces. The printing of big electrodes using a dispenser is a slower process than other methods, but it has the advantage of producing electrodes with a low profile that can be dispersed across a defined area. Since dispenser printing is performed without physical contact, ink can be applied to surfaces that are not even [104].

Ink Jet Printing

In recent years, inkjet printing with highly conductive inks has become immensely popular method to print Antennas and RF circuits. Latest inkjet material printers function by depositing ink droplets as small as a few Pico liters. As a result, these printers can accurately produce compact designs with little details [105]. Ink jet printing makes use of conductive inks composed of various nanostructured materials, such as silver nanoparticle ink, which is extensively employed because of its conductivity. Ink jet printing has two categories: continuous and drop on demand. The print quality is mostly determined by the ink's viscosity, particle Size and surface tension. Additionally, the substrate's surface structure, print head setting and platen temperature all have a role. The printing procedures and configurations are entirely controlled by the user's computer. As a consequence of this, it is not necessary to operate in a clean room, which helps keep the levels of environmental contamination to a minimum [106]. Inkjet printing transfers a precise number of ink droplets from the nozzle to the predetermined spots. As a result, no trash or byproduct is generated, resulting in an affordable, environmentally friendly, and rapid solution. The process of ink jet printing is depicted in the figure below [85].

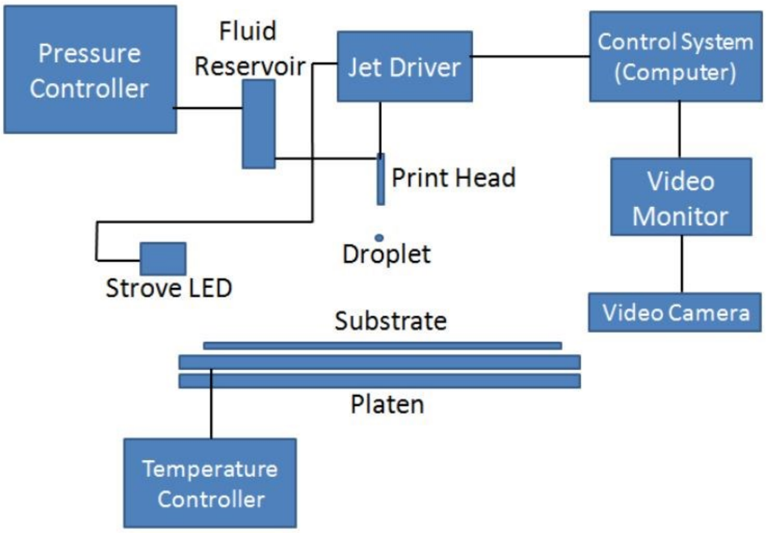


Figure 25. *Ink Jet Printing process [85]*

Flexography

Flexography is a technique for creating relief prints. A print is created by inking the protruding surface of the printing plate matrix while leaving the recessed portions uninked. Image printing is a straightforward technique that entails inking the matrix's protruding surface and bringing it into touch with the substrate [85]. Flexography has garnered considerable interest from RFID antenna designers for its comparatively high resolution, cost effectiveness, and high throughput. Additionally, this approach necessitates the use of a lower viscosity ink than screen printing. To compensate for the higher sheet resistance, flexography inks should have better bulk conductivity than screen printing inks. The ink layer thickness of the printed trace relies on the substrate's porosity, hydrophobicity, and surface energy. Printed antenna efficiency is largely determined by traced design electrical conductivity. The sheet resistance is also affected by the consistency of ink film thickness and line width [107].

3. EXPERIMENTAL AND MODELLING METHODS

This chapter outlines the experimental and modelling methodologies utilized in this thesis.

3.1 Experimental Method of Supercapacitor

This section will provide a concise overview of the fabrication and characterization of the supercapacitors utilized in this thesis.

3.1.1 Supercapacitor Fabrication

Supercapacitors are typically manufactured commercially by coating electrodes on current collector foils, placing the separator between two coated current collector foils, and then filling and packaging [108]. Figure 12 illustrates various fabrication techniques for printed SCs. In this thesis, supercapacitors were printed on flexible substrates to produce flexible Supercapacitors [23][31][109]. A flexible substrate is used to print the different layers of the SCs. In this instance, the AC electrode must be tens of micrometres thick, and high-resolution patterning is not essential. The easiest method to print SCs is doctor blade coating, in which a sharp blade spreads ink at a configurable distance from the substrate. Screen printing and bar coating are also suitable methods for this purpose [22]. The diagram depicted in figure 26 is a schematic illustration of doctor blade coating [67]. On flexible or rigid surfaces, blade coating layers of generally uniform thickness can be applied. The distance that separates the blade from the substrate serves as a measurement for the layer's thickness. Patterning can be achieved by utilizing stencils to which ink or paste is applied [31]. Figure 27 illustrates the printing process utilizing a stencil arrangement.

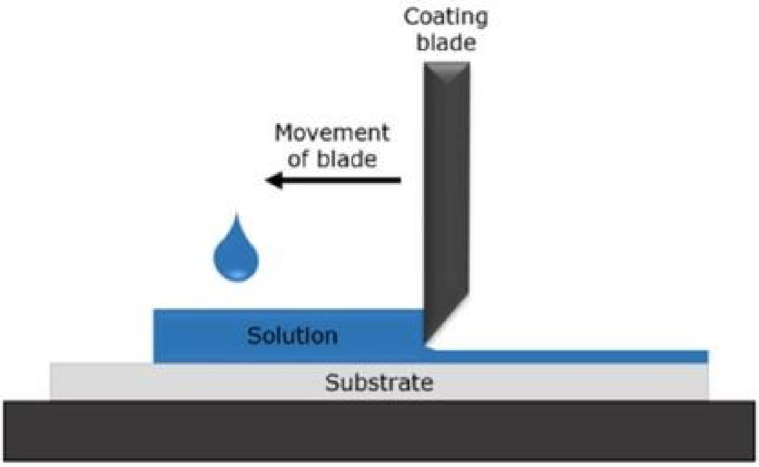


Figure 26. *Schematic representation of doctor blade coating [67]*

Figure 27. *Printing with a stencil setup [22].*

Before progressing on to the next step in fabricating SCs, the liquid inks must change into solids through drying. When the ink dries, the solvents are taken away by evaporation. Some drying or curing processes, like polymerization and crosslinking, involve chemical changes [110]. Drying and curing processes are often carried out in an oven or through the use of UV light in the printing industry [111]. It is also required to improve the particle interaction in many inks. Sintering at high temperatures can improve contact by allowing diffusion in the particles to form necks between them [112].

