

Battery-Free Water Leak Detector Design Towards High-Scale Production

by

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Author's Declaration

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

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

Abstract

Water leaks can be a significant destructive environmental phenomenon that can result in extensive damage if not addressed promptly. Internet of Things (IoT) sensors help connect objects to the Internet for recording and processing data. IoT water leak detectors in the market all use an external power supply (generally batteries) to stay active and detect leaks. Alongside the environmental footprint, batteries result in, they can cause severe flaws in performance because of their variability with temperature and extreme environmental conditions. To fill the gap in this field, previous students working in the team developed a battery-free water leak sensor. The conceptual base of the leak detector design uses a water-induced energy harvesting method. In this thesis, the leak detector electronics and assembly design are optimized for high-scale production.

The electronics unit, which includes the Energy Harvesting board and Bluetooth Low Energy (BLE) board, requires an energy harvesting scheme to activate a BLE chipset. The first step includes understanding the power generation capacities of the water-induced energy harvesting method. Subsequently, the current consumption patterns of the BLE chipset (nRF52832) are investigated at this stage. The performance of the first released design is tested, and it is clear that due to the transient nature of the water-induced energy harvesting method, the energy harvesting technique requires modifications. This involved changing resistor components, which in turn enhanced the performance of the device. Finally, a new BLE chipset (IN100) is investigated and used in the board design for lower current consumption and lower cost. The electronics unit is notably simplified to a single board.

Following the simplicity of the new electronics unit, the sensor unit (power generation unit) also needs simplification in the assembly process. Besides designing a new assembly procedure, it is necessary to understand the flaws and inaccuracies in the current sensor unit enclosure design for future design iterations. The new sensor unit assembly procedure reduces the total assembly time for each sensor by 40%, compared to the initial assembly process. Finally, the performance of the final device using the new sensor unit assembly procedure and the single board electronics design is verified when applying Acceptance Quality Limit (AQL) testing.

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I received tremendous support from graduate student Nathan Johnston. Nathan helped with my onboarding and then continued to assist me through his time with the team. Without his support, I doubt I could have proceeded with the research as smoothly as I did.

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Dedication

To my late aunt, Baano. I regret that I cannot share this accomplishment with her in person, but I am certain she would have been proud of me, and that brings me great joy. Baano, you taught me that it is possible to find happiness even in the most difficult times of life, and for that, I will always be grateful.

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List of Abbreviations

Abbreviation	Definition
IoT	Internet of Things
POC	Proof of Concept
MVP	Minimum Viable Product
BLE	Bluetooth Low Energy
CNF	Carbon Nanofiber
EHB	Energy Harvesting Board
PCB	Printed Circuit Board
OCV	Open Circuit Voltage
DMM	Digital Mutimeter
SMU	Source Measurement Unit
LDO	Low Drop Out
QC	Quality Control
DOE	Design of Experiment
AQL	Acceptance Quality Limit

Chapter 1

Introduction

1.1 Background

Water leak damage is one of the most frequent and expensive insurance claims [1]. IoT water leak detectors all use batteries or a wall outlet, which brings up problematic aspects. Since wall outlets are not available in all possible deployment locations, it is a limiting factor, and since batteries require frequent maintenance, it is not the best option for hard-to-reach spots. To solve the issues associated with an external power source (battery or wall outlet), a previous colleague worked on mechanical packaging (enclosure design) of a self-powered materials-based water leak detector [2]. The battery-free water leak detection system consists of a leak detector that generates power and sends a Bluetooth signal when it encounters water as little as 1 mm deep. The Bluetooth signal is received by a Gateway which connects to a cell tower and forwards the Bluetooth signal to the Cloud. Finally, the notification is sent to the user via text and email. The battery-free leak detection system process and its advantages are shown in Figure 1.

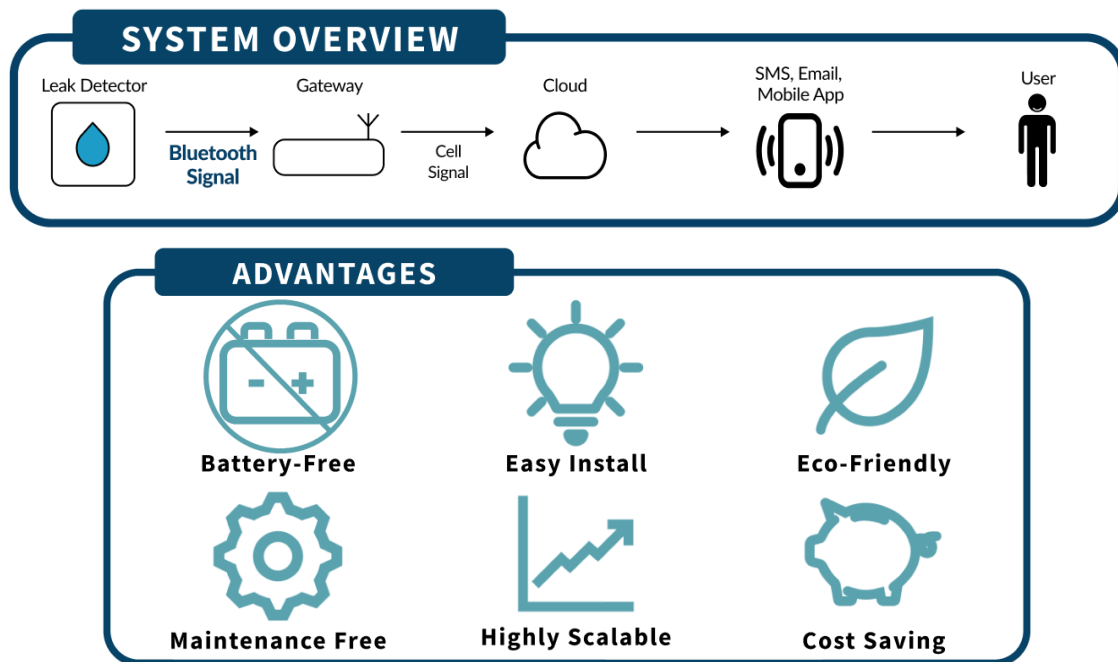


Figure 1: AquaSensing battery-free water leak detection system and its advantages over battery-based IoT leak detection systems

There is a several-step transition in moving from a Proof of Concept (POC) to a product with high-scale production. The current battery-free water leak detection system is in the Minimum Viable Product (MVP) stage, and to move to a Product, there are important tasks to fulfill. Product design consists of continuous customer feedback and evaluation, which is vital for constructing a user-friendly and easy-to-use system. Simultaneously, the hardware design and assembly procedure must be optimized to lower the costs of the final device. Figure 2 shows the iterative approach used in product design, alongside the timescale for each step [3].

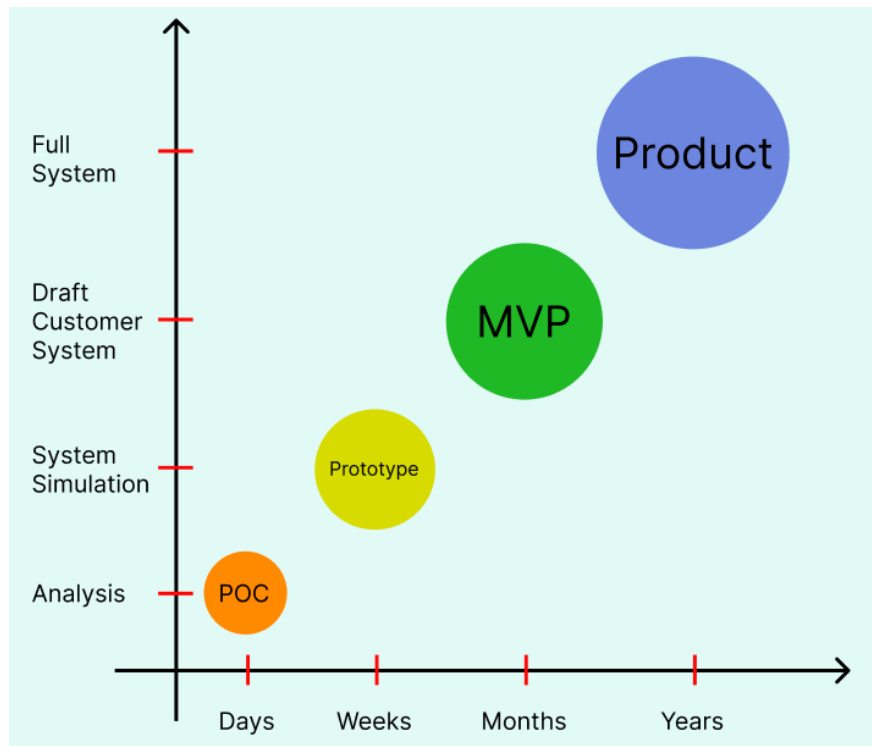


Figure 2: Product design transitions, starting from POC all the way to the final product [3]

1.2 Objective

The main objective of this thesis can be expressed as scaling a lab made, battery-free water leak detector. To achieve this goal, the two subunits of the device (sensor unit and electronics unit), must be individually investigated.

For the electronics unit, the goal was to design, test, verify an energy harvesting circuit that could be compatible with a water induced, materials-based power generator. Then simplify the circuit to become a scalable solution. Secondly, the sensor unit materials assembly should be optimized to lower down the cycle time and increase the efficiency of the assembly procedure. Alongside lowering hardware and assembly costs, it is necessary to understand failure modes for a future re-design of the device. Finally, the overall performance of the device should be acceptable within the standards set.

1.3 Thesis Outline

The chapters of the thesis are explained here. Chapter 2 provides a literature review on the purpose of using IoT sensors in environmental monitoring, as well as water leak sensors available in the market and the energy harvesting schemes available to eliminate conventional power sources. Chapter 3 focuses on the sensor unit power generation capacities, the initial energy harvesting scheme used, and the optimized energy harvesting circuit utilized, along with an evaluation of the repeatability of each energy harvesting circuit. Chapter 4 involves introducing a modified material assembly procedure, as well as the failure modes associated with the current sensor unit design. Chapter 5 presents the conclusion, recommendations, and directions for future works.

Chapter 2

Literature Review

2.1 Introduction to Chapter 2

The emerging technology known as the Internet of Things (IoT) has extensive potential for measuring environmental variables and enabling the development of smart cities. To satisfy the diverse requirements of different IoT systems, various wireless protocols have been designed in different spectrums, each providing its own set of advantages. This being known, the many available IoT water leak sensors in the market vary by wireless protocol, and many other specifications, however, they all use an external power supply (battery) to work. To move away from the issues caused by the use of batteries, energy harvesting techniques are discussed in a broad sense, and then the core technology of the self-powering water leak sensor presented in this thesis is reviewed.

2.2 Internet of Things (IoT)

The Internet of Things (IoT) is an emerging technology that is defined as connecting physical objects with sensors through wireless networks to record data and send the captured data over the Internet [4]. IoT can be used extensively for observing environmental variables [5]. The purpose of environmental monitoring is to ease the comfort level of humans by remotely recording data related to the living environment, energy consumption, and industrial needs, then reporting it via the Internet [6]. IoT can be used for monitoring environmental parameters, which can be applied to various aspects such as water & air pollution, waste management, agricultural control, and many other applications [7]. A worldwide effort is in place to prevent further damage to natural resources, and considering the advances in IoT, it can play a vital role in capturing data and providing remote access to the recorded data [8]. Figure 3 shows smart environment monitoring using IoT sensors [8]. A projection on the number of IoT devices connected worldwide shows that by 2025 this figure will reach 75 billion devices [9].

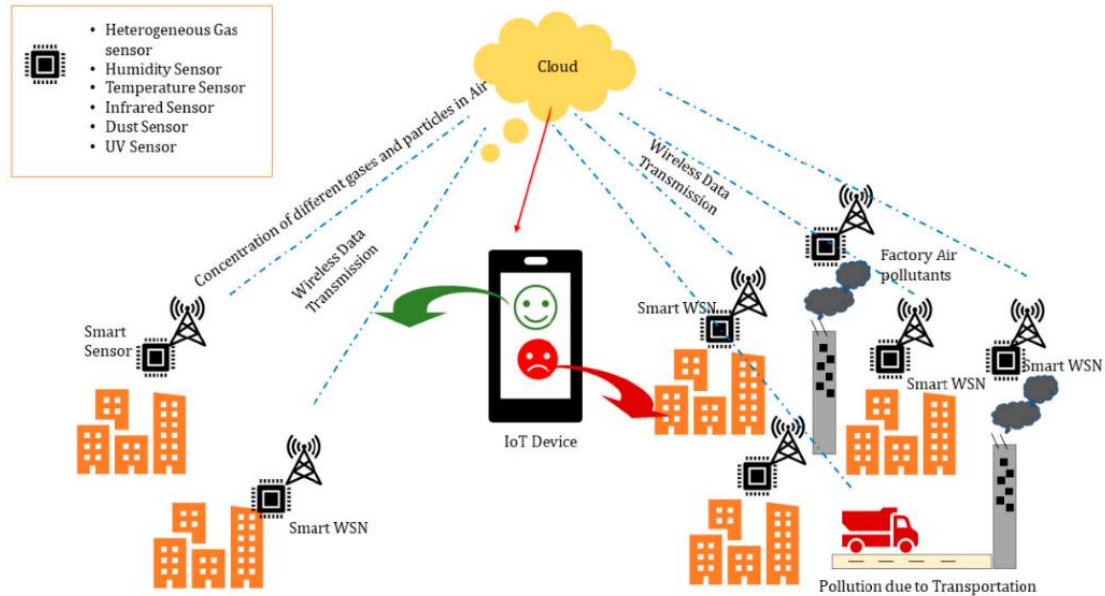


Figure 3: Smart environment monitoring using IoT sensors [8]

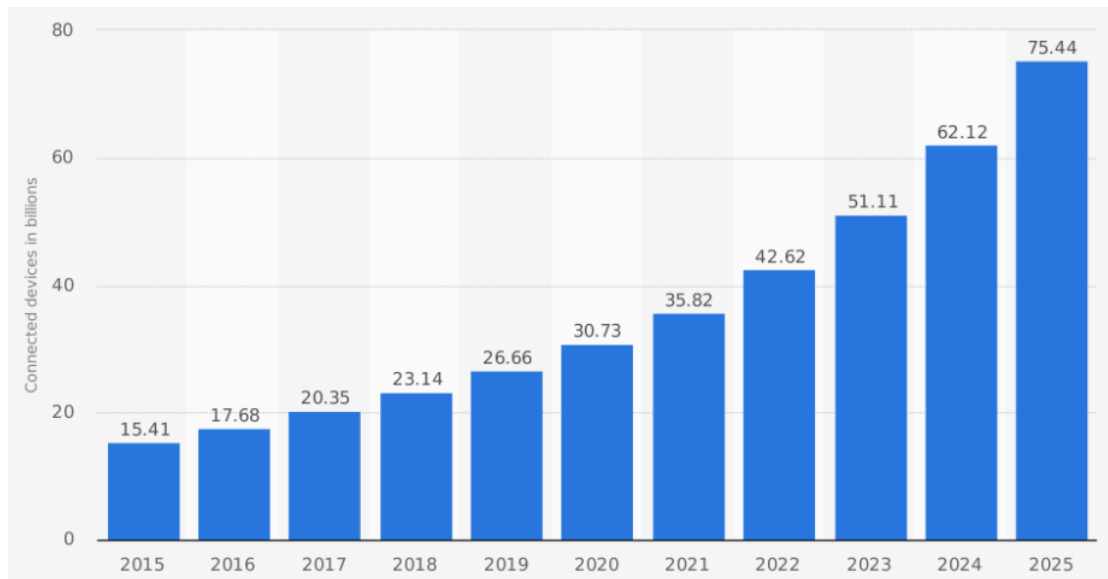


Figure 4: Worldwide connected IoT devices from 2015 with a forecast to 2025 [9]

2.2.1 Wireless Protocols

Several communication protocols have been specifically designed for IoT applications. The application's purpose and requirements must be considered for determining which wireless protocol is the most suitable for an application. [10]. A summarized comparison of a few well-known IoT wireless protocols can be seen in Table 1, which indicates the spectrum, peak current consumption, range, and data rate (maximum amount of data that can be wirelessly communicated per second) for each wireless protocol. An essential factor of a wireless protocol is its ability to penetrate through walls and obstacles, which depends on many factors, including the frequency band it uses. Wireless protocols, which operate in the sub-GHz frequency band, can penetrate through walls more effectively than those in the 2.4 GHz band [11].

It is crucial to investigate the current consumption of the communication protocol for achieving more extended battery life for IoT sensors. The current consumption can be categorized into peak and average current consumption. Peak current consumption serves as a valuable metric for comparing the power requirements of different wireless protocols and determining the size and capacity of the power source necessary to utilize a wireless protocol. Although both BLE and Zigbee are recognized as ultra-low power wireless protocols, a previous study [12] found that BLE is more energy-efficient under similar testing conditions than Zigbee regarding the number of bytes transferred per Joules spent. It is vital to note that chipset variations, even for the same wireless protocol, can result in different current consumption patterns and magnitudes; therefore, the values stated in Table 1 estimate the peak current consumption for each protocol. A previous study [13] has shown that under similar application conditions (temperature sensing), the lifetime of an IoT device working with two AAA batteries, is ~24 years if BLE is chosen and ~1 year if LoRa is used.