3.1.2 Supercapacitor layout and assembly procedure

For the purposes of this thesis study, laminated face-to-face supercapacitors are utilized. Following the theme of the "Lightning Sensor" initiative, it is strongly recommended to make use of materials that are non-toxic, recyclable, and combustible. Since this sensor node has so many potential uses, it had to be built for a low cost. Figure 28 shows the Schematic structure and a layout of a laminated face to face supercapacitor [31].

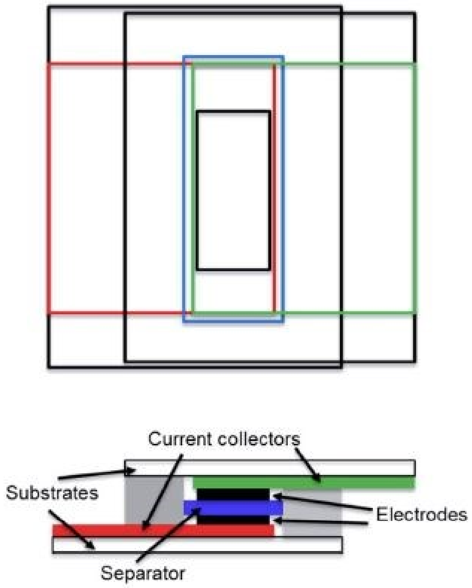


Figure 28. *Schematic structure and layout of a laminated face to face supercapacitor*

Current collector of the supercapacitor was graphite ink “Acheson PF 407C” and it had the dimensions of 30 mm * 30 mm. Acheson PF 407C was applied on the substrate using the doctor blade method and it was cured for 30 minutes at 95°C temperature. Electrodes had the dimensions of 18 mm * 10 mm. “Activated carbon (AC) - Kuraray YP-80F” had been used to fabricate the electrodes. Electrodes were separated by a 40 µm thick “Dreamweaver Silver AR40” cellulose separator paper. Then the device is filled with NaCl electrolyte which was in deionized water in 1:5 mass ratio. Then the two substrates are laminated together and sealed with adhesive tape (468MP-200MP from 3M) [31][22][23][70][113]. Figure 29 shows a fabricated laminated face to face supercapacitor.

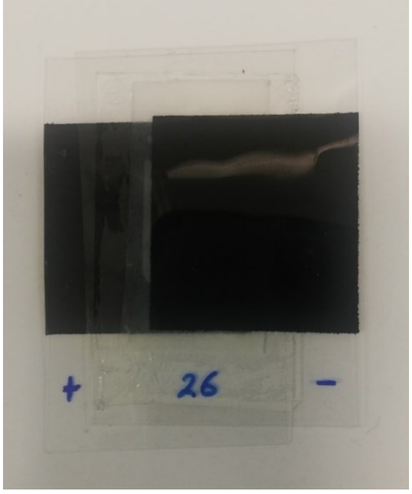


Figure 29. *Laminated face to face supercapacitor*

3.1.3 Characterization of Supercapacitor

The capacitance, leakage current and ESR were determined according to the IEC 62391-1 standard [20] using a Maccor 4300 test system [114]. The devices were charged and discharged three times with constant current (1, 3 and 10 mA) between 0 and 1 V. The leaking current was measured by keeping the supercapacitor at a constant voltage for one hour. The ESR was calculated from the IR drop in the measurement with discharge current [115]. Figure 30 shows a laminated face to face supercapacitor connected to Maccor 4300 test system with crocodile clips during the measurement process.

Figure 30. *Laminated face to face supercapacitor connected to Maccor 4300 test system using crocodile clips during the measurement process*

3.2 Experimental Method of the Antenna

This section will give an overview of the antenna design process utilized in this thesis.

The primary goal of this “LightningSense “is to develop an energy autonomous, low power, flexible wireless sensor node. The block diagram of the IoE node visualized in the Lightning Sense project is shown in Figure 3. The size of this sensor node is comparable to those of a credit card. Therefore, each individual component of the sensor node needs to be designed in such a way that it can be accommodated within the sensor node. Figure 31 is a draft of this sensor node architecture with all of its components. The main objective of this thesis is to design a printed flexible antenna that operates at 432 MHz, has a higher radiation efficiency, and is smaller so that it can be integrated into a wireless sensor node.

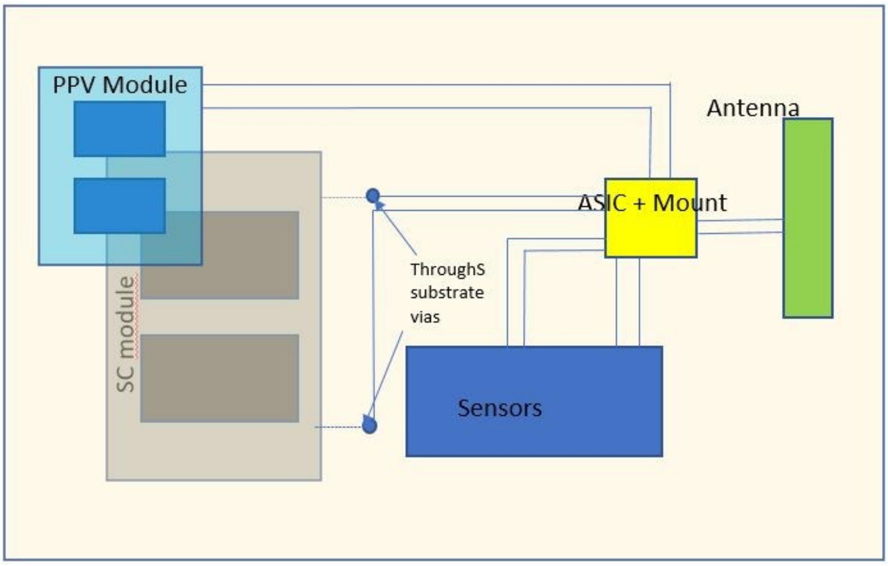


Figure 31. *Draft sensor node architecture*

A wide range of wireless electronic devices incorporate antennas of various sizes. Due to the rapid development of the mobile communications industry, the allure of small antennas has increased in recent years. In designing an antenna, it is necessary to take into account not only the small dimension of the antenna but also its improved performance and efficiency. Miniaturization that has excellent antenna performance poses challenges due to size and performance limitations. Miniature antennas have low bandwidth and efficiency. Therefore, these factors must be considered during the antenna designing process. [116][117].

3.2.1 Antenna Designing

The dipole antenna is a popular example of a simple and easily adaptable antenna design [74]. Utilizing a meander line pattern in the design of the antenna is one strategy that can be utilized to bring down the overall size of the device [118][119]. The idea behind a "meander-line" antenna is to create a shorter, more compact antenna by folding the conductors back and forth. This category of antennas offers a significant decrease in size at a given frequency at the trade-off of a narrow bandwidth. A meander line antenna functions at low frequencies such as 315 MHz [120][121] . 433MHz Meander Line based A 232.5 mm long and 16.4 mm wide printed dipole antenna has been built for unmanned aerial vehicle (UAV) telemetry systems [122]. Three alternative PCB meander line antennas with an operating frequency of 433 MHz have been designed for use in an integrated transceiver design [120]. Researchers were looking for antenna designs that could function at 400 MHz when they came up with the printed dipole antenna, the printed meander line dipole antenna, and the printed monopole antenna utilizing the meander line technology [123].

Development of the printed flexible meander line antenna had been done using CST Studio Suite electromagnetic field simulation software [124]. Silver ink with a thickness of 0.001 mm had been used with PET substrate with a 0.125 mm thickness. Experimented with different number of meander lines with various combinations of length and width values to optimize and fine tune the antenna design at 432 MHz operation frequency. Parameter list of the antenna design is listed in Table 2. Finalized antenna design is 61 mm long and 25 mm wide. Figures 32 – 35 illustrates the front view, side view and the back view of the antenna design. The antenna element is printed on the top side of the PET substrate.