Depending on the application of the IoT device, the range can be a critical factor. A standard classification for the range of wireless protocols is long-range networks (such as Lora and SigFox) and short-range networks (such as BLE, Zigbee, and WiFi) [14]. The range of a wireless protocol can be increased by configurations such as TX power level and PHY settings that are used for programming a wireless chipset. A study [15] shows that the latest BLE 5 can reach an outdoor range of nearly 800 m, using a TX power level of 9 dBm. Although, it needs to be noted that changes to TX power levels or PHY configurations alter the current consumption patterns and can lead to an overall increase in power consumption.

Table 1: Comparison of wireless protocols available in the IoT industry

Wireless Protocol	Spectrum	Peak Current Consumption (mA)	Outdoor Range (m)	Data Rate	Relative Cost
BLE [16]–[18]	2.4 GHz	15	100	1 Mbps	Very low
Zigbee [16], [17], [19]	2.4 GHz/915 MHz/868 MHz	30	100	250 kbps	Low
WiFi [16], [20]	2.4 GHz	100	100 to 250	54 Mbps	Medium
Z-Wave 700 [17], [21]	900 MHz	40	1600	100 kbps	Low
LoRa [18], [22], [23]	868 MHz	120	3000 to 5000	300 kbps	High
SigFox [18], [23]	915 MHz	230	3000 to 10,000	1 kbps	High

2.3 Water Leak Sensors

An environmental variable that is deemed to be a destructive phenomenon for homeowners and industrial facilities is water leaks. Water leaks can cause vast and extreme damage, and also the importance of water sources create high demand for finding solutions for this major worldwide problem [24]. A report released [1], stated that 48% of the insurance claims in Canada correspond to water damage. Moreover, the same report said that 47% of the paid claims are also related to water damage, which can emphasize the importance and severity of water damage.

Many IoT companies have stepped forward to tackle this frequent yet hard-to-identify phenomenon using remote and wireless sensing. The result of the efforts is many industrial IoT sensors, which activate and send users notifications when they come in contact with water, known as “water leak sensors.” Studies have shown that water leak sensors effectively reduce the costs associated with water damage in about 60% of the cases [25]. Noticing that a \$2 billion figure [26] is stated as the annual water damage loss worldwide; reducing even part of this loss can result in extremely large savings.

Table 2 compares some available water leak sensors in the market. All the available spot water leak sensors in the market use an external power source, mainly a “battery,” to stay active. The common detection mechanisms for the leak detectors available in the market are i) conductive probes which result in a closed circuit when they come in contact with any fluids, ii) flow measure through a pressure valve. The leak detectors in the table below use conductive probes as the detection mechanism. Table 2 only shows the pricing of the leak detector component of the water leak detection system. Therefore, it does not provide insight into the access point (gateway or hub) pricing or any monthly subscriptions (if applicable) required for the system to function.

Table 2: Comparison of available water leak sensors in the market

Brand	Price per sensor unit (CAD)	Wireless Protocol /Spectrum	Operating Temperature (°C)	Lifetime (years)
D-Link (DCH-S163) [27]	35	915 MHz	0 to 40	5
Nowa (NOWDSF300) [28]	-	319.5 MHz	0 to 49	10
Yo – Link (YS7903 UC) [29]	33	LoRa	0 to 50	5
Eddy Solutions	-	LoRa	0 to 60	3
Aqara [30]	35	Zigbee	-10 to 55	2
Govee [31]	37	433 MHz	0 to 60	2
Centralite (3315-G) [32]	48	Zigbee	0 to 40	2
Dome (DMWS1) [33]	35	Z-Wave 500	0 to 40	3
B-Hyve [34]	30	BLE	0 to 70	1
SkyLink WA-MT [35]	36	433.92 MHz	0 to 40	2

2.3.1 Battery Issues

Even with low-power wireless communication protocols, the feasibility of implementation for IoT systems in high volumes is questioned due to the energy limitations and costs associated with batteries and their unfriendly environmental characteristics while being disposed of. Previous studies [36] have elaborated on ecological and health impacts caused by batteries. The considerable rise in energy consumption due to the significant growth of the world population means precautionary measures should be placed to prevent further environmental harm [37].

Although the lifetime of batteries varies from a couple of years up to ten years, it has been proven that in reality, these numbers can be impacted by multiple factors including environmental parameters and the application of use [38].

Nowa states that their sensor's battery life is ten years but in a separate report in their website, the issues due to low batteries and the sources of reducing battery life are elaborated [39]. One of the sources of limiting battery lifetime are temperatures lower than 0 degrees Celsius, which can cause the battery to die only in a couple of hours and Nowa asks customers to check the functionality of the battery when they have the opportunity [39]. Mechanisms of ageing and performance decay for lithium-ion batteries at low temperatures is investigated in previous literature [40].

Furthermore, battery swapping leads to many hours of maintenance work per year and difficulty for hard-to-reach sensor locations (which may be locations with low temperatures and can accelerate battery draining severely). Figure 5 shows the number of batteries in each sensor unit, apartment/condo unit, and building. Finally, low or drained batteries can cause water damage without the user being notified.

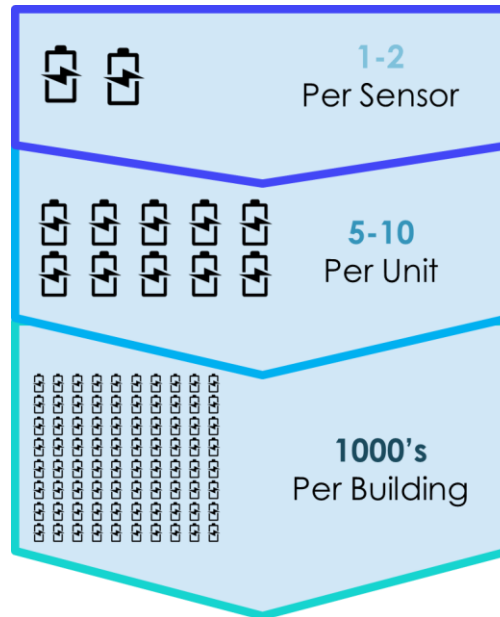


Figure 5: Each sensor requires one to two batteries. Subsequently, each apartment/condo unit with a few sensor units deployed inside would need five to ten batteries. Finally, each building needs thousands of batteries for the water leak sensor. The high number of batteries emphasizes the maintenance work and time required to swap batteries.

2.4 Energy Harvesting

A general description of energy harvesting is collecting energy from the environment, which would be lost due to heat if not captured [41]. Energy harvesting only sometimes requires gathering energy on large scales. Most energy harvesting systems consist of tiny amounts of power, ranging from nanowatts to milliwatts [41]. Energy harvesting systems are a popular replacement for batteries because of the energy limitations of high-scale IoT system deployments. Some environmental energy sources which are extensively made use of are solar [42], wind [43], thermal [44], vibration [45], and ambient radio frequency [46]. In previous studies [47], these types of energy sources have been shown to be suitable substitutes for conventional sources for various applications. Figure 6 categorizes energy harvesting schemes that can be transformed into electrical energy [41].

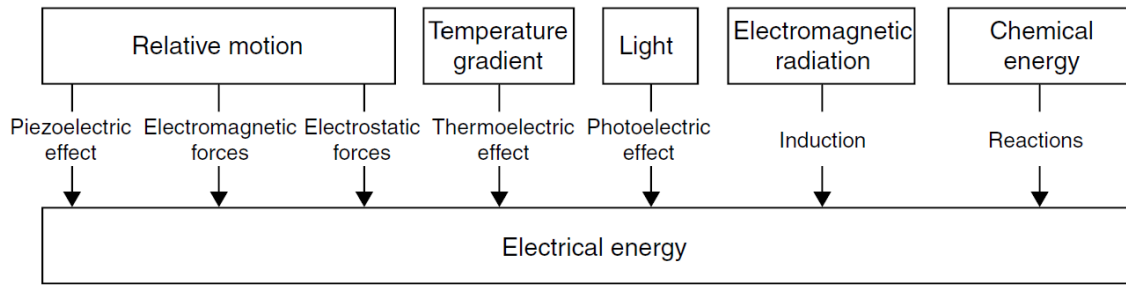


Figure 6: Categorizing energy harvesting schemes [41]

Different energy sources can be suitable for various applications depending on the application's requirements. Energy harvesting solutions may only sometimes be the correct path, especially if batteries, the primary available power source in the market, are already successfully fulfilling the lifetime, cost and ecological needs. The application of use must be carefully investigated to determine the necessity of using energy harvesting systems and the benefits they can provide. Table 1 shows the energy density for some energy harvesting sources.

Table 3: Energy density (per unit square) for different sources

Energy Source	Type	Energy Density (mW/cm^2)
Solar [47]	Electromagnetic	15
Wind [48]	Mechanical	28.5
Thermal [48], [49]	Heat	20×10^{-3} to 60×10^{-3}
Tidal Water [50]	Mechanical	6×10^2
Ambient Radio Frequency [49], [51], [52]	Electromagnetic	2×10^{-7} to 10^{-3}
Water [53]	Electrochemical	166.8×10^{-3}

2.4.1 Water Induced Power Generator

Investigations were conducted on energy harvesting methods developed for applications in water detection. An energy harvesting method from a previous work [54] showed that the Magnesium (Mg) and Carbon Nanofiber (CNF) combination is a hygroelectric generator. Figure 7 shows the concept of the power generation of these materials. It was shown that when the materials are exposed to water, there is voltage and current generation, indicating that it can be identified as a water-induced power generator.

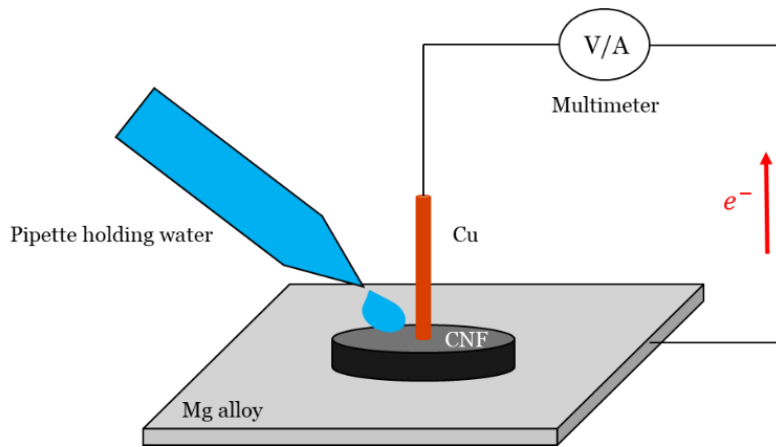


Figure 7: Moisture-induced materials-based energy harvesting technique [54]

Based on this fundamental concept, a self-powered water leak detector was designed and fabricated. However, a replacement of a low-priced porous and conductive material was used instead of CNF, which is relatively expensive. The self-powered leak detector device uses Bluetooth Low Energy (BLE) as its communication method, as it consumes the least power among the other well-known IoT wireless communication protocols. In the water-induced energy harvesting method, power does not increase if a higher volume of water is applied to it. Whereas for the other energy sources in Table 3, the power harvested is a function of the ambient conditions and the concentration of the power triggering variant (sunlight, wind, radio frequencies and rise and fall of tides).

2.5 Summary of Chapter 2

IoT provides remote and wireless monitoring that can reduce possible environmental damages, one of which is known as water leak damage. Most IoT water leak sensors in the market use batteries as the external power source, and few use a wall outlet (which limits deployment locations). Using batteries for IoT sensors has significant flaws, including low battery issues, system scaling issues, and high maintenance requirements for swapping the batteries when drained out. In order to eliminate batteries, the next step is searching for environmental energy harvesting methods that could be used for water leak sensing. A water-induced electrochemical energy harvesting scheme based on Mg and CNF is chosen to fabricate an IoT, battery-free water leak sensing device.

Chapter 3

Electronics Unit Design, Implementation and Results

3.1 Introduction to Chapter 3

Knowing that the sensor unit should be capable of powering up a wireless chipset for communications provides the initiation to finding the sensor unit's electrical performance under various load conditions. Likewise, this chapter will follow two main goals: firstly, reviewing the test procedures and test setups for observing the sensor unit's potential for electrical generation. Second, the Energy Harvesting circuitry design and observation of design performance for two different BLE chipsets. Finally, the two PCB designs will be compared, referencing performance and simplicity (cost).

3.2 Sensor Electrical Performance

Amongst the various methods that can be utilized to observe the electrical characteristics of a power source, load tests are a standard procedure which provides valuable and principal data regarding the power source. A load test, as the name suggests, is a test procedure in which an electrical load (etc. resistance, current) is placed in parallel with the power source (in our case, the sensor unit), draining the power produced from the power source. The result of load tests is a crucial parameter known as the discharge capacity [Watt. Hour]. Watt is the SI unit of power; therefore, discharge capacity indicates the sensor unit's power over the variable of time. As AquaSensing's sensor unit is a transient power source, a time-dependent response can improve comprehension of the sensor characteristics. A constant current electrical load was used in the testing done on the sensor unit. The purpose of this test is to measure the time the sensor can last under specific values of constant current loads and ultimately obtain the discharge capacity of the sensor. This test can also indicate the optimized value of the constant current load.

3.2.1 Experimental Procedure

To start the test, the DMM is set to measure the output voltage of the sensor and the source measurement unit (SMU) is controlled to draw a constant current load from the sensor. The schematic of the load test is illustrated in Figure 8.

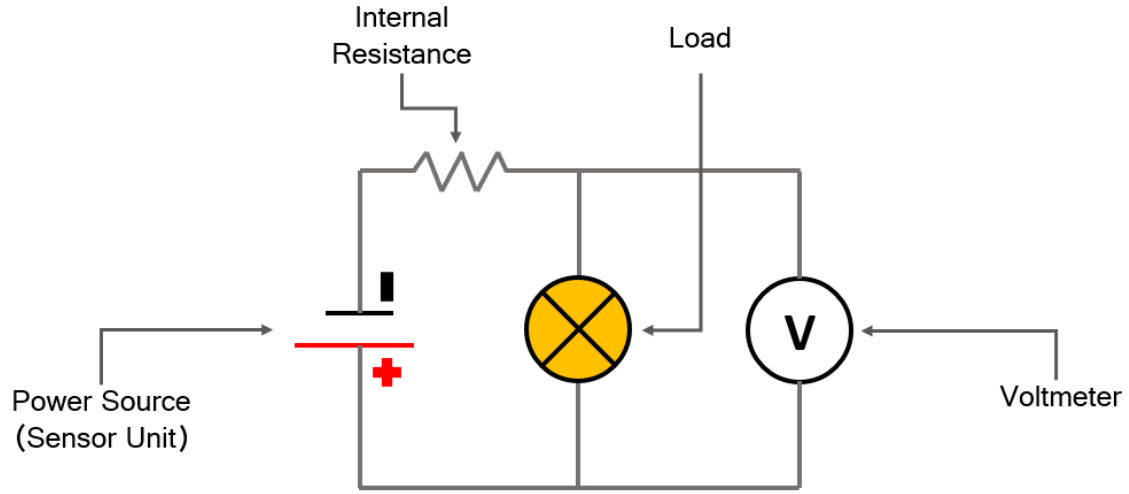


Figure 8: Load test setup, including sensor unit, the internal resistance of sensor unit, and voltmeter for recording voltage of sensor unit

The first stage of the experiment is to start the voltage readings of the DMM, then place the sensor in the water container while the sensor's voltage rises. Since different sensor samples are not identical in reaching their maximum voltage, the procedure was to wait for each sensor to achieve its unique maximum voltage (1.9 - 2.1 V) without any load applied to the sensor. Then after 5 seconds of reaching that voltage, the SMU would be turned on to load the sensor. The end of the test was determined when the sensor's voltage came to 0.5 V because this is the minimum value required to power up the beacon while the EHB is also connected.