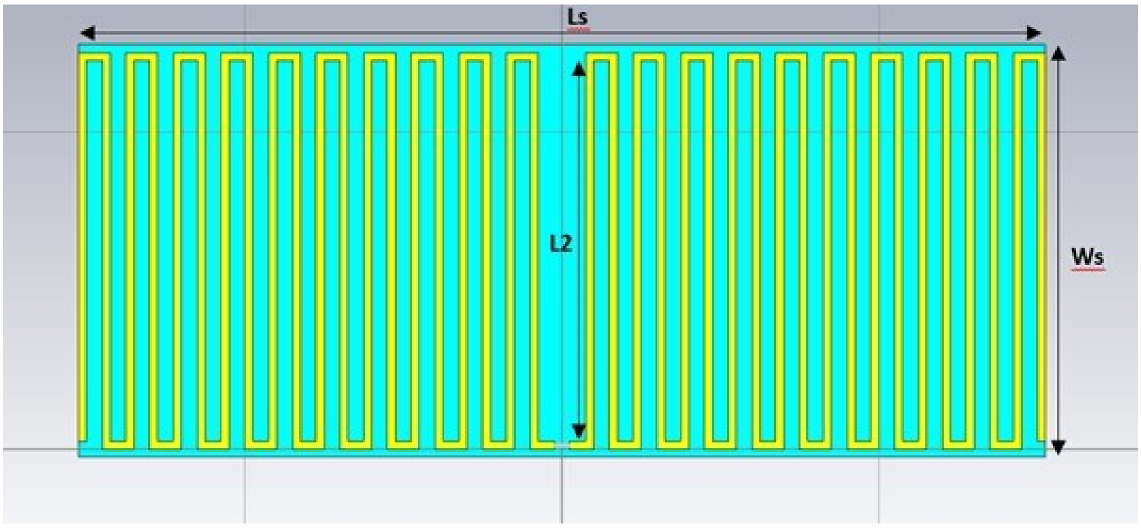


Figure 32. *Antenna Design : Front View*

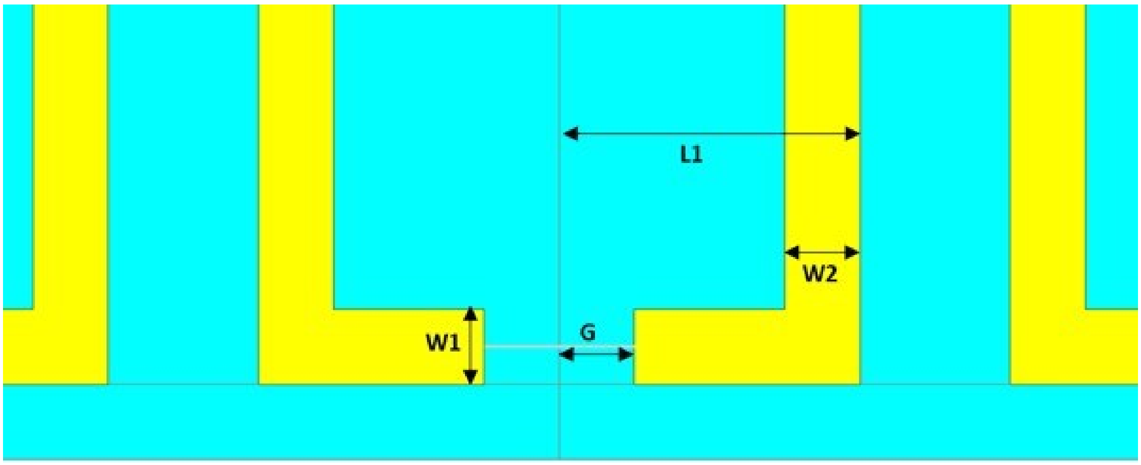


Figure 33. *Antenna Design : Front View – Zoomed in*

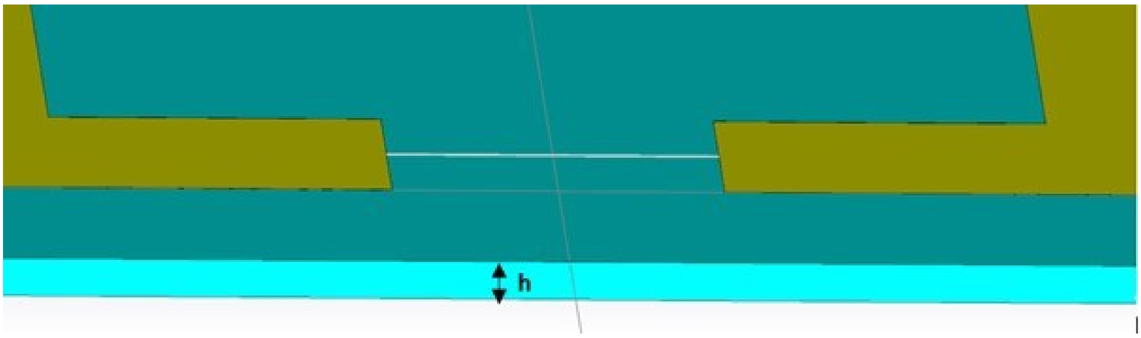


Figure 34. *Antenna Design : Side View*

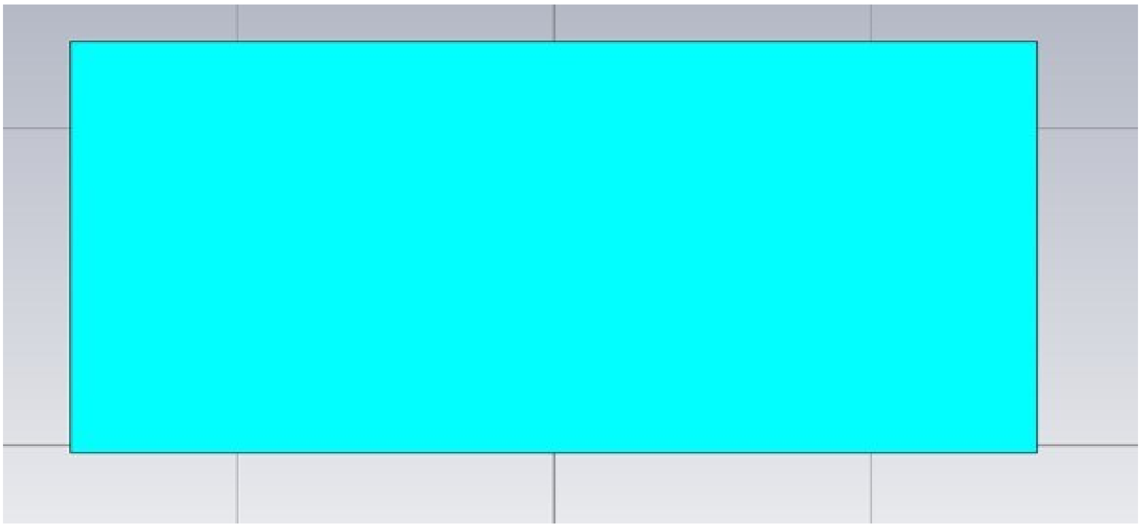


Figure 35. *Antenna Design : Back View*

Table 2. *Parameter list of the Antenna Design*

Parameter Name	**Value (mm)**	**Parameter Description**
L1	2	Length of Line 1
L2	24	Length of Line 2
W1	0.5	Width of Line 1
W2	0.5	Width of Line 2
G	0.5	Gap
St	0.001	Silver Thickness
Ls	61	Length of Substrate
Ws	25	Width of Substrate
h	0.125	Thickness of Substrate

This antenna design had been fabricated using the flexography method. Figure 36 shows the fabricated antenna design. The design has been measured using Vector Network Analyzer, and chapter 4 presents a comparison of simulation and measurement results.

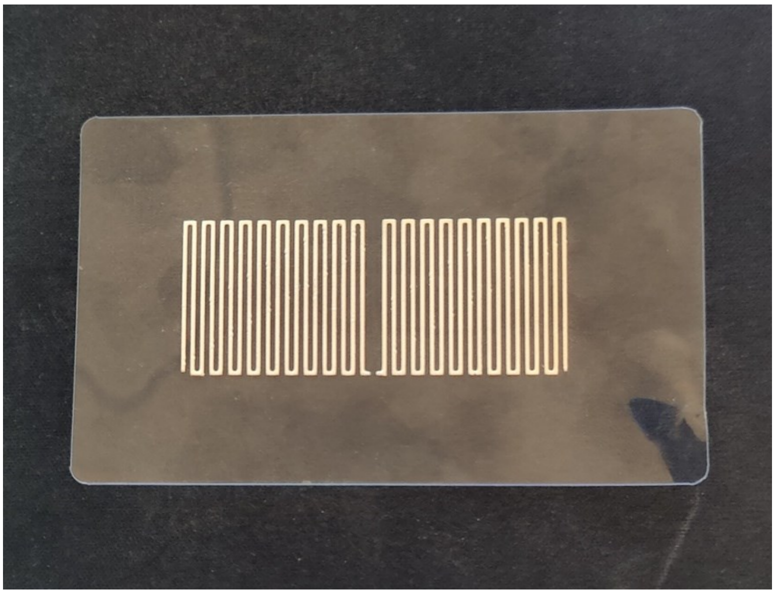


Figure 36. *Fabricated Antenna design*

4. EXPERIMENTAL AND MODELLING RESULTS

This chapter addresses the supercapacitor experimental results, antenna simulation, and testing results that are related to this thesis.

4.1 Supercapacitors

This section presents the results of the Supercapacitors described and fabricated in section 3.1. Several Supercapacitor samples were fabricated during this thesis work. Figures 28 and 29 show the structure of the SCs as well as how they looked after fabrication. Table 3 displays the results of two of the best performing Supercapacitors. The dimensions of the electrodes were 18 mm * 10 mm, and the dimensions of the current collector were 30 mm * 30 mm. Measurements were taken using the Maccor 4300 test system on the same day that the SCs were made.

These achieved Capacitance, ESR and Leakage current value are comparable to the experiment values achieved under Lightening sense project [22][113]. Figure 37 (a) displays the charge-discharge cycle of Supercapacitor sample 27 at 1 mA, 3 mA, and 10 mA constant current. This plot clearly shows the IR drop. Figure 37 (b) illustrates the charge/discharge cycle using different count of cycles and CV measurements.

Table 3. *Experimental results of the Supercapacitors*

Sample No	**Capacitance (mF)**	**ESR (Ω)**	**Leakage Current (μA)**	**Specific leakage current (μAF−1)**
25	186.2354	11.0232	3.7693	20.239
27	198.9639	10.1514	4.3361	21.793

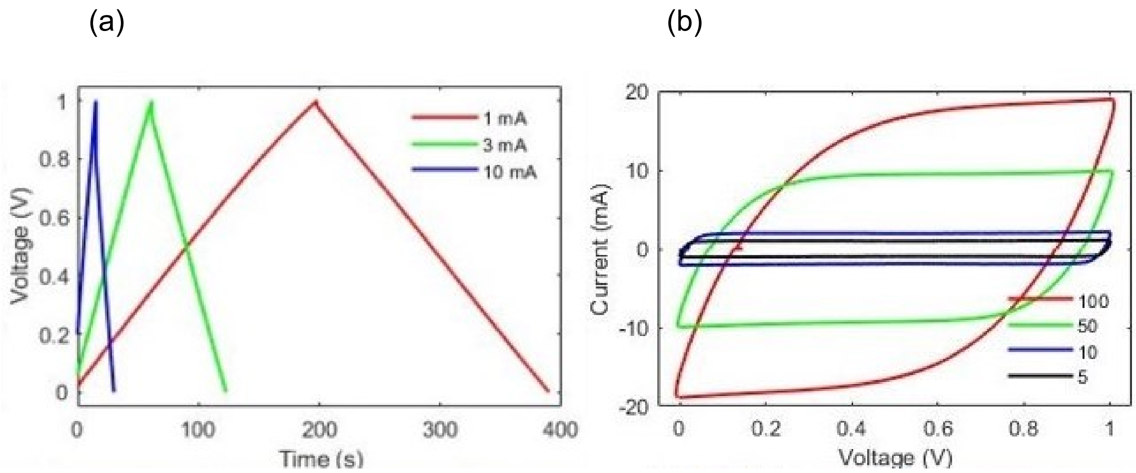


Figure 37. *Supercapacitor Sample No 27.: (a) Charge-discharge cycle with 1 mA, 3 mA and 10 mA , (b) CV curve with 5 ,10, 50 & 100 cycles*

4.2 Antenna Simulation

As stated in section 3.2.1, CST Studio Suite software was utilized for modelling printed flexible meander line antenna shown in figure 32. Parameter values shown in table 2 were the antenna dimensions utilized for this simulation. Utilized the following Simulation settings for the simulation process.

Simulation Settings:

- Time Domain
- Accuracy: - 80 dB
- Adaptive mesh refinement: On
- Maximum delta value: 0.002

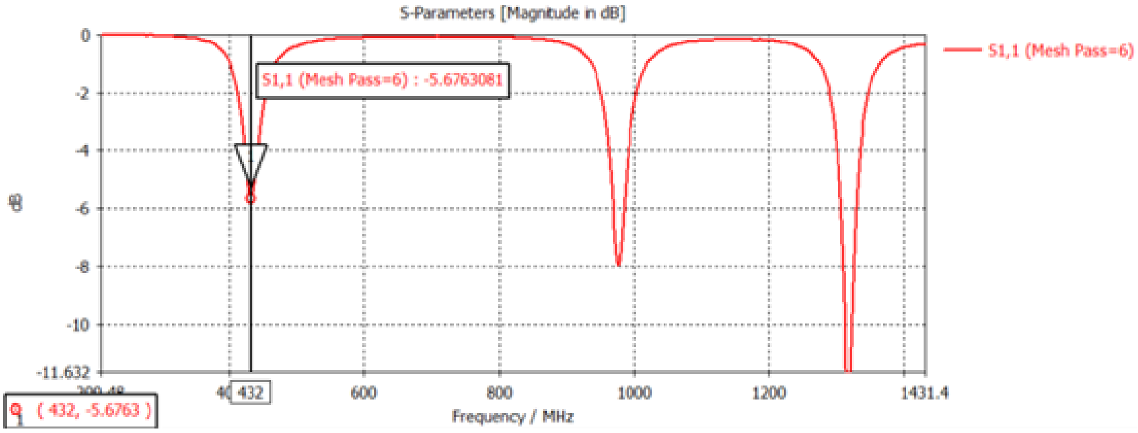


Figure 38. *Antenna Simulation: S parameter(Magnitude in dB)*

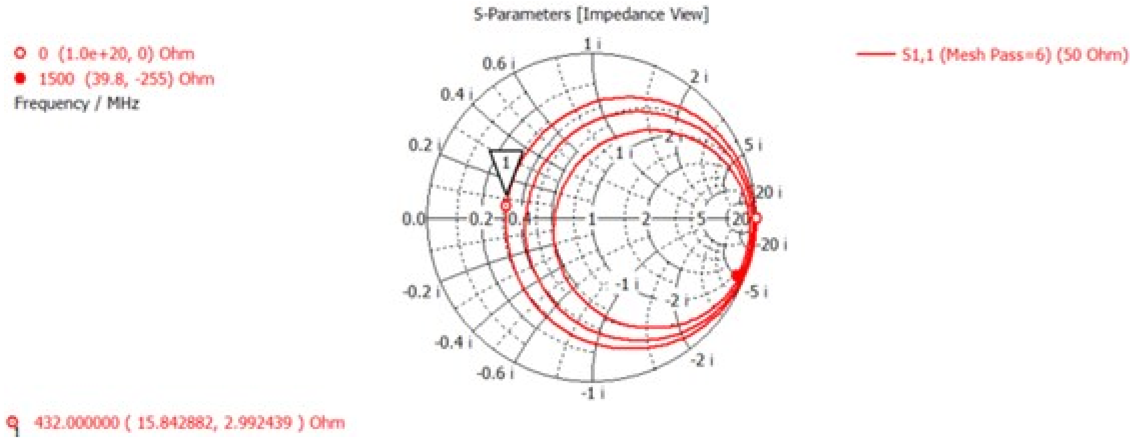


Figure 39. *Antenna Simulation: S parameter(Impedance view)*

The Simulated S_{11} parameter (Return loss) for the antenna design is shown in Figures 38 and 39. The S_{11} value at the operating frequency of 432 MHz is 5.67 dB. S_{11} value at 432 MHz operation frequency is at 5.67 dB. You want your S11 parameter to be as low as feasible (usually less than -10 dB) for the frequency you're operating your antenna at. However, given the fact that this antenna is intended to be integrated into the wireless sensor node shown in Figure 31, I had to keep it within a small dimension. Hence, this is the best S11 value I was able achieve for this antenna design after a lot of fine tuning and parameter optimization. Figure 40 below shows the simulation plot of the VSWR for the antenna design. The simulated VSWR value at 432 MHz is 3.16. In general, a VSWR value below 2 is regarded as an excellent antenna match. Nevertheless, the achieved VSWR of 3.1 is an acceptable value given the miniature design.