After finishing the experiments, the next step was to calculate the discharge capacity of the sensor. For doing so, the area under the curve for the voltage–time graph is found from the constant current load tests (Equation 1). The calculations were done using trapezoidal numerical integration, which was done in MATLAB.

$$\text{Discharge capacity} = \int I \times V(t)dt \quad \text{Equation 1}$$

Because there is a constant current being used as the load, Equation 1 can be simplified further to Equation 2.

$$\text{Discharge capacity} = I \times \int V(t)dt \quad \text{Equation 2}$$

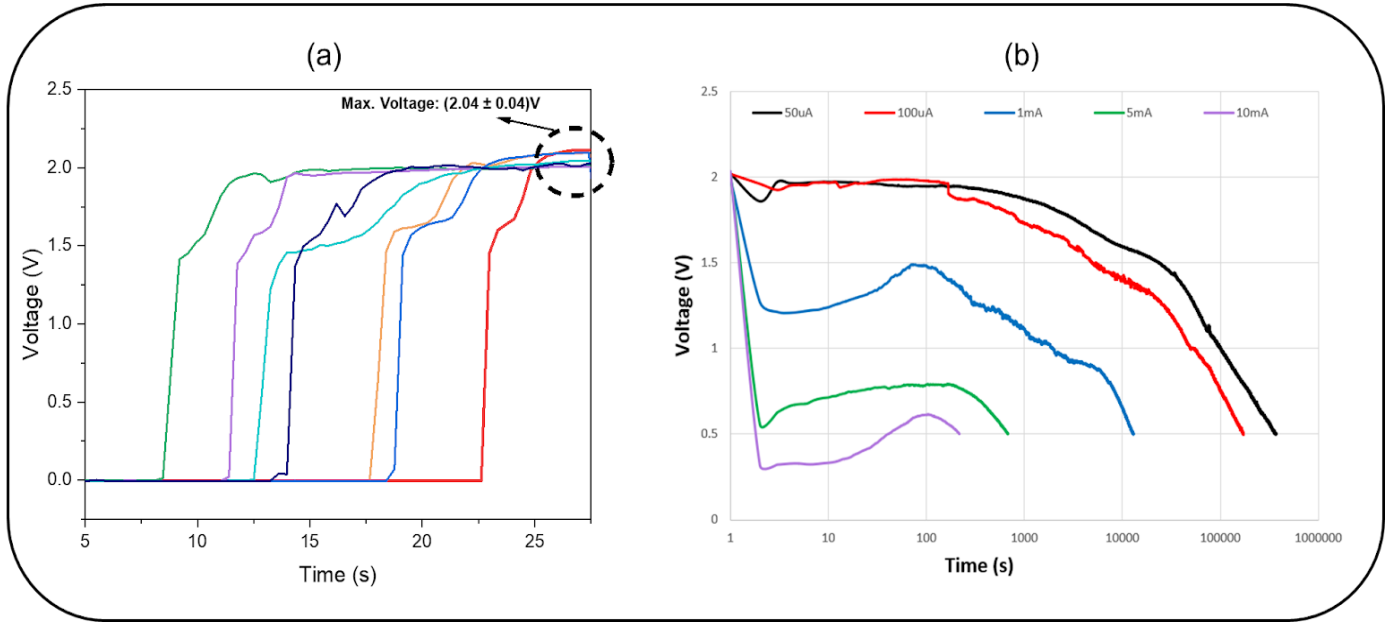


Figure 9: Voltage vs time graphs for sensor unit in the following conditions a) without any external load (OCV) and b) with various constant current external loads [55]

3.2.2 Results

Five different load currents chosen were: $50\mu A$, $100\mu A$, $1mA$, $5mA$ and $10mA$. As expected, the lowest load ($50\mu A$) showed the highest discharge capacity ($301.23 \mu Wh$), whereas the highest load ($10mA$) indicated the lowest discharge capacity ($22.36 \mu Wh$). As expected, the discharge capacity falls with the load increase, and vice versa. Figure 10 shows the discharge capacity versus constant current load graph. In addition, Figure 10 also shows that the decreasing load from $100 \mu A$ to $50 \mu A$ does not play a significant role in alterations of discharge capacity. Therefore, to find an approximately constant current load in which the sensor can work with little change in the power characteristics, we can choose either $50 \mu A$ or $100 \mu A$. Considering that the voltage decay is minimal in the voltage-time graphs in Figure 9 for $50 \mu A$, it was chosen as the optimized value for the load tests, and the load tests hereon in this thesis were all done using this value.

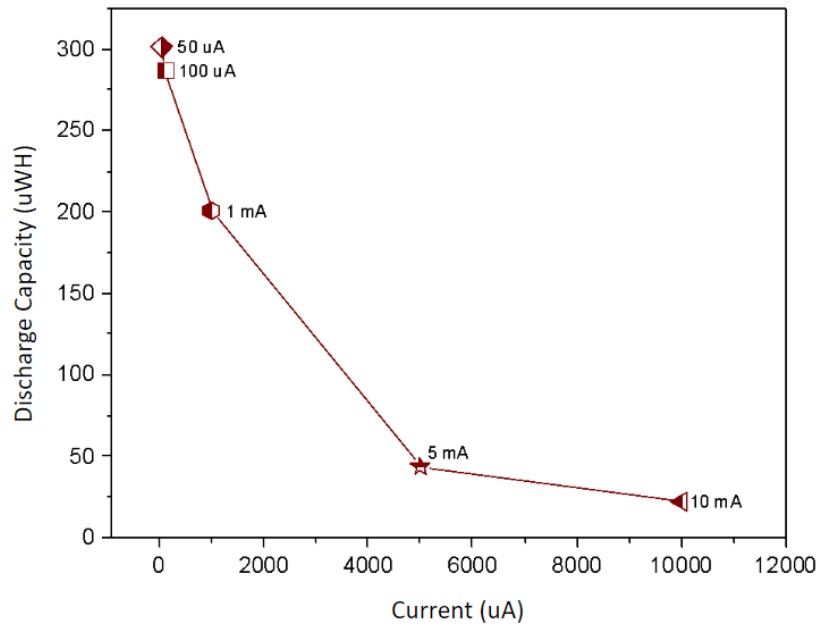


Figure 10: Alterations in discharge capacity for constant current loads consumed [55]

3.3 nRF52832 Chipset

In order to advertise a wireless signal, a chipset which utilizes a wireless protocol (Bluetooth Low Energy) is used in the circuitry. The initial chipset used in AquaSensing's PCB designs was nRF52832 chipsets from the Norwegian company Nordic.

3.3.1 nRF52832 Current Consumption

Before designing an electrical circuit, the primary source of load on the sensor must be evaluated. Since the wireless chipset is the most demanding component in consuming power, understanding the power consumption patterns in the chipset is a critical task. When observing the power consumption of a chipset, since the voltage demand is at a constant level (Can activate in the range of 1.7 V - 3.6 V), the oscillating demand is related to the current. Nordic's online power profiler for BLE provides detailed information on the current consumption pattern of the BLE chipsets, using the user inputs on the settings chosen for the chipset. The user inputs were set as voltage value at 1.8 V (approximate to the sensor's OCV and chipset minimum Voltage requirement), the radio TX power at 0dBm and the advertising interval as 1000 ms (indicating that the Bluetooth advertisements occur every one second).

The results of the Nordic power profiler can be seen in Table 4. This table shows the different steps in the beacon advertisement and the associated current consumption and time for each step. The current consumption pattern can be divided into two main parts: the high load state when the beacon is advertising data in the advertisement interval period (Also known as TX mode). The second is the Idle mode when the load is low. In order to find the average current consumption, all the different modes of consumption can be averaged while considering the time of each step. This approach is similar to what is used in a previous work [56] and can be seen in Equation 3.

$$I_{\text{average}} = \frac{\sum I_s \times t_s}{t}, \quad S \in \{\text{TX, Idle}\} \quad \text{Equation 3}$$

In Equation 3, I_s is the current consumption in each of the TX and Idle modes, and t_s is the relevant time duration of current consumption for each mode.

Table 4: Current consumption of the Nordic nRF52832 BLE Chipset during the high load state

Step	Current Consumption (mA)	Time (μ s)
Pre-processing	6	60
Crystal Ramp-up	1.6	400
Standby	0.9	1386
Start Radio	3.7	382
Radio TX	9.9	1128
Post-processing	2.8	350

The total time for the high-load state is about 4 ms, and the average high-load state current consumption is calculated to be 4.2 mA. The low load state, when the chipset does not advertise (in Idle mode), is stated to be 2.4 μ A. Figure 11 illustrates the Idle and BLE TX states of current consumption in the nRF52832 BLE chipset.

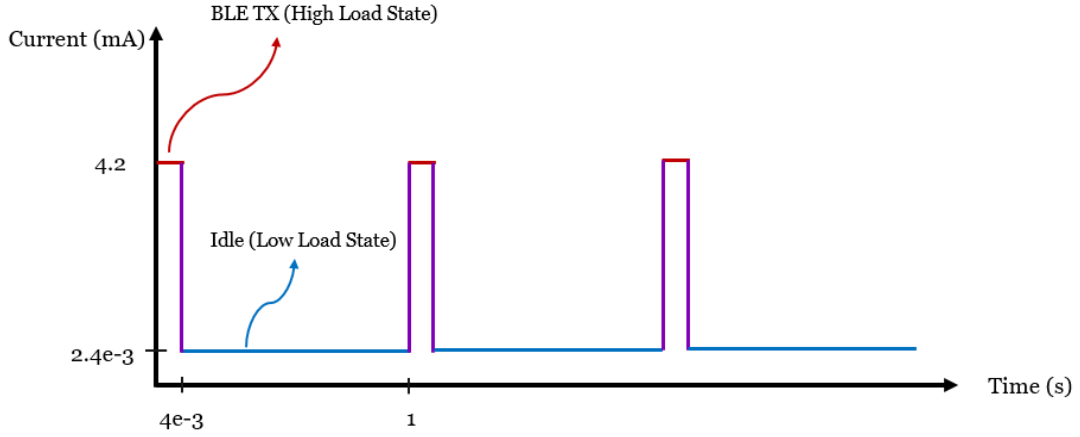


Figure 11: Current consumption vs time for the nRF52832 BLE Chipset, indicating the high load and low load state

To summarize, considering a voltage of 1.8 V to activate the chipset, the chipset's power consumption can be divided into a maximum and average value. The maximum power should be calculated using the maximum current consumption, 9.9 mA, associated with the Radio TX step. The average current consumption is stated as 19 μ A in the Nordic Power Profiler. The maximum and average power consumption are shown in Equations 4 and 5.

$$P_{\text{Maximum}} = V \times I_{\text{Maximum}} = 1.8 \text{ V} \times 9.9 \text{ mA} = 17.8 \text{ mW} \quad \text{Equation 4}$$

$$P_{\text{Average}} = V \times I_{\text{Average}} = 1.8 \text{ V} \times 19 \text{ } \mu\text{A} = 34.2 \text{ } \mu\text{W} \quad \text{Equation 5}$$

3.3.2 Energy Harvesting Scheme

In order to build a scheme for harvesting the energy produced from the sensor and using it to power the beacon, three main steps are used. First, raising the sensor voltage for multiple uses of each sensor unit is required, as the sensor voltage will drop through each round of connectivity to the BLE chipset (load). Then the energy should be stored to support the high load state of the BLE chipset, where the sensor cannot provide the demanding current. Finally, to compensate for the time it takes for the sensor to reach the maximum power, a delay is required to prevent the BLE chipset load from becoming enabled and put on the sensor. This scheme is illustrated in Figure 12.

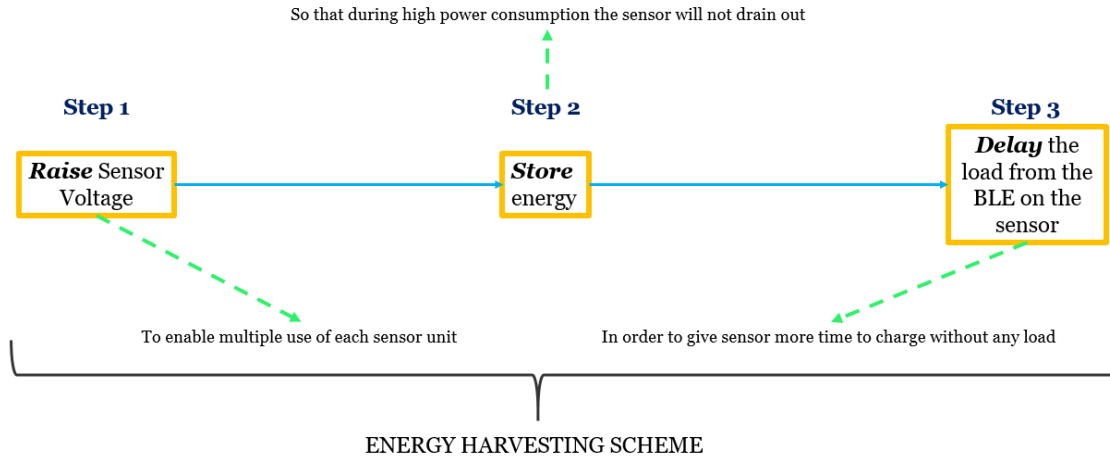


Figure 12: Energy harvesting scheme used in AquaSensing's EHB circuitry

The electrical components associated with each of the three main steps listed above are i) a DC-DC boost converter to raise the sensor unit output voltage, ii) a 470 μF bulk capacitor to store the energy for use in the high load state and finally, iii) a Low Dropout (LDO) regulator to delay the BLE load and regulate the voltage to a constant value for the BLE chipset. The top-view image of the EHB circuitry is seen in Figure 13.

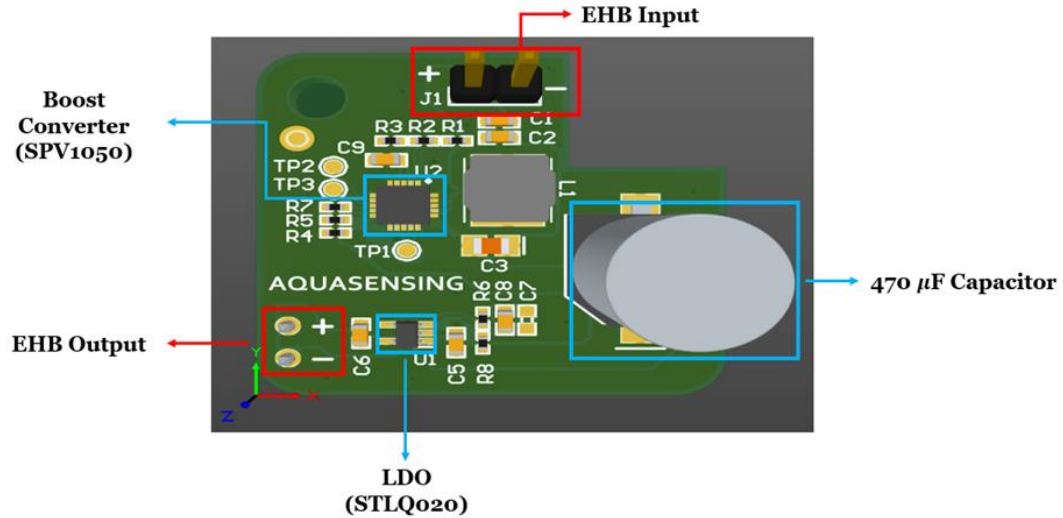


Figure 13: AquaSensing EHB layout, including the EHB input, boost converter, 470 μF bulk capacitor, LDO and EHB output

Finally, after the energy harvesting is done, the power should be transferred to the BLE chipset to advertise the Bluetooth packets. The workflow of the device can be seen in Figure 14.

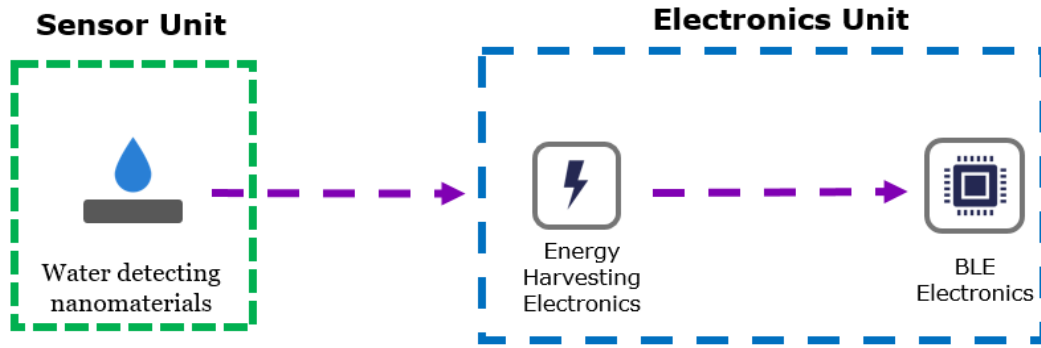


Figure 14: Workflow of AquaSensing sensor unit, starting from generating power when droplets of water come in touch with the nanomaterials, all the way to harvesting and amplifying the power, and finally powering up the BLE chipset

Figure 15 shows the current flow through the circuit, indicating that the boost converter's output is stored in the bulk capacitor. The energy stored in the bulk capacitor is then used to control the enabling of the LDO with the help of the voltage divider circuit and is used towards powering the BLE chipset in the BLE board.