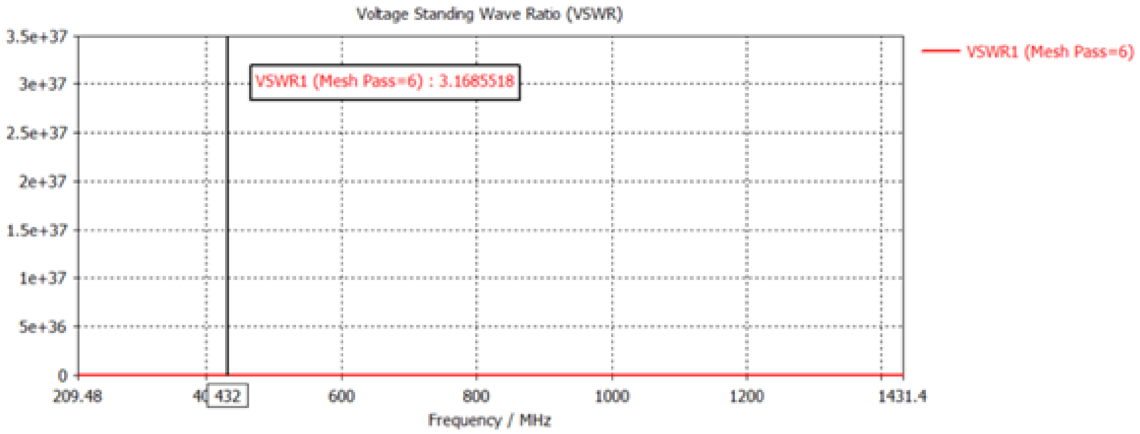


Figure 40. *Antenna Simulation: VSWR at 432 MHz frequency*

Figures 41–43 below show the simulation results for the antenna's Farfield directivity, Farfield gain, and Farfield realized gain at 432 MHz. This antenna has an ominidirectional radiation pattern in which the radiated energy is nearly identical in all directions within that plane.

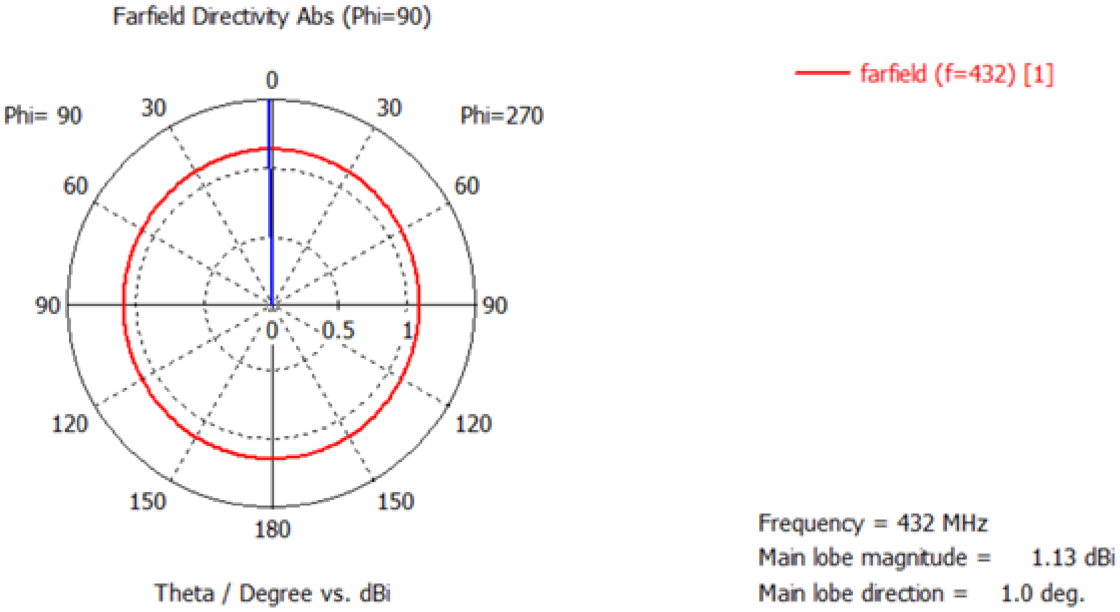


Figure 41. *Antenna Simulation: Farfield Directivity Abs*

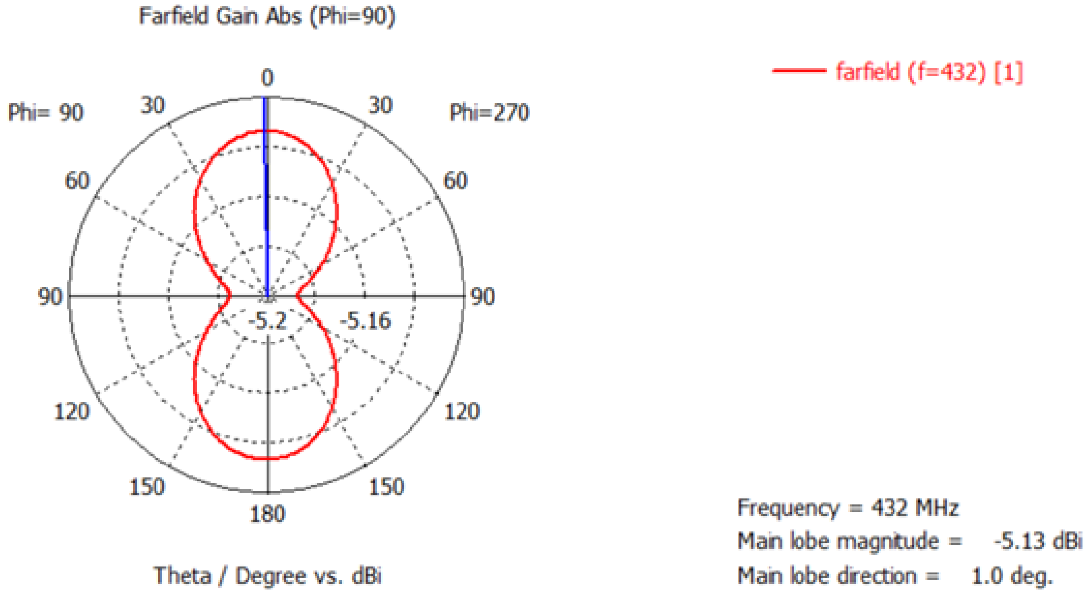


Figure 42. *Antenna Simulation: Farfield Gain Abs*

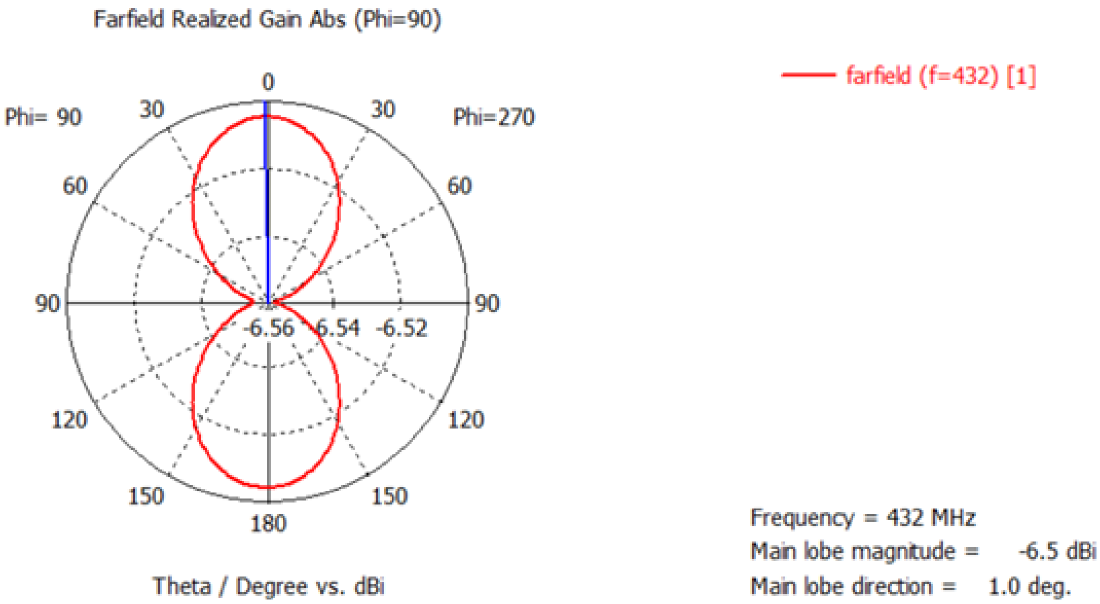


Figure 43. *Antenna Simulation: Farfield Realized Gain Abs*

4.3 Antenna Testing

The designed Antenna was tested in order to validate its performance. Utilized the fabricated antenna design depicted in figure 36 to carry out the measurements. The Keysight E5080A ENA Vector Network Analyzer was utilized to take measurements.[125]. The measurement device was properly calibrated prior to measurements being taken. Measurements were performed at the antenna's designed center frequency of 432 MHz. The results of S parameter measurements are shown in the figures below.

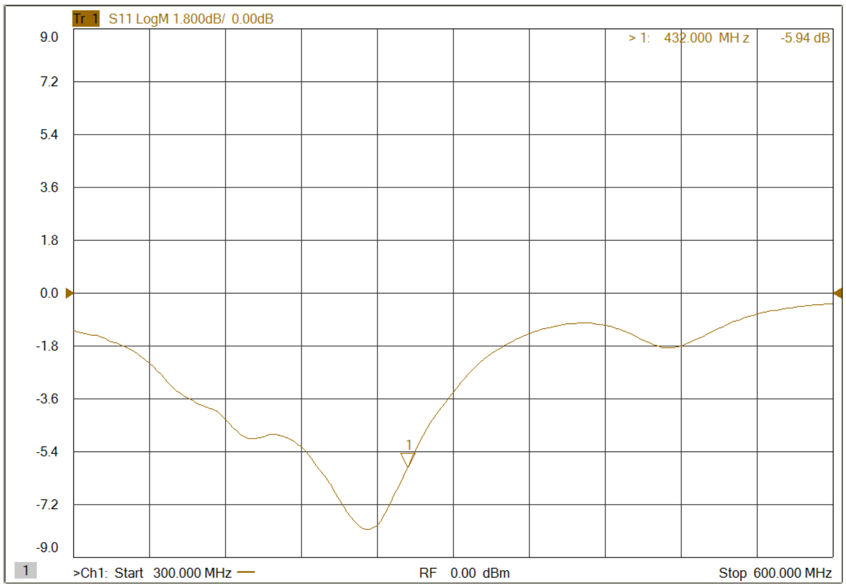
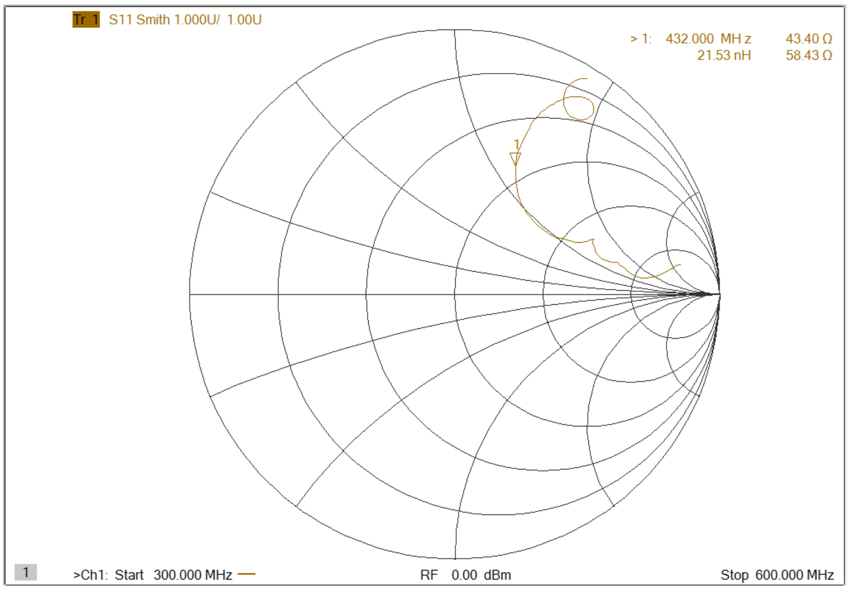


Figure 44. *Antenna Measurement: S parameter(Magnitude in dB)*



S11 Smith 1.000U/ 1.00U

> 1: 432.000 MHz 43.40 Ω
21.53 nH 58.43 Ω

>Ch1: Start 300.000 MHz

RF 0.00 dBm

Stop 600.000 MHz

Figure 45. *Antenna Measurement: S parameter(Impedance view)*

It was obesrved that measured S_{11} parameter (Return loss) value at 432 MHz operation frequency was around 5.94 dB and it has a low bandwith. The simulated S11 parameter value at 432 MHz operation frequency was about 5.67 dB, which is close to the measured value. This measurement indicates that the proposed antenna design is capable of operating at the intended 432 MHz frequency. There is a tradeoff between the size of the antenna and its return loss. Reducing antenna size decreases return loss. Hence, it is difficult to obtain higher return loss values for miniature antenna designs such as ours. When looking at the measurement results, one observes that it is feasible to achieve a slightly higher return loss value by shifting the resonant frequency to the right. This should be possible by performing some parameter tuning and antenna optimization in the design to achieve further improvement.

5. CONCLUSION

5.1 Challenges

The goals of this thesis work are outlined in Section 1.3, and numerous difficulties were encountered while working on it. Following is a list of some of the most significant ones.