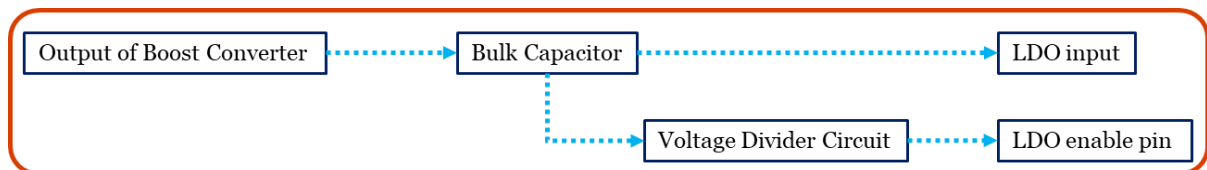


Figure 15: The flow of current through the EHB circuitry starts from the output of the boost converter, then charging the bulk capacitor, and finally triggering the LDO enable pin threshold, and passing the power through to the LDO input

Figure 16 shows a schematic of the electrical components in the EHB design, along with the voltage trends in different circuit points. The bulk capacitor voltage, which is shown as V_{cap} , illustrates the rise in voltage with respect to time as the capacitor charges. The LDO enable voltage, shown as V_{LDO-en} , determines LDO enable pin voltage rise, and it is critical because when this voltage reaches the triggering threshold, the LDO starts regulating the bulk capacitor voltage and feeding it to the BLE board. The LDO output (also referred to as the EHB Output Voltage) is zero until the LDO enable pin triggering threshold is reached; thereon, it reaches a constant value of 1.8 V to supply the BLE chipset with a regulated voltage.

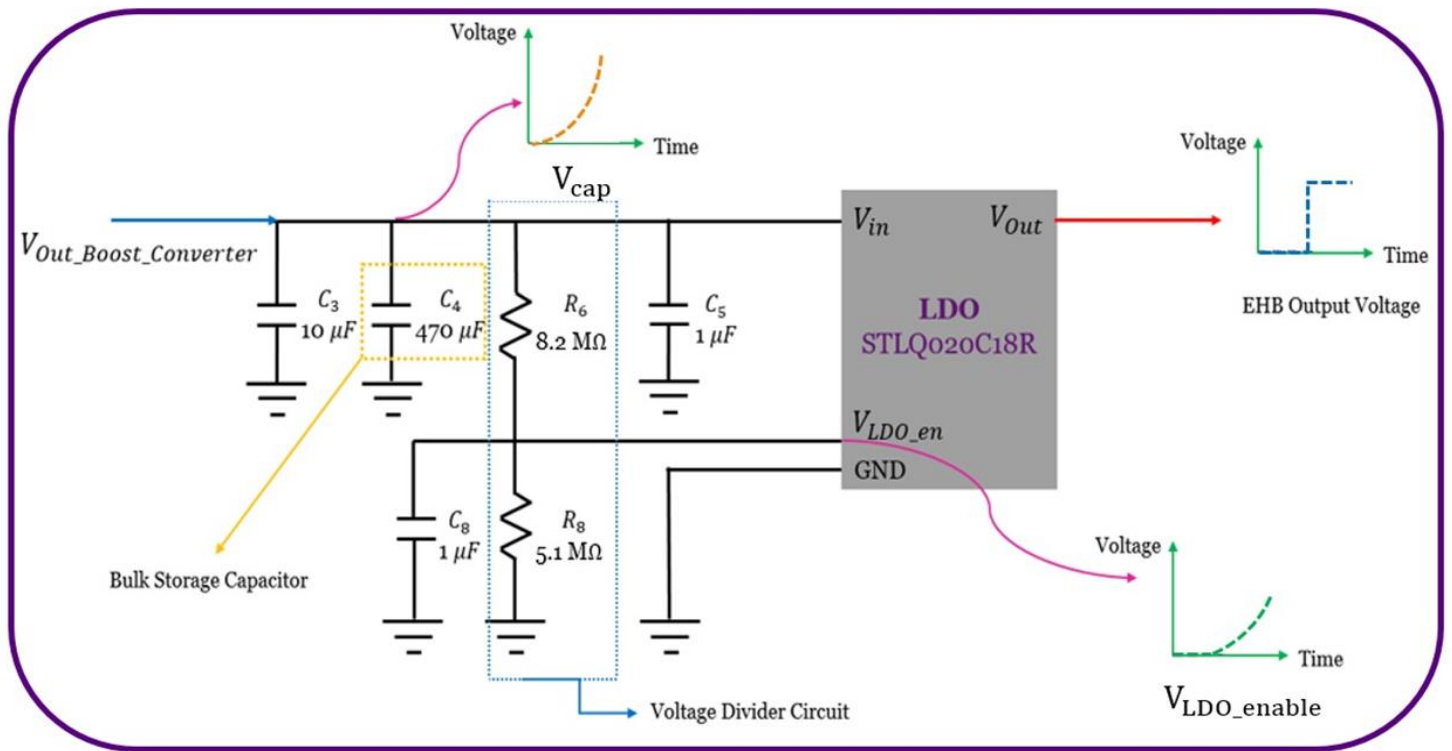


Figure 16: Schematic of the EHB circuitry and the voltage rise with respect to time in the bulk capacitor, the LDO enable voltage and the EHB output voltage

Figure 17 shows the voltage-time graph for the 3 points mentioned above. As explained above, the triggering of the LDO enable voltage (“b” in Figure 17) is a crucial point as it determines when the BLE chipset load is placed onto the sensor. This LDO enable-pin triggering threshold is an embedded characteristic of the component. After the enabling threshold of the LDO is reached, consequently, with a small delay, the EHB Output rises to the desired value to power the BLE chipset. In addition, the bulk capacitor voltage is in-phase with the LDO enable voltage because they are connected through the voltage divider circuit. The value “a” is the corresponding triggering voltage of the LDO enable pin on the bulk capacitor.

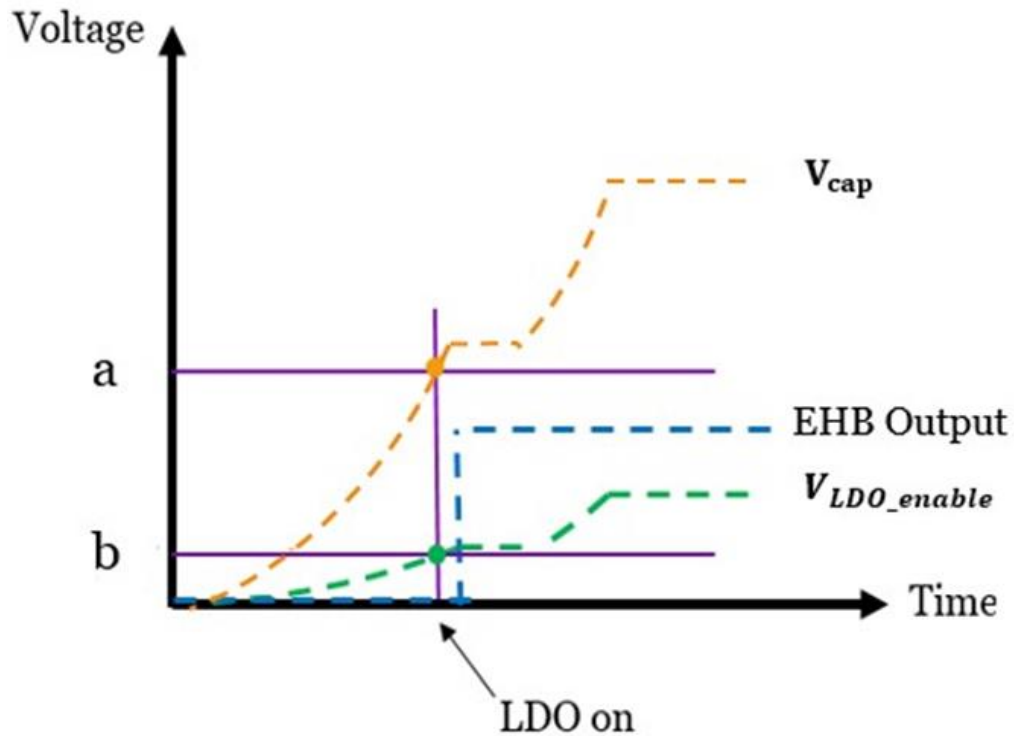


Figure 17: Voltage vs time schematics for bulk capacitor, EHB output and LDO enable

3.3.2.1 Voltage Divider Circuit

The voltage divider circuit connects V_{cap} and V_{LDO-en} , therefore controls when the LDO enable trigger threshold is initiated. In other words, V_{LDO-en} is a portion (scalar multiple) of V_{cap} through the relation shown in Equation 6.

$$V_{LDO_enable} = \frac{R_8}{R_6 + R_8} \times V_{cap} \quad \text{Equation 6}$$

Therefore, the trigger threshold of the LDO-enable can be related to the bulk capacitor voltage through the fraction of the resistor values in the voltage divider circuit. This relation means that depending on the resistor values chosen and the resultant fraction, the time the LDO enable voltage hits the triggering threshold can be altered. The voltage divider circuit and the resistors used are illustrated in Figure 18.

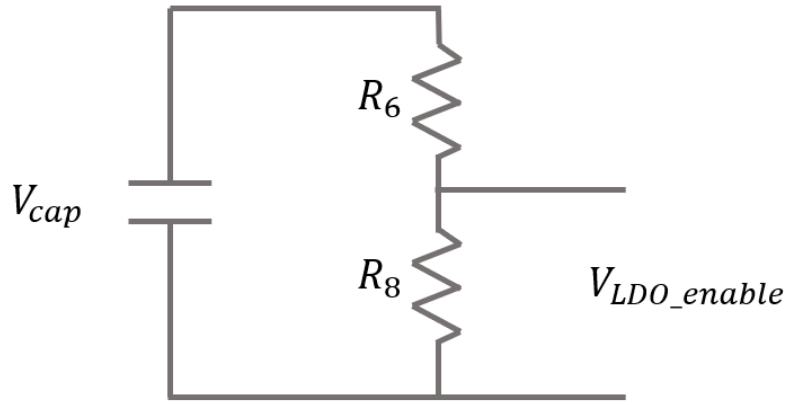


Figure 18: The voltage divider circuit implemented in the EHB

Assuming the values of the resistors are chosen correctly, the enable voltage of the LDO will reach its trigger threshold when the sensor has reached its maximum voltage and has already charged the bulk capacitor, and therefore, the bulk capacitor voltage will only experience a slight and quick drop when the BLE Chipset starts up and will continue rising after that. However, supposing the values of the resistors are not chosen precisely. In that case, it could lead to the LDO enable voltage triggering too soon, resulting in a considerable drop in the bulk capacitor voltage or a stop in the rising trend. This can be seen in Figure 19, which shows the bulk capacitor voltage changes in two different time scenarios.

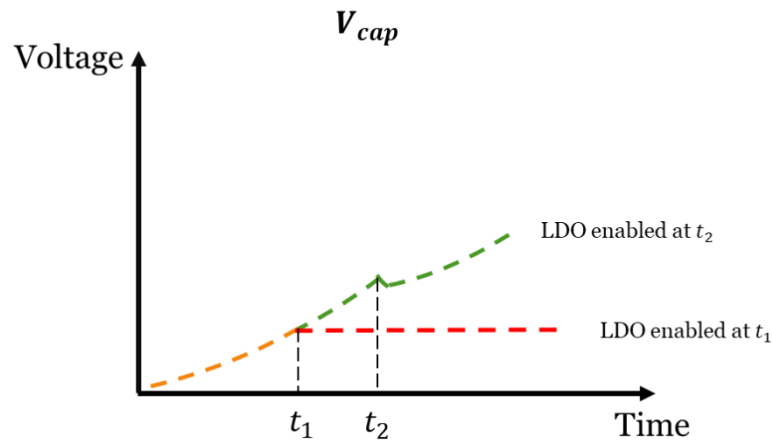


Figure 19: Bulk capacitor voltage behavior if the LDO enable threshold is triggered at t_1 & t_2

In the testing, in order to understand when the enable voltage is triggered, the EHB Output voltage can be monitored. The expected value for the EHB Output voltage is zero until the LDO enable pin trigger threshold is reached; at that instance, the EHB will show an LDO-regulated voltage which is connected to the BLE PCB. Therefore, the indication of triggering for the LDO enable is a step function rise from zero to the regulated voltage (1.8 V). Figure 20 shows a step function rise in voltage for the EHB output.

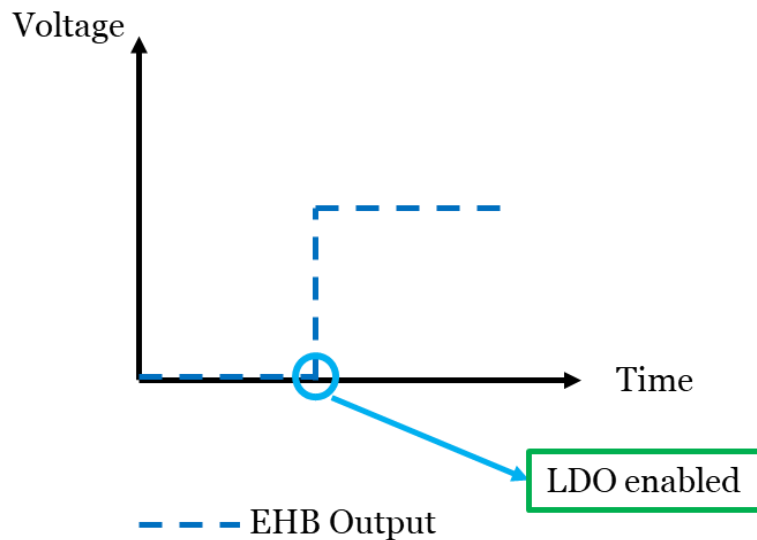


Figure 20: Voltage vs time for EHB Output, indicating a step function rise when the LDO enable threshold is triggered

The embedded trigger threshold of the LDO enable pin is 1.2 V in the datasheet of the component. In the initial design of the EHB, resistor values consisted of R_6 and R_8 as 8.2 M and 5.1 M, respectively. Following Ohm's law, the resistors were chosen in the Mega-Ohm scale to minimize the current being passed through the voltage divider circuit, leading to the LDO enable pin.

Calculations based on the voltage divider equation show that for the following values, $V_{\text{LDO-enable@trigger}} = 1.2 \text{ V}$, $R_6 = 8.2 \text{ M}\Omega$ and $R_8 = 5.1 \text{ M}\Omega$, the $V_{\text{cap@LDO enable trigger}}$ is equal to 3.12 V. This means that at a bulk capacitor voltage of 3.12 V, the trigger of the LDO enable is expected to be reached. The calculations are shown in Equations 7 and 8.

$$1.2 = \frac{5.1}{8.2+5.1} \times V_{\text{cap@LDO enable trigger}} \quad \text{Equation 7}$$

$$V_{\text{cap@LDO enable trigger}} = 3.12 \text{ V} \quad \text{Equation 8}$$

3.3.3 Testing Initial Design

After fabricating units with the initial design, testing was done. A total of 50 individual beacon activation tests were done, meaning that the sensor was exposed to water, and a Bluetooth scanner application on a smartphone was monitored to receive the advertised Bluetooth packet. A failure in this test setup is determined if a sensor is not able to activate the beacon within 3 minutes of water exposure. Only 64% of the conducted tests were successful. The LDO enable was suspected to be triggering ahead of the total charge of the bulk capacitor.

Since V_{cap} and the EHB Output were monitored in the test setup, processing the data to find the bulk capacitor voltage when the LDO enable was triggered could provide insight into the source of the problem. The sensor was connected to the EHB using a positive and negative lead. The bulk capacitor and the EHB Output were connected to two separate DMMs through the breadboard using leads. The BLE board input was connected to the output of the EHB through the breadboard. The test setup can be seen in Figure 21.

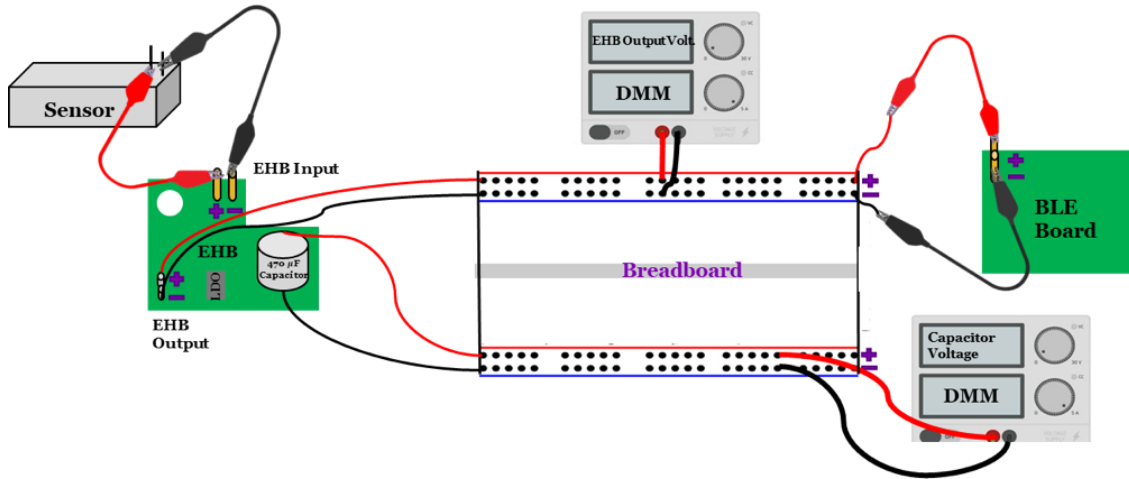


Figure 21: Test setup using DMMs to record EHB Output and bulk capacitor voltage

After data processing, the hypothesis of the early triggering of the LDO enable pin was verified, meaning that the bulk capacitor voltage when the LDO enable was triggered was much lower than 3.12 V (Expected value based on calculations). The voltage versus time graphs for the 28 failed tests were very similar because the bulk capacitor voltage stopped rising when the LDO enable pin was triggered. The successful trials were similar in voltage trends as well, and this observation was made because the bulk capacitor voltage and the EHB Output were in a continuous oscillation until they stabilized. In other words, the successful units were at the edge of failure, and the slight variations in sensor unit electrical performance sourced this inconsistency in functionality. Figure 22 illustrates a case for the successful and failed test units.