- Based to the goals of the "Lightning sense" project, the Sensor node's dimensions have to be about the size of a credit card. The design of this structure must accommodate all the Sensor node's components. Therefore, designing a miniature antenna at the operating frequency of 432 MHz was very challenging.
- It was difficult to determine an antenna design that met the frequency and size requirements of the wireless sensor node.
- The Antenna Simulation procedure required significant time and effort. For the simulations to be completed in an acceptable amount of time, substantial computational power is needed. Each simulation and parameter tuning required a great deal of time due to computational capacity constraints.
- Due to the size and frequency requirements of the wireless sensor node, it was very challenging to design an antenna with high efficiency and bandwidth. In order to fulfil the dimension constraint, some degree of efficiency has been sacrificed.

5.2 Future Prospects

The primary objective of this "Lightning sense" research project is to investigate each of the individual components of future IoE systems and integrate them into a wireless sensor node that is flexible, lightweight, compact, environmentally friendly, and autonomous in terms of energy. The figure below depicts the finalized sensor node design after all components have been integrated. Antenna, IC, Supercapacitor, and Solar cells are integrated on both sides of the PET substrate, as shown in the figures 46 & 47 below.

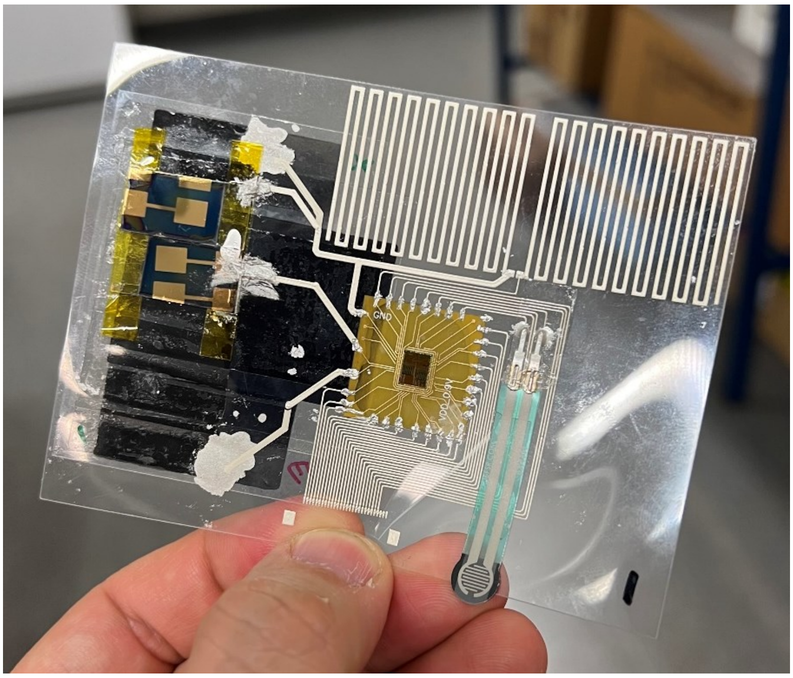


***Figure 46**. Sensor Node : Front View*

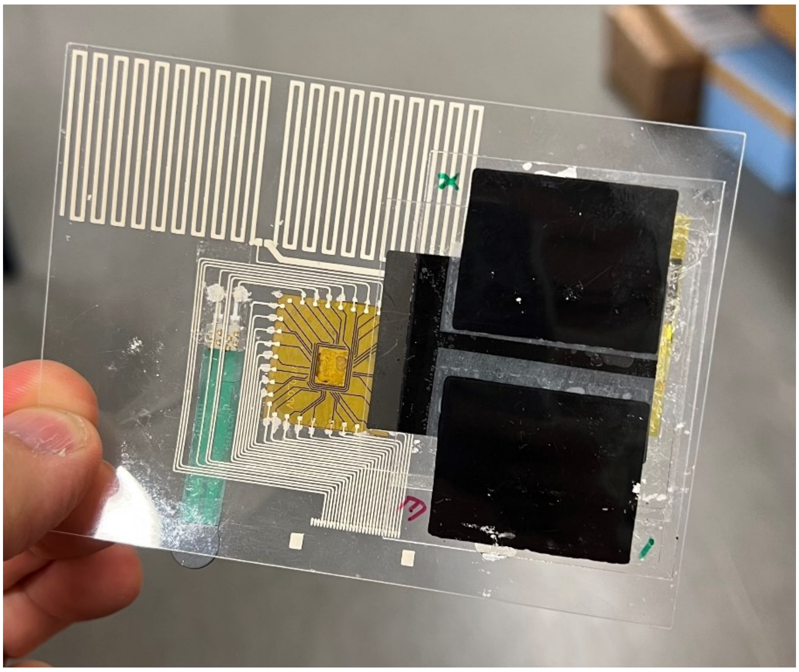


***Figure 47.** Sensor Node : Back View*

This sensor node design can be considered as a steppingstone for future IoT / IoE systems. This sensor node design can be further developed by conducting additional research in a variety of ways. Some of these methods are listed below.

- Testing the functionality and the performance of the sensor node.

- Adding various types of sensors and then monitor and evaluate the performance of sensor node.
- Optimizing and fine tunning the antenna design (without increasing the antenna dimensions) to improve the performance and efficiency of the antenna.
- Conduct application test for a long period of time to monitor the performance of the sensor node

5.3 Conclusion

The primary objective of this thesis was to design a miniature flexible antenna operating at 423 MHz that would fit into the design of the miniature sensor node intended for the "Lightening sense" project. The second objective was to measure this antenna and compare the test outcomes with the simulation results. And the other objective was to fabricate and test the laminated face-to-face supercapacitors.

This antenna design process began with an investigation into potential antenna designs for this frequency and application type. For the antenna design, a meander dipole structure was settled on, and simulations were carried out using different meander line antenna designs, involving parameter tuning and optimization. After extensive attempts, a miniaturized meander dipole antenna that performs well at 432 MHz frequency was successfully designed. The antenna design was then built, and when the antenna simulation results were compared to the antenna testing results, it was obvious that this antenna operates well in actual situations. Laminated face-to-face supercapacitors were manufactured, and their performance was measured. After making multiple samples, the results were comparable to those from this "Lightening Sense" research.

This antenna design and the supercapacitors have been integrated into the Wireless sensor node design, as detailed in section 5.2, and further testing should be carried out in the future to evaluate and improve this sensor node design. This sensor node design can be viewed as a foundational step towards developing environmentally friendly IoT wireless sensor nodes in the near future.

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