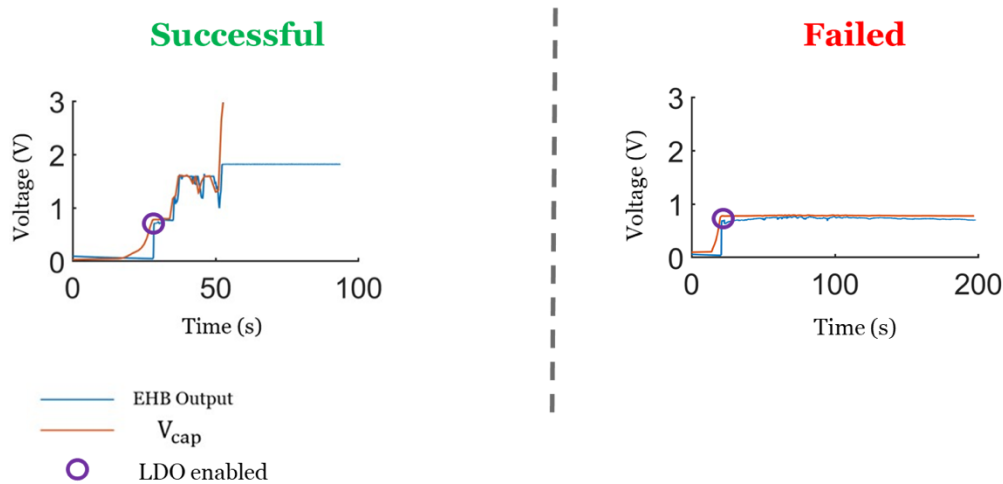


Figure 22: An example of a successful and failed case of beacon activation using the initial design of the EHB

3.3.4 Trigger Voltage of the Low Drop Out (LDO) Enable Pin

At this stage, the main goal was to find the trigger point of the LDO enable pin, as the test results were evident towards an early LDO enabling, hence an early execution of the BLE load onto the bulk capacitor. The test setup was designed so that a replicated but controlled scenario could be conducted. The main intention was to directly charge the bulk capacitor with a slew rate similar to the previous test results via the B2911A power supply and monitor the LDO enable voltage and the EHB Output voltage using an oscilloscope. Interpretation of the results should be simple, showing us the LDO enable voltage when the EHB Output voltage goes through the step function rise to the regulated 1.8 V.

In order to find an approximated value for the slew rate fed to the bulk capacitor, the slew rates of samples 19 to sample 25 of the test were found and averaged. In order to find the slew rate, the rise in the bulk capacitor voltage was observed from the beginning of the rise to the point where the EHB Output rise (indication of LDO enabling) began. In order to show how the time range for the slew rate calculation was selected, two images of the voltage-time plots have been shown in Figure 23 and Figure 24. Interestingly, the bulk capacitor voltage at the LDO enabling is under 1 V for all the samples shown.

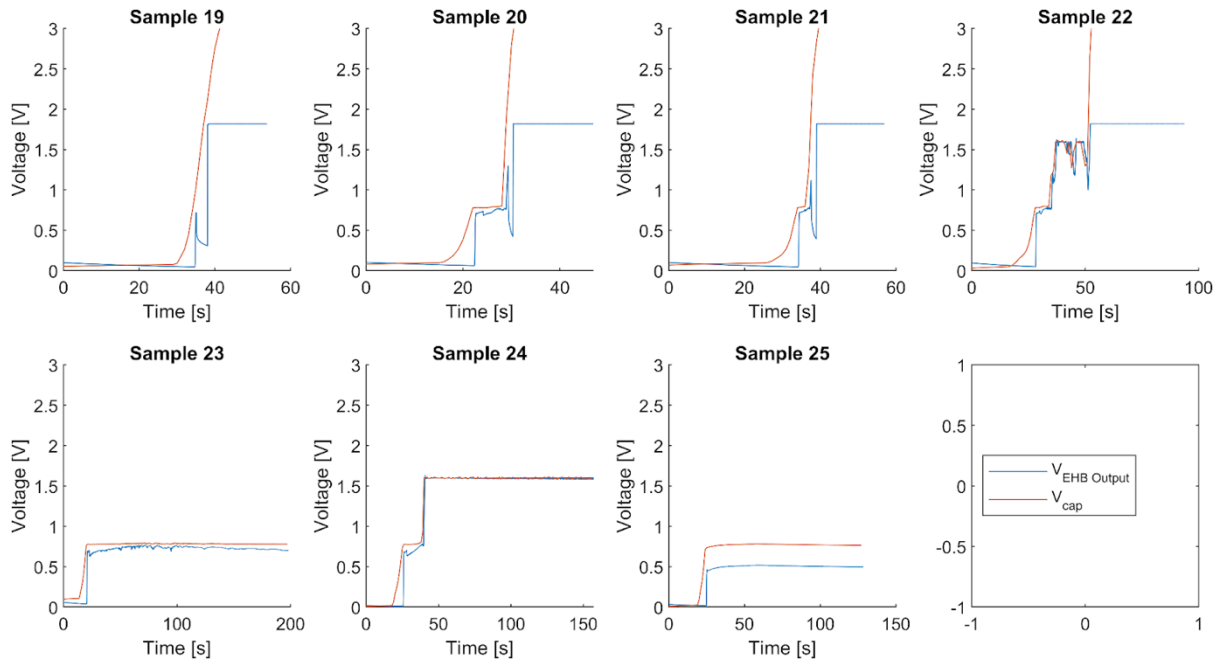


Figure 23: EHB Output and bulk capacitor voltage for 7 sensor specimens

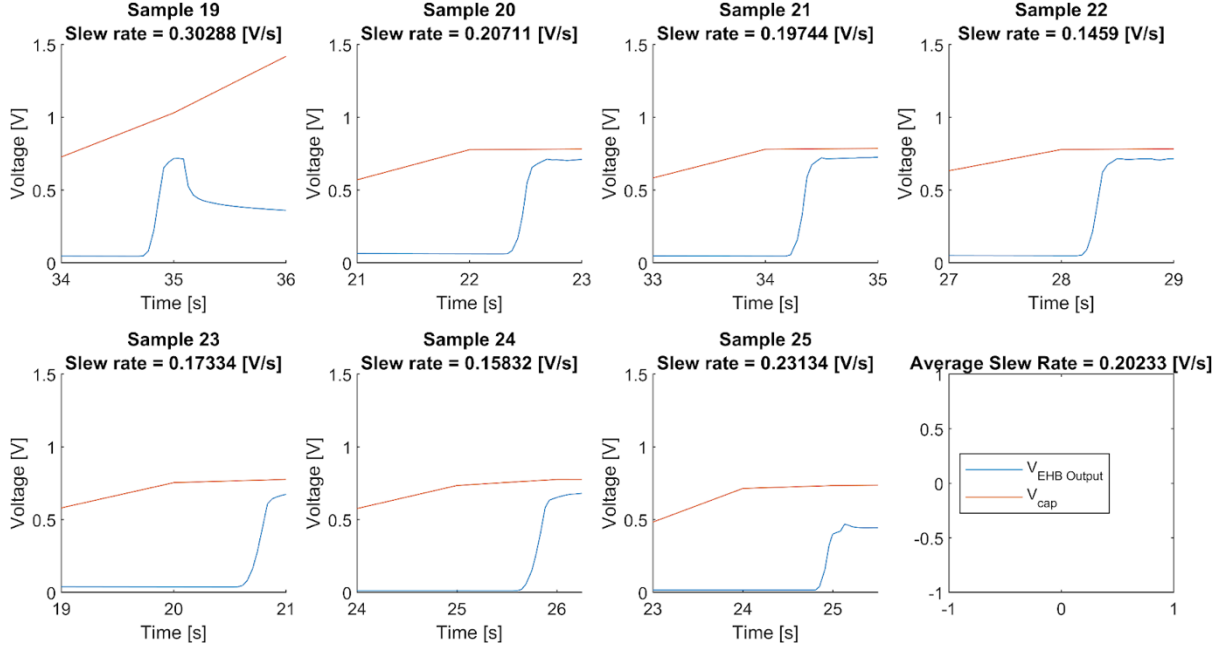


Figure 24: Magnified Figure 16 voltage vs time graphs, along with the slew rate of each sample (indicating the rate of voltage rise before the EHB Output experiences increase)

The calculated average slew rate is 0.2 V/s, and to use a moderated slew rate that eliminates any possible errors arising from a rapid bulk capacitor charge, 0.1 V/s is chosen as the slew rate for the test. The test setup is shown in Figure 25. According to the setup, the B2911A power supply was connected to the bulk capacitor using electrical leads. Simultaneously, the oscilloscope was connected to the LDO enable pin along with the EHB Output to record readings for the voltage.

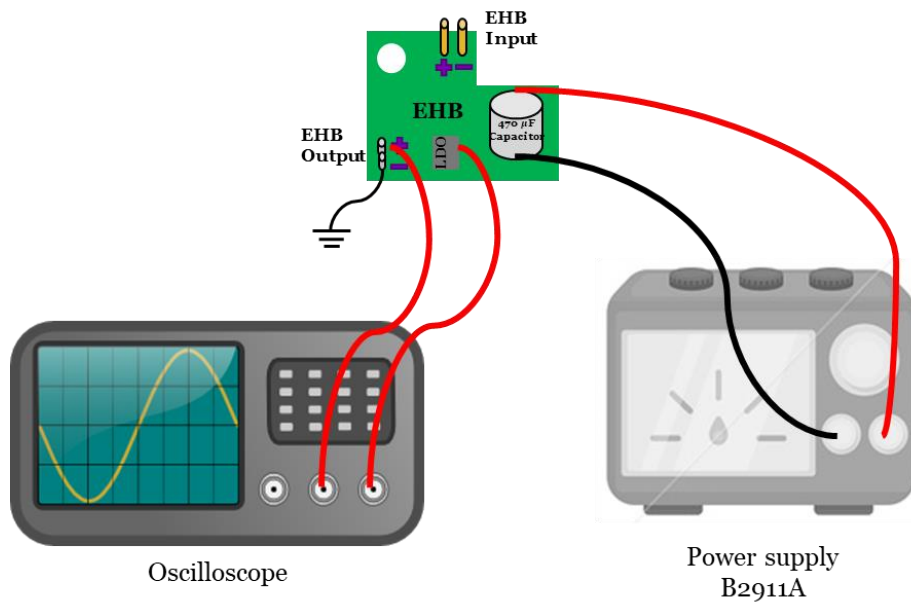


Figure 25: Feeding the bulk capacitor a voltage input with a slew rate of 0.1 V/s using the power supply and measuring the LDO enable and EHB Output using an oscilloscope

The input signal supplied to the bulk capacitor via the power supply and the readings recorded using the oscilloscope can be seen in Figure 26. It is clear from the results that when the LDO switching to the BLE board occurred, the LDO enable voltage was 0.7 V. This is the trigger value of the LDO enable voltage which was mistakenly taken as 1.2 V in the design calculations.

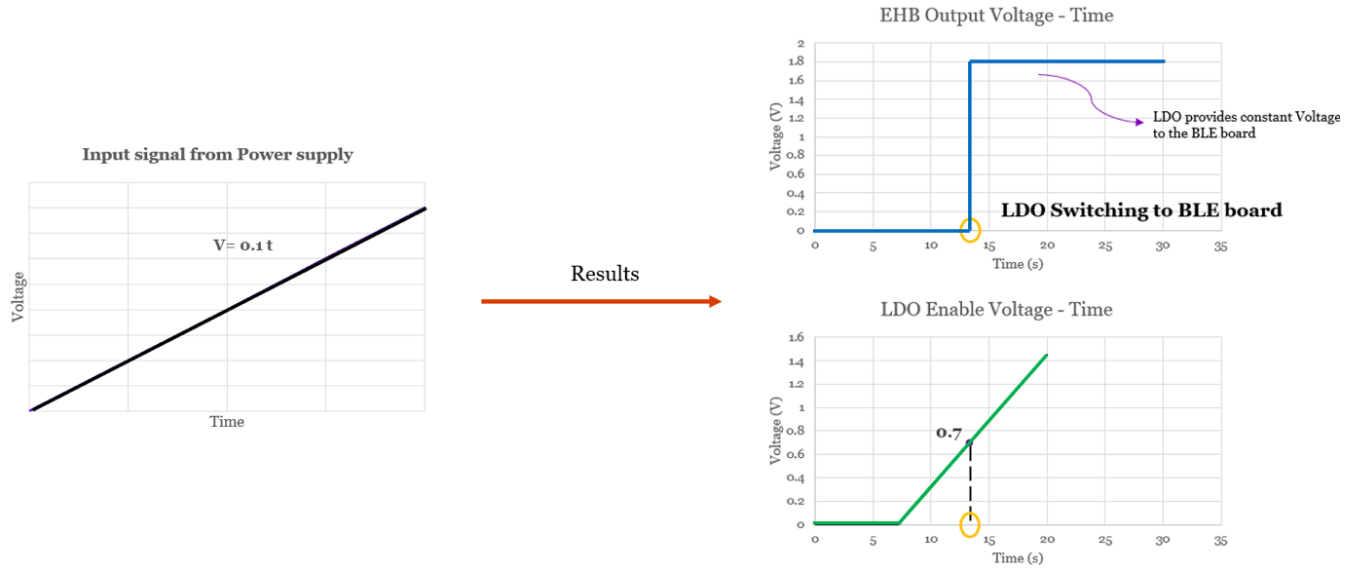


Figure 26: The signal supplied to bulk capacitor and the recordings of the EHB Output and LDO enable from the oscilloscope showing an enable voltage triggering of 0.7 V

3.3.5 Modification of Resistor Values in Voltage Divider Circuit

Since the triggering voltage of the LDO enable pin is a non-configurable property of the component, in order to solve the issue, changing the resistor values in the voltage divider circuit can be an easy solution. The goal was to increase the $V_{\text{cap@LDO enable trigger}}$ or delay the occurrence of the BLE chipset load until the bulk capacitor is fully charged. The bulk capacitor voltage can be calculated using the resistor values along with the LDO enable trigger voltage. As can be seen in Table 5, the bulk capacitor voltage at the event of the LDO enable triggering was at 1.83 V in the initial design; this is just slightly above the 1.8 V which is supplied to the BLE board. This small margin can further explain the reason for the failures and unpredictable behaviour of the bulk capacitor voltage. In the modified design, the bulk capacitor voltage at the trigger of the LDO enable has been raised to 2.25 V, which is well above 1.8 V, regulated by the LDO.

Table 5: Resistor values, LDO enable trigger voltage and bulk capacitor voltage at LDO enable trigger for initial design and modified design of EHB

Description	Resistors in Voltage Divider Circuit	$V_{\text{LDO-enable@trigger}}$	$V_{\text{cap}} = \frac{R_6 + R_8}{R_8} \times V_{\text{LDO-enable}}$
Initial Design	R6=8.2 M Ω ; R8=5.1 M Ω	0.7	1.83
Modified Design	R6=6.65 M Ω ; R8=3 M Ω	0.7	2.25

20 EHB resistors were swapped for the modified EHBs, and 35 tests were conducted with a connected BLE board. All the tests were successful in activating the beacon. Additionally, to visually recognize the difference in the bulk capacitor voltage trend, V_{cap} and the EHB Output were monitored using an oscilloscope. The results showed a smooth transition in the bulk capacitor voltage while the LDO enable was triggered along with a quick and slight drop. This behaviour can be seen in one of the samples in Figure 27.

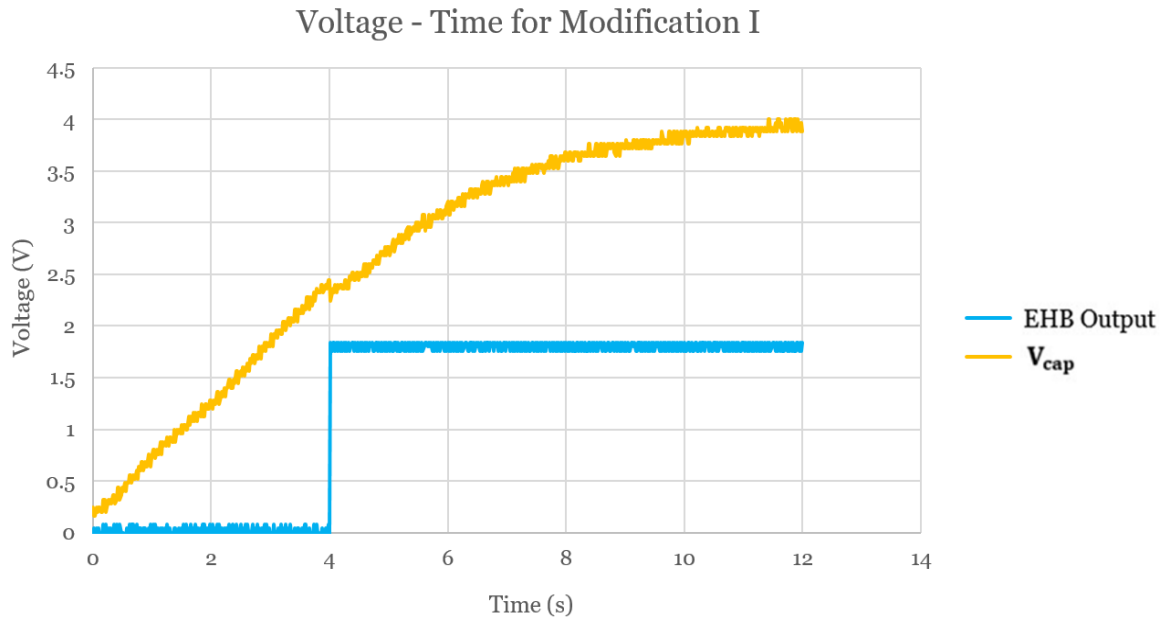


Figure 27: EHB output and bulk capacitor voltage for Modification I EHB

3.3.6 Repeatability of EHB + nRF52832

The last performance measurement for the electronics unit is the number of times the sensor unit can repeatedly power up the beacon after drying. The known influencing parameters in the repeatability count are the time sensor is kept in water after the beacon activates, drying time, and continuous connection between the sensor unit and electronics.

The chosen parameters for the repeatability tests were: 5 minutes wait time after the beacon activates, one-week drying time at room temperature (natural drying), and continuous connection between the sensor unit and electronics, meaning that the electronics unit is not removed from the sensor unit during the testing period. A *failed unit* is a device which takes more than 5 mins to activate. The tests showed that this electronics unit could be used for up to 4 rounds of repeated use without any failure. However, one failure was detected on the fifth round of the test, and therefore the test was aborted. Table 6 indicates the activation time results with respect to the repeatability.

Table 6: Repeatability of EHB + nRF52832-based BLE Board

Sample #	Activation Time (s)				
	Round #1	Round #2	Round #3	Round #4	Round #5
1	21	32	35	37	25
2	19	63	40	33	28
3	23	59	39	96	38
4	25	41	36	43	36
5	23	107	60	54	FAIL
6	13	39	49	39	25
7	13	109	39	186	24
8	30	54	39	166	82
9	20	74	56	47	34
10	12	40	49	73	41
Average (s)	19.9	61.8	44.2	77.4	37

3.4 IN100 Chipset

IN100, Inplay's SoC solution, was the next candidate for the new generation of AquaSensing PCBs. Using BLE as the wireless protocol and having low power consumption characteristics were the main initiations towards choosing this chipset. Another primary reason for considering IN100 as a possible replacement for the nRF52832 chipset was the considerably lower cost of the IN100 compared to the nRF52832.

The main goal was to move onto a single board design which can significantly reduce production costs and simplify the design. Unlike the previous energy harvesting scheme, where a DC-DC boost converter was utilized to raise the sensor unit output voltage, in this design, to reduce costs and simplify the design, the boost converter was eliminated. This decision was made considering the low power consumption specifications of the chipset, indicating that a voltage as low as 1.1 V and an average current of about ten μA can activate the chipset. Additionally, since the IN100 BLE chipset has a built-in LDO, there is no need to have an external LDO component in the circuitry. Executing these eliminations in the circuitry was equivalent to cutting a large percentage of the cost associated with the energy harvesting method.

In order to verify the ultra-low power consumption characteristics stated in the datasheet of this chipset, the first test done on the prototype circuit with the IN100 chipset was checking the current consumption.

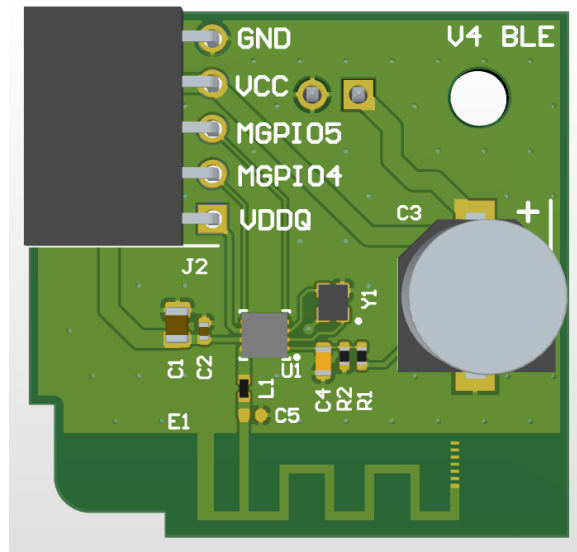


Figure 28: AquaSensing Inplay based custom electronics unit

3.4.1 IN100 Current Consumption

There was no documentation or online platform similar to the online power profiler that existed on Nordic's website for observing the current consumption of the IN100 chipset for different input settings. The test setup for finding the current consumption consisted of a power supply, a resistor, an oscilloscope and finally, the PCB using the IN100 chipset. The test was carried on by supplying a voltage to the AquaSensing Custom IN100 PCB using the power supply with a resistor (7.1 Ω) in series with the PCB. Voltage drops across the resistor were recorded using an oscilloscope. After the voltage readings were finished, using Ohm's law and having the resistor value in series with the PCB, the current consumption of the IN100 PCB was found. The test setup can be seen in Figure 29.

The Inplay PCB was programmed with the following settings: Radio TX power at 0dBm and the advertising interval as 1000 ms (indicating that every second, a Bluetooth advertisement is made). The voltage supplied from the power supply (B2911A) was altered throughout the tests to find the effect of the input voltage levels on the current consumption behaviour of the chipset.

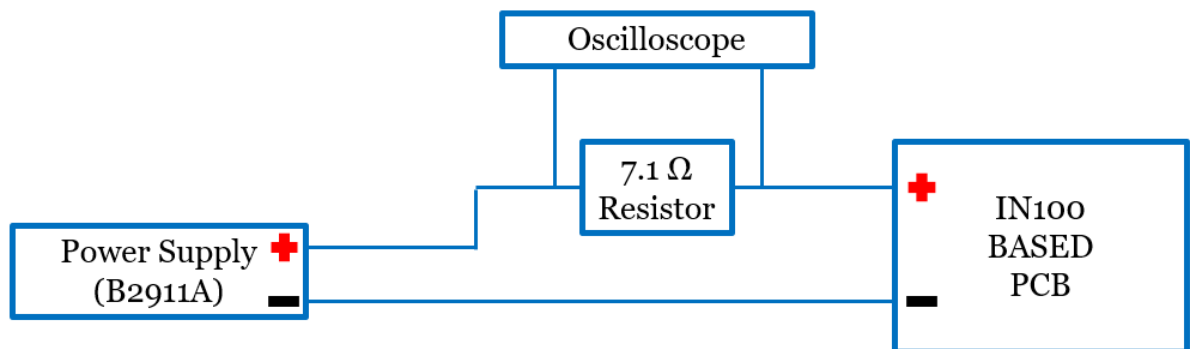


Figure 29: The test setup used for finding current consumption of IN100 BLE Chipset

Changing the oscilloscope's time scale and trigger settings allowed finding two different graphs for the voltage-time behaviour across the resistor. Figure 30 (a) was for a time scale of 500 ms per horizontal unit, which indicated that the only significant voltage changes were related to the advertisement of the Bluetooth packets, set to occur every 1 second. In other words, this proved that there is no high load condition applied to the source from the beacon, except for the event of the beaconing.

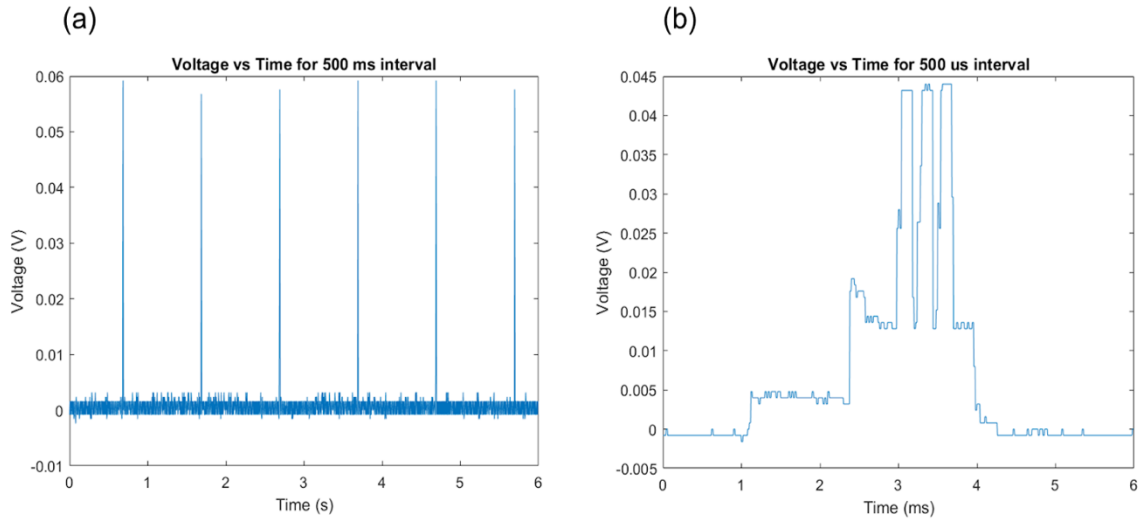


Figure 30: (a) BLE data pulses every one second are the only source of current consumption, indicating the advertising interval of one second (b) Current consumption in every BLE TX (high load state), including radio wake-up, pre-processing, Radio TX and post-processing

Figure 30 (b) was recorded with a time scale of 500 μ s of the scope, indicating how each one-second pulse contains different stages of voltage change (current consumption), including radio wake-up, pre-processing, radio TX and post-processing.

The average current consumption was about nine μ A, less than the current consumption of the nRF52832-based PCB. The nRF52832-based current consumption measure does not consider that the EHB used in the previous design, in addition to the BLE board, inevitably adds load to the sensor, even though the magnitude of this load is not comparable to the load sourced from the BLE chipset. In Table 7, the results of the current consumption behaviour for different input voltages can be seen.

Table 7: IN100 average and peak current consumptions for various input voltages

Input Voltage (V)	Average Current Consumption (μA)	Peak Current Consumption (mA)
1.2	8.5	6.5
1.5	9.1	7.3
1.8	9.4	7.5
2.5	9.7	7.5
3	10	7.8

Table 7 shows that the input voltage levels, from 1.2 to 3 V, do not significantly impact the average current consumption of the IN100 BLE chipset. The maximum average current consumption is ten μA for an input voltage of 3 V.

Concluding the current consumption measurements and seeing consistent behaviour in beacon activation tests for new sensors, takes this electronics unit to the final evaluation test, which is repeatability testing.

3.4.2 Repeatability for IN100 (Single PCB Design)

The repeatability test conditions were identical to the repeatability performance test conducted for the Nordic PCB. A similar testing setup allows easy comparison of electronic variation's effect on the device's overall performance. Table 8 summarizes the results of the repeatability tests.

Table 8: Repeatability of AquaSensing IN100 Custom BLE PCB

Sample #	Activation Time (s)									
	Round #1	Round #2	Round #3	Round #4	Round #5	Round #6	Round #7	Round #8	Round #9	Round #10
1	17	42	31	40	40	36	29	24	25	27
2	22	58	70	69	74	45	40	43	32	36
3	17	88	68	56	62	54	40	38	26	25
4	17	37	44	51	53	49	43	49	45	40
5	18	53	47	83	42	56	44	31	29	28
6	17	35	36	34	33	49	45	42	41	29
7	17	25	31	30	30	48	43	33	35	31
8	15	55	40	38	74	44	45	39	44	44
9	16	32	31	62	43	70	38	37	42	49
10	18	24	28	30	37	34	36	49	38	40
Average (s)	17.4	44.9	42.6	49.3	48.8	48.5	40.3	38.5	35.7	34.9

3.5 Summary of Chapter 3

Knowing the electrical specifications of the sensor unit and the current consumption patterns of the nRF52832 BLE chipset provided insights for designing an EHB and powering up the beacon. After initial testing of the EHB + Nordic BLE PCB, resistor modifications were made to prevent the early triggering of the LDO enable pin. The repeatability test indicated that the sensors worked without failure for up to 5 consecutive rounds, with only one failure in the fifth round.

In the next step, the current consumption patterns for the new Inplay BLE chipset (IN100) were found to move from a two-PCB design to a singular one. Using the AquaSensing IN100 BLE PCB enhanced the device's overall performance, allowing up to ten repeatability rounds without any failures. Moving from the EHB and nRF52832-based BLE PCB to a singular IN100-based PCB was an approximate 70 % reduction in PCBA costs.

The exploded view drawing of the assembled electronics unit, with the IN100-based PCB, can be seen in Figure 31.

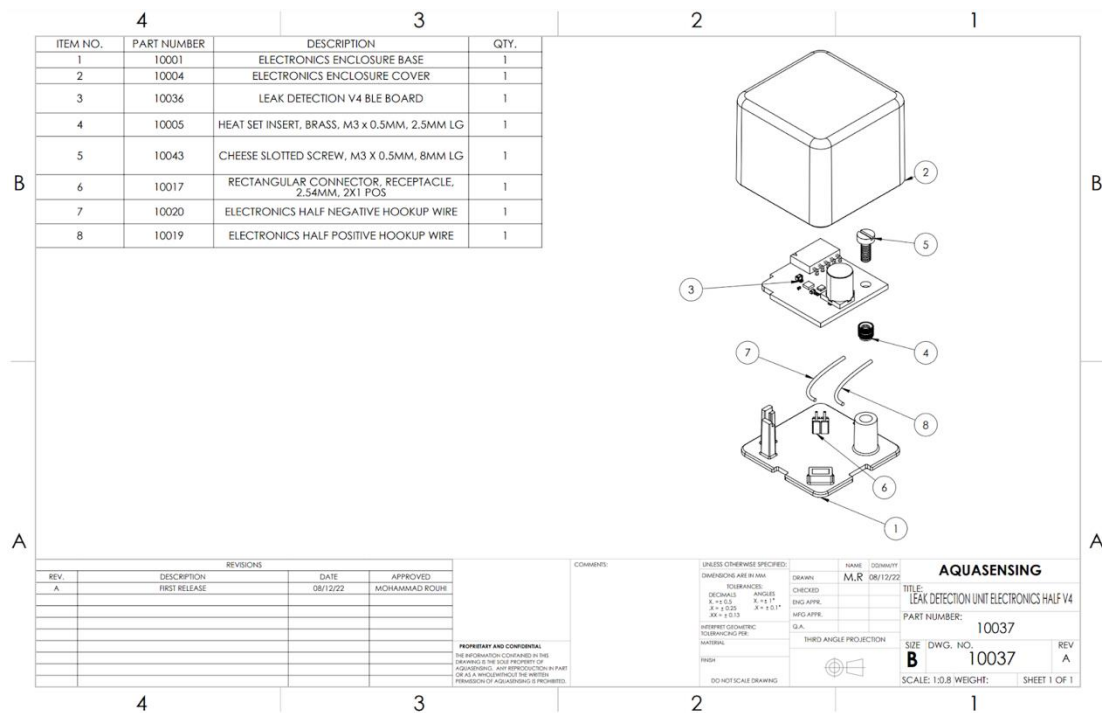


Figure 31: Exploded view drawing of AquaSensing's assembled Electronics Unit, using the IN100-based PCB

Chapter 4

Sensor Unit Assembly Design, Implementation and Results

4.1 Introduction to Chapter 4

In order to move from a lab-fabricated device to a device with the capability of high-scale production, three main goals should be achieved:

1. Looking for sources of performance inconsistency and finding a suitable solution to prevent them.
2. The manufacturing process needs refinement, and the design components should be revisited to modify/change in successive iterations. This chapter will introduce and describe sources of sensor performance malfunctioning and process control guidelines, as well as a significant change in the device's manufacturing process, which helps move towards high-scale production.
3. A comparison between the initial and newly developed manufacturing method will be shown, considering yield rate and manufacturing cycle time as the evaluation parameters.

Figure 32 shows a flow chart of the sensors' initial lab-based manufacturing/production process. This chart is divided into three main categories: Materials, Process and Assembly. The estimated average time for the assembly category of this procedure is 306 seconds per unit, known as the cycle time. Additionally, considering the time loss between making one unit and starting the next (takt time = cycle time 0.1), a total of 302.5 seconds per unit is obtained. This results in 84 daily units for a single full-time assembly worker. Table 9 indicates the cycle time, takt time and total time of the sensor fabrication using the lab-based procedure.

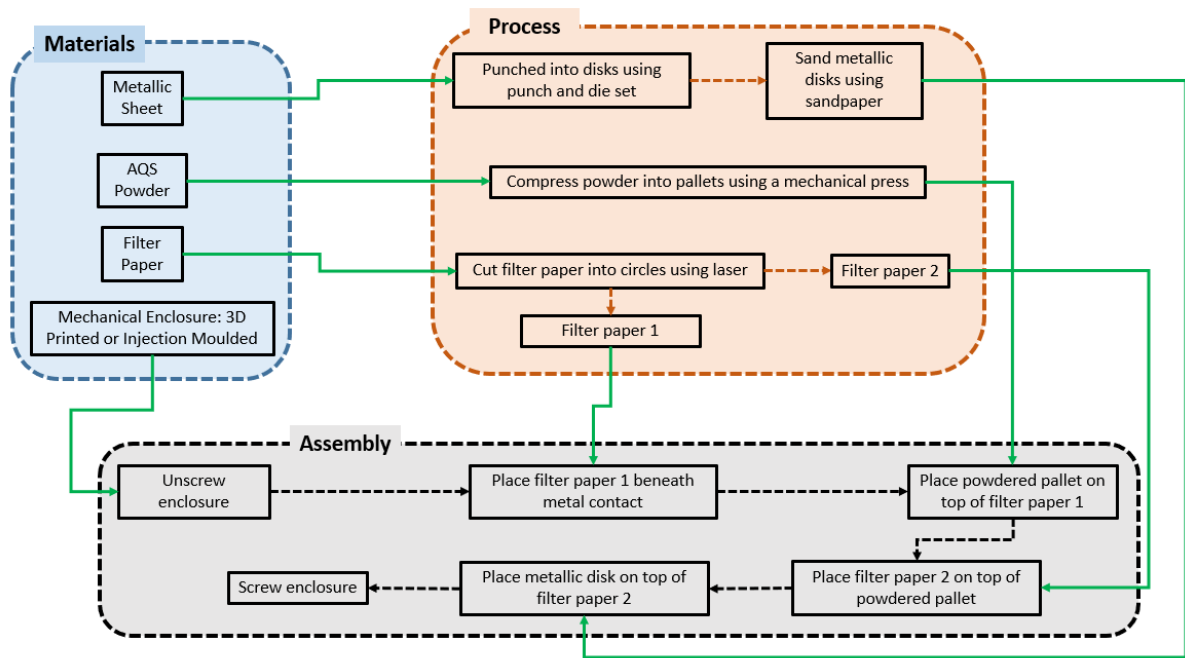


Figure 32: Initial lab-based manufacturing/production process of battery-free water leak sensor

Table 9: Cycle time, takt time and total time for sensor fabrication using lab-based procedure

Step No.	Type	Task	Time (s)
1	Process	Powdered pallet preparation with single pallet mould	140
2	Process	Sanding each metallic disk	60
3	Process	Laser Cutting filter paper	5
4	Assembly	Opening and closing screws + Assembly of metallic disk	35
5	Assembly	Placing powdered pallet inside enclosure	30
6	Assembly	Placing filter papers inside enclosure	70
Cycle Time (s)			275
Takt Time (s)			27.5
Total Time (s)			302.5

4.2 Metallic Disk

The metallic disk is connected to the negative electrode of the sensor. Therefore, a proper connection between the spring contact and the metallic disk must be maintained for stable power output. In this section, the failure modes related to the metallic disk will be reviewed, and a QA step will be introduced to manufacture the sensors and prevent malfunctioning of the sensors.

4.2.1 Metal Disk Sanding

The metallic sheets were received with an oxide layer covering them. The lab-based processing of the metallic sheets consisted of punching the sheets and having them sanded manually one by one. As a new trial, instead of sanding the disks one by one, the sheets were handed over to the machine shop, and they were asked to sand both sides of the metal sheet with an orbital sander and sandpaper (120 grit). After the sheets were sanded using the orbital sander, they were punched, and it was noted that the sheet/disks should not be exposed to grease or any liquids while or after punching. Figure 33 shows the (a) metallic sheet after sanding with orbital sander, (b) metallic sheet before sanding, (c) metallic disk, sanded using orbital sanding metallic sheet before punching (d) metallic disk, sanded manually one by one, after being punched.

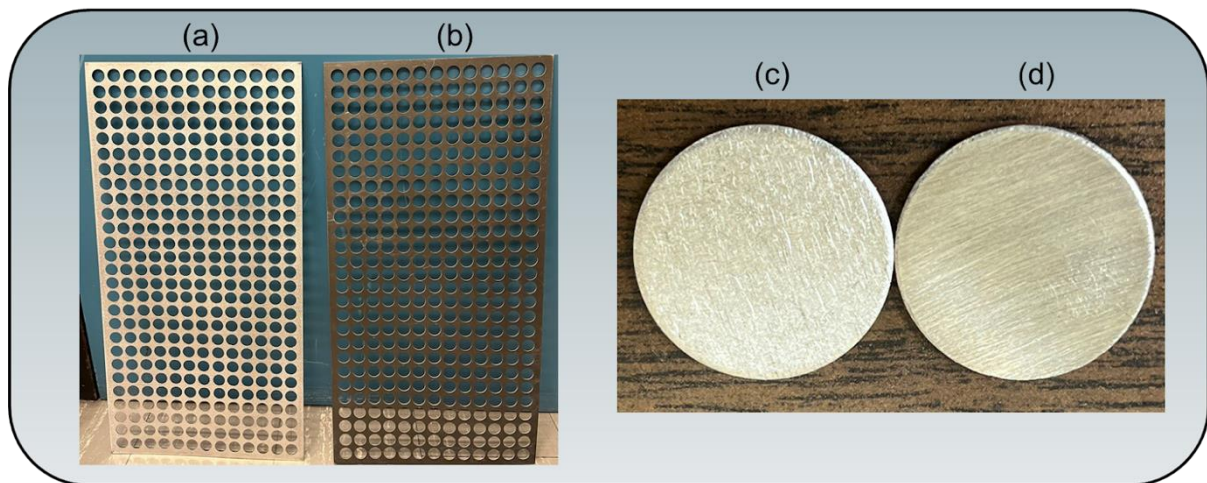


Figure 33: (a) Metallic sheet after sanding with orbital sander, (b) Metallic sheet before sanding, (c) Metallic disk sanded using orbital sanding metallic sheet before punching, and (d) Metallic disk sanded manually one by one after being punched

After receiving the metallic disks from the machine shop, the performance of the disks was evaluated using the load test procedure introduced in the previous chapter. Sensor units were assembled using the lab-based method, using eight randomly chosen disks. The constant current load drawn from the sensor units was the standard 50 μA . The results indicated that the peak OCV of the sensor, before the load was applied, reached above the threshold of 1.9 V in only one out of eight samples, although 1.9 V peak OCV is the minimum expected peak OCV threshold based on the baseline tests. Specifically, an average maximum OCV of 1.84 was recorded from the samples with the orbital sanded disks. Two samples did not reach 1.8 V, showing the existence of significant alteration in sensor performance. The following critical parameter to observe throughout these tests was the voltage decay after a specific amount of time the load was applied (3 minutes was used in this case). The sensors showed an average voltage of 1.62 V after 3 minutes of the load test, which is considerably lower than the baseline voltage expected after 3 minutes for the load tests (1.8 V). Table 10 shows the results of the load test.

Table 10: Load test results for eight samples assembled with orbital sanded metallic disks, indicating maximum OCV and voltage of sensor after three minutes of the load test has passed

Orbital Sanding of Metal Sheets (120 grit sandpaper)		
Sample No.	Maximum OCV (V)	Voltage after 3 minutes of load test (V)
1	1.84	1.62
2	1.84	1.62
3	1.77	1.57
4	1.84	1.63
5	1.87	1.58
6	1.95	1.67
7	1.83	1.63
8	1.78	1.62
Average (V)	1.84	1.62

In order to prevent performance variance, a new work instruction document was prepared to sand the sheets. In the work instruction, an additional step was issued after sanding the sheets using the orbital sanding machine, in which the sheets should be sanded on both sides with water and in the length direction until a smooth and shiny surface is obtained. After the sheet length is sanded in a single direction and the surface condition is as desired, the surface should be dried with a clean and dry cloth to avoid oxidation formation.

It was also seen that pallets that had been sitting on the shelf for up to 2 months after the sanding was done had no performance alteration compared to the freshly sanded pallets used in the assembly of the sensor enclosures.

4.2.2 Deflection of Spring Contact and Disk Oxidation

While opening the enclosures, some spring contacts were not visually as deflected as others. Additionally, some metal disks had oxidation buildup on the top surface, which could theoretically lead to high resistance. A schematic of the improper connection between the spring contact and the metallic disk can be seen in Figure 34 (a). Figure 34 (b) shows the visual oxidation spotted on a metallic disk.

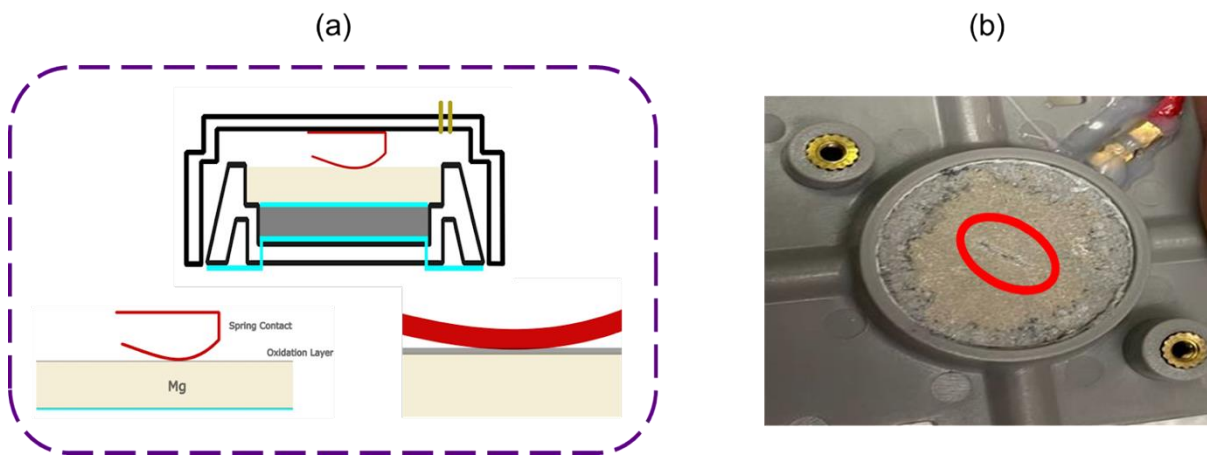


Figure 34: (a) Thin oxidation layer on the top surface of the metallic disk, interfering with spring contact connection to the top surface of the disk, and (b) Visual corrosion on the top surface of the metallic disk, along with a thin line associated with the spring contact connection

Some samples verified the hypothesis of high resistance due to oxidation, leading to non-stable sensor open circuit voltage output. For example, Figure 35 (a) shows a sensor with an open circuit voltage of less than one volt, but as soon as the top of the sensor enclosure was pushed, oscillations were seen. After several drops (from pushing the top of the sensor enclosure) and rises (from releasing the push on the top), the sensor voltage bounced up to approximately 1.6 V.

After opening the sensor unit enclosure and inspecting the top surface of the metal disk, high oxidation was visually found, and a thin line was scratched off in the middle of the disk due to the continuous manual push and release exerted on the top of the sensor enclosure. The disk image can be seen in Figure 35 (b).

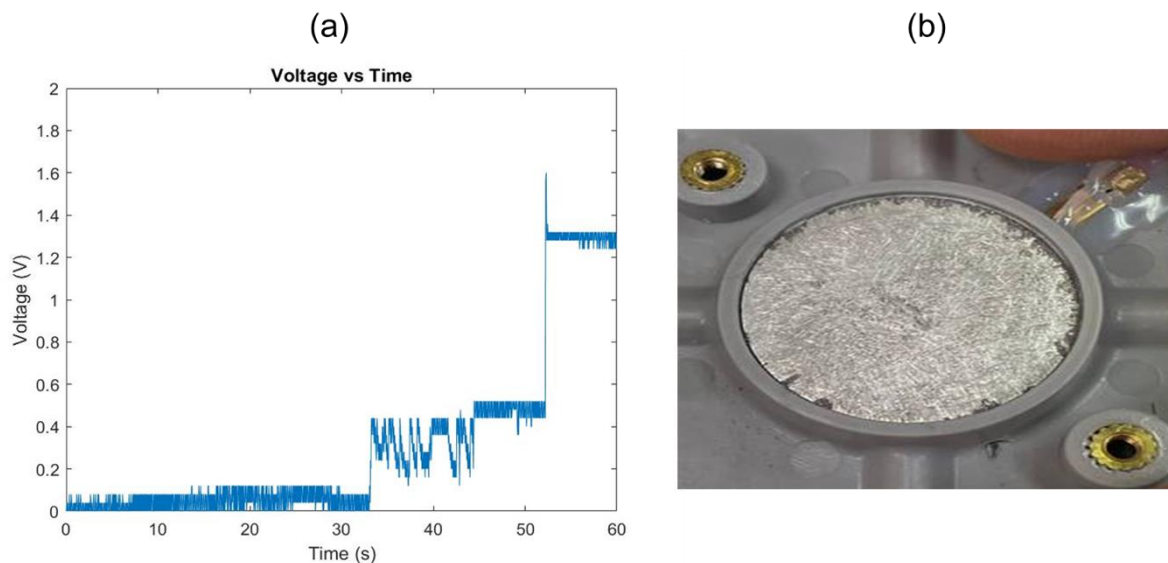


Figure 35: (a) Sensor unit voltage-time graph during beacon activation test, indicating low voltage and oscillations after the top of the enclosure was pushed, and (b) Visual inspection of the disk that had several drops and rose when pushing the enclosure

4.2.2.1 Resistance Measurements

To further investigate the effect of the spring contact deflection on the performance of the sensor, the alterations in disk resistance were measured with various forces and different disks (each with different numbers of uses). A test fixture was designed with three main parts: the top, the disk holder, and the bottom. The flanges of the top part can sit on three different levels when placed onto the disk holder piece. Since the top spring contact is assembled onto the top part, the three levels determine the amount of interference of the top spring contact with the top surface of the Mg disk. The bottom part of the test fixture, which includes the bottom spring contact, is fixed to the disk holder piece using screws. The resistance between the bottom and top spring contacts indicates how much the resistance value varies with each displacement for the top spring contact. Figure 36 illustrates the exploded view drawing along with the BOM of the resistance test fixture design.

Three scenarios exist, depending on which level of the disk holder piece the top part is placed. Firstly, the middle level replicates the "inside enclosure" scenario, where relatively low resistance is expected. The top level, 0.4 mm higher than the middle level, determines a lower interference between the top spring contact and the disk than the inside enclosure case. Therefore, high resistance is predicted. Finally, 0.4 mm below the middle level, the bottom level causes high interference between the spring contact and the disk. Therefore, low resistance is expected to be monitored.

This test involves placing a metallic disk into the disk holder, then pushing the position stabilizers to keep the disk in place while the spring contacts are in place. In the next step, connect the top and bottom spring contacts' wires to a DMM to record the resistance measurements. For the testing, the resistance values are recorded starting from the top level, then the middle level and finally, the bottom level. In order to keep the results consistent, for each metallic disk, a new top and bottom spring contact should be assembled to prevent the deflected spring contacts from the previous tests from affecting the upcoming tests.

ITEM NO.	DESCRIPTION	QTY.
1	TOP PART	1
2	BATTERY CONTACT SPRING, STAINLESS STEEL, TIN-NICKEL PLATE	2
3	POSITION STABILIZER IN HORIZONTAL PLANE	2
4	DISK HOLDER	1
5	METALLIC DISK	1
6	SENSOR HALF NEGATIVE HOOKUP WIRE	2
7	HEAT SET INSERT, BRASS, M3 x 0.5MM, 2.5MM LG	2
8	BOTTOM PART	1
9	CHEESE SLOTTED SCREW, M3 X 0.5MM, 8MM LG	2

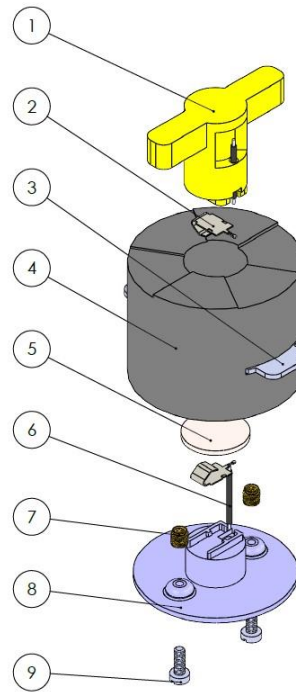


Figure 36: Exploded view BOM of the resistance test fixture

Two main conclusions were made from the results shown in Table 11. Firstly, as expected, the top level indicates the highest resistance for each disk. In contrast, the bottom level (highest interference state between the top spring contact and the disk) shows the lowest. Secondly, the times the disks have been used play a significant role in the resistances recorded, verifying the hypothesis that the resistance increases as the disk ages.

Table 11: Results of the resistance test indicated that resistance increased when i) the sensors were repeatedly used and ii) the deflection of the spring contact decreased

Disk Usage Round #	Resistance Between Top and Bottom Contact (mΩ)		
	Top Level	Middle Level	Bottom Level
0	20	18	9
1	28×10^3	37	16
3	39×10^3	45	25
11	120×10^3	62	34
12	500×10^3	2.3×10^3	120

4.2.2.2 Quality Control Step

In order to reduce the chances of an improper connection between the spring contact and the surface of the metallic disk, a QC step has been added to the enclosure assembly procedure of the components. The spring contact should be pulled with a tweezer after installation into the sensor unit enclosure to ensure that the deflection is sufficient to touch the top surface of the disk efficiently.

4.3 AQS Powder

The AQS Powder is another important constructive component of the AquaSensing device. The powder is compressed and transformed into a pallet. In the lab-made devices, the powder was weighed, and compressed under the tensile machine, using a compression rate of 10 mm/min and stopping the compression at a force of 100 N. This pallet production procedure means that the thickness and porosity are two parameters kept constant throughout the pallet production procedure.

Changing the weight of the powder and the compression stop force can alter the pallet's physical attribute (thickness), leading to inconsistency in device performance. The alteration in physical attributes can be seen in Figure 37, where three pallets were compressed using the same compression force and with different powder weights.

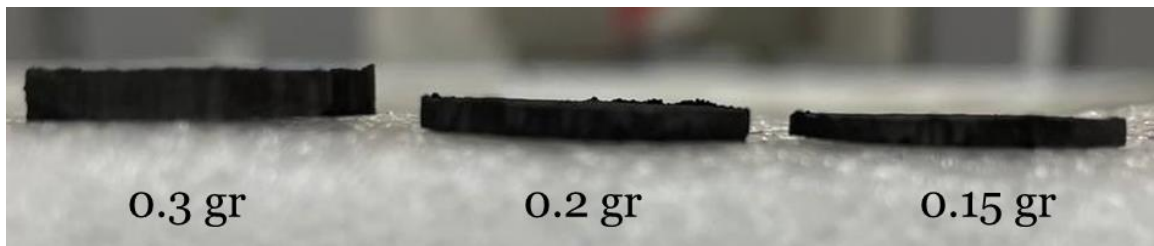


Figure 37: AQS powdered pallets with 0.3, 0.2 and 0.15 grams of powder

After water enters the enclosure, the pallet is saturated and experiences volumetric expansion, leading to the wetness of the metallic disk. In this process, if the predefined thickness of the pallet (2.5 mm) changes, it can cause issues in the device's power generation.

4.3.1 Handling and Shipping

The powdered pallet's brittle characteristic emphasizes the importance of the device's resistance to drops and impacts. Shipping and handling conditions can cause changes in product performance which should be evaluated before entering a product into the market. This investigation was initiated due to some failures spotted on the field, although the sensors were factory-tested (activated with water) before shipping to clients. A drop test procedure was developed to assess the sensor's robustness, and the testing was conducted.

4.3.1.1 Design of Experiments (DOE), Parameters and Response Variable

Our testing aims to find the robustness of the CNF-based sensor design and monitor the sensor performance and possible alterations from the expected behaviour after conducting drop tests on the sensor unit. In order to conduct the drop tests, we will conduct three levels of tests as follows: i) without drop test level, which indicates the sensor performance as a baseline to compare the other results, ii) 1-meter drops and iii) 2-meter drops.

The experiment setup is to place two sensing devices in a small sensor box (12 x 6 x 6 cm) and drop the sensor box from the determined height in the associated treatment. We must drop the sensor boxes on all faces, which means conducting six drops for each box. The drop height and the number of drops were chosen from a standard shipment testing document [57]. Ten independent tests are conducted for each of the three treatments (without drop, 1-meter drop and 2-meter drop).

The experiments' single response (output) is the beacon's activation time. As explained in the previous chapter, this measures how long it takes for the Bluetooth signal to be advertised by the device. Testing conditions will affect the results; therefore, the conditions chosen will be explained. To draw water into the sensor unit enclosure, we can either use a wicking agent with legs, meaning that it covers the exterior of the sensor unit, enhancing the water entrance or utilize a design without legs, which means the water channels in the mechanical enclosure (cutouts) are used to suck in water. Figure 38 shows the difference between with and without legs condition. Also, the nRF52832-based PCB was used for the beacon activation.

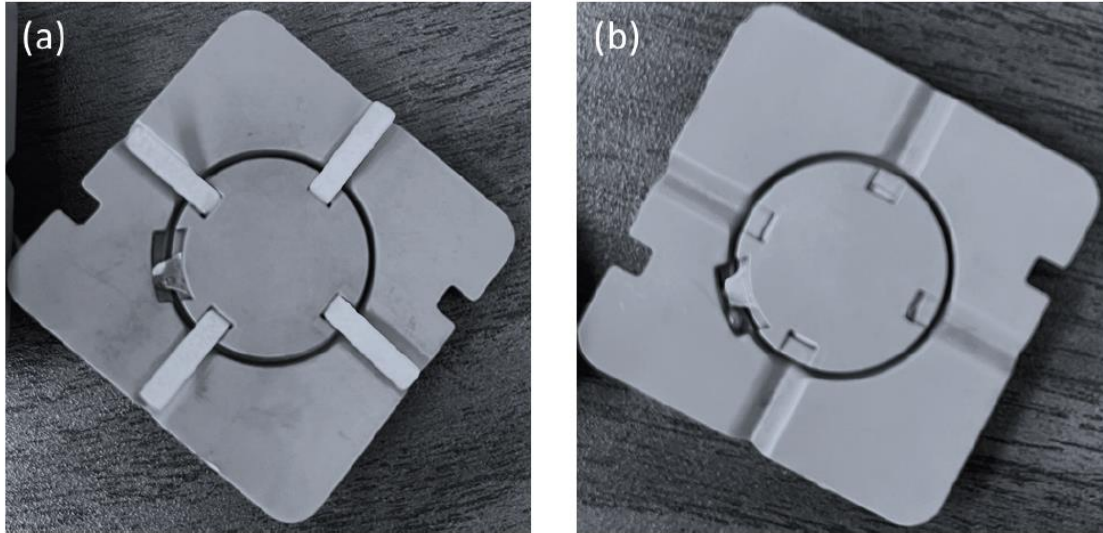


Figure 38: (a) Sensor unit with filter paper legs, and (b) Without filter paper legs (using a circular filter paper)

The test was done using the without-legs condition to comprehend if the failures were caused by losing the powder content because of exiting the sensor enclosure via the water channel openings. Knowing that in the “without legs” condition, there is no opening for the powder content to exit the enclosure since the water channels are covered with a circular wicking agent; therefore, if any alteration in sensor performance is observed, it is just the change in morphology of the pallet sourced from drops. A schematic of the hypothesized cracks in the powdered pallet can be seen in Figure 39.

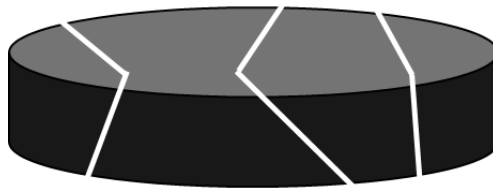


Figure 39: Cracks created due to drop in the very brittle CNF pallet

4.3.1.2 Test Results

Table 12 shows the results of the three treatments throughout the ten samples tested for each of the three treatments. They are arranged based on an ascending order. The significance level chosen for the hypothesis testing is 5%.

Table 12: Results of experimental setup conducted for drop tests

Sample No.	Activation Time (s)		
	Without drop	1 m drop	2 m drop
1	16	25	42
2	18	26	63
3	20	46	69
4	23	49	78
5	25	65	118
6	32	75	155
7	55	75	250
8	80	120	276
9	95	125	280
10	110	215	296

An observation from the datasets is that there are two groups. A lower and an upper bound of results refer to devices with low and high activation times. Identifying two groups can lead to a hypothesis of performance alteration for a percentage of devices. Based on Grubb's outlier test, the only outlier in the three data sets is related to the 215 second datapoint for the one-meter drop. The data points above the 200 second threshold are chosen as the upper bound; subsequently, the data points below it are known as the lower bound data points.

Based on Figure 40, the upper bound, which is above the 200 s threshold explained, is marked with a red region, whereas the lower bound is in green. There is a data point in the two-meter drop, which lies between the upper and lower bound and has a value of 155 s (marked as a gray point in Figure 40). In order to determine if this point can be associated with the upper or lower bound, an outlier test should be conducted for two cases, once with the lower bound and also with the upper bound. Furthermore, in the case of the one-meter drop, we monitor one out of ten points (10%) in the failure region, whereas for the two-meter drop, we monitor four out of ten points (40%).

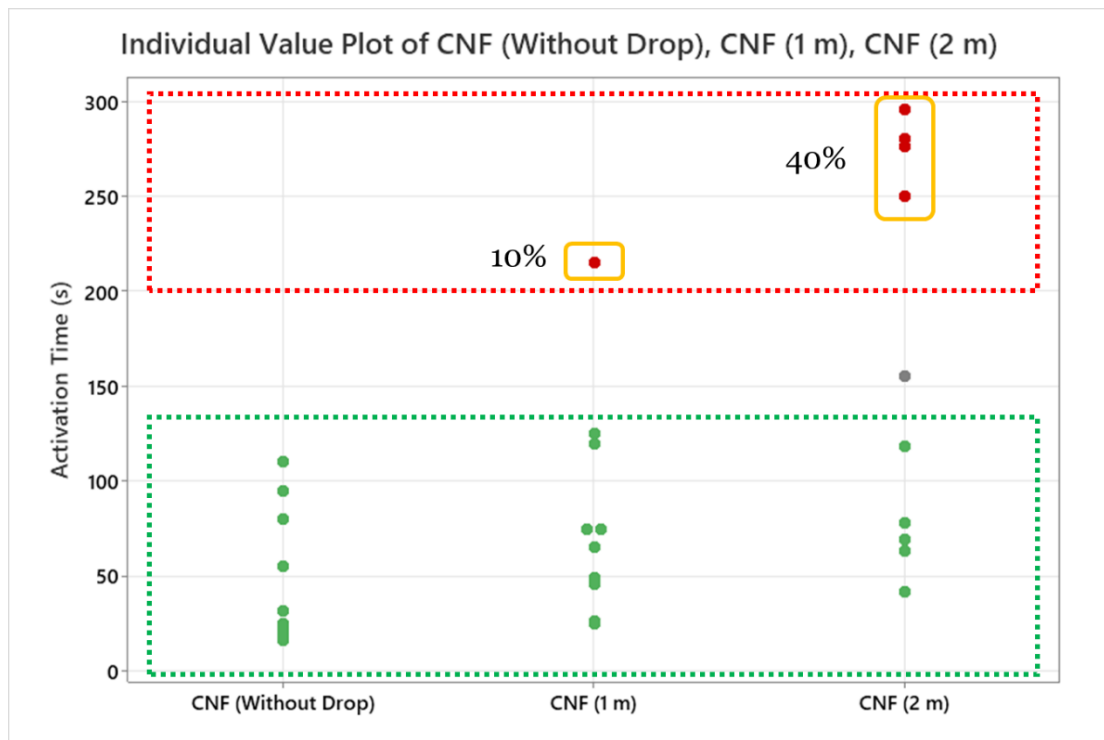


Figure 40: The approach of splitting data of CNF-based sensors into upper (“failures” indicated within a red rectangle) and lower (“passed” indicated within a green rectangle) bounds and a middle point (gray)

Figure 41 shows the two outlier tests conducted for the (a) lower and (b) upper bound. The P-Value of each test is respectively 0.39 and 0.055; this indicates that the middle point in the two-meter drop dataset is closer to being associated with the lower bound due to its higher P-Value.

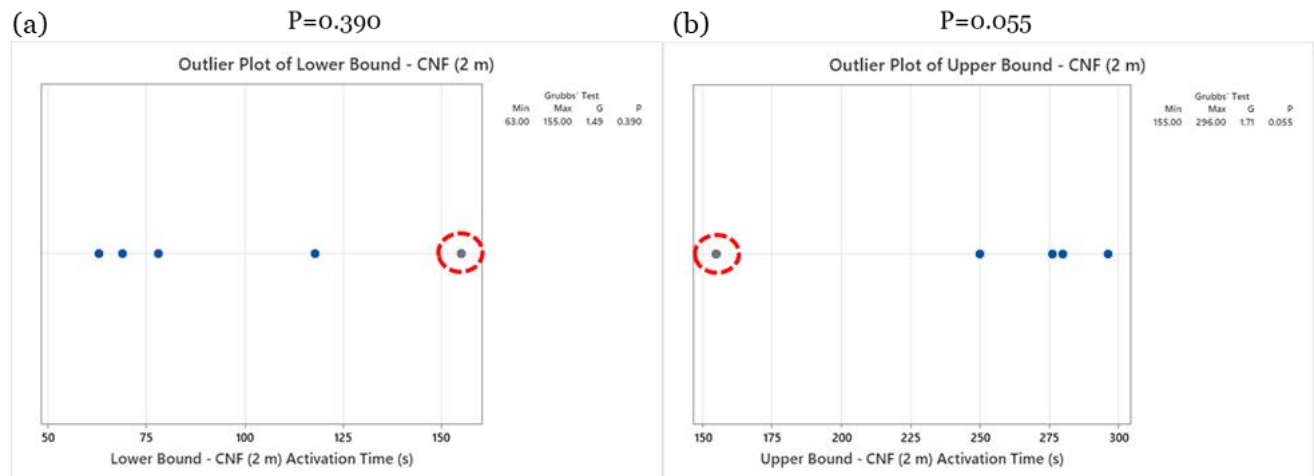


Figure 41: Grubb's outlier test in two cases for the middle point in the 2 m drop dataset (a) associated with the lower bound, and (b) Associated with the upper bound

As a requirement of hypothesis testing, the normality of the datasets (lower bounds and upper bounds) was also observed using Minitab's normality check (RJ method) and the datasets were all determined as normally distributed.

4.3.1.3 Hypothesis Testing

The goal was to find if the data points in the lower bound of the without drop, the one-meter drop, and the two-meter drop are statistically equal in means. If this hypothesis was true, we could conclude that the difference in the performance of the devices only happens at a specific frequency and doesn't affect the whole batch of sensors.

A conventional one-way ANOVA is used for the significance test of the lower bounds of the datasets. This test is chosen because the three data sets have close standard deviations and variations based on the general statistics in Table 13.

Table 13: General statistics for all three testing conditions (only lower bounds for 1 m and 2 m drop), including number of data points, mean and standard deviation

Variable	Number of data points	Mean	Standard Deviation
Without drop	10	47.4	35.3
1 m drop	9	67.3	36.3
2 m drop	6	87.5	41.4

The results of the One-Way ANOVA indicate a P-Value larger than the significance level of 5%. Therefore, the null hypothesis can be accepted, which means that the means of the three compared treatments are equal.

The real-life implications of the analysis are that a frequency of failure is associated with each drop height; this means that it is expected that as the drop severity (which is a function of the drop height and the number of drops) increases, the yield rate of the sensors decreases, indicating more sensors will take longer to activate. In the case of the experimental setup used, only two drop heights existed, which were one-meter and two-meter and resulted in a 10% and 40% failure rate frequency, respectively.

The test procedure described in this section was repeated for a well-fit and packaged box (including bubble wrap and foam) containing multiple sensors, and the results showed no inconsistency, leading to the development of a packaging protocol for the devices.

4.3.2 Tri-Press

The initial method of preparing a powdered pallet was to use a single pallet mould, in which the powder was compressed and then transferred to the inside of the enclosure. The previous attempts at preparing a mould for multiple pallet compression were unsuccessful, mainly due to disassembly difficulties sourced from high friction between 3D printed parts; therefore, the pallets were damaged and cracked while disassembling the mould.

Considering the available tensile machine dimensions, the maximum number of pallets that could be prepared from a single mould was three. The objective was to prevent complete contact between the surface of components so that they could be easily disassembled once the pallets were compressed. To utilize the tri-press mould, the cavity (purple component) was placed on top of the base (yellow component), ensuring that the shorter circular walls of the purple component were in contact with the yellow piece. The graphite was then inserted into the three openings. The Top Press (pink component) was placed on top. After compressing the powder using the tensile machine, the entire device was flipped so that the top press was at the bottom; then, the base was removed. The cavity was then pushed down, causing the pallets to rest on top of each cylinder of the pink top press.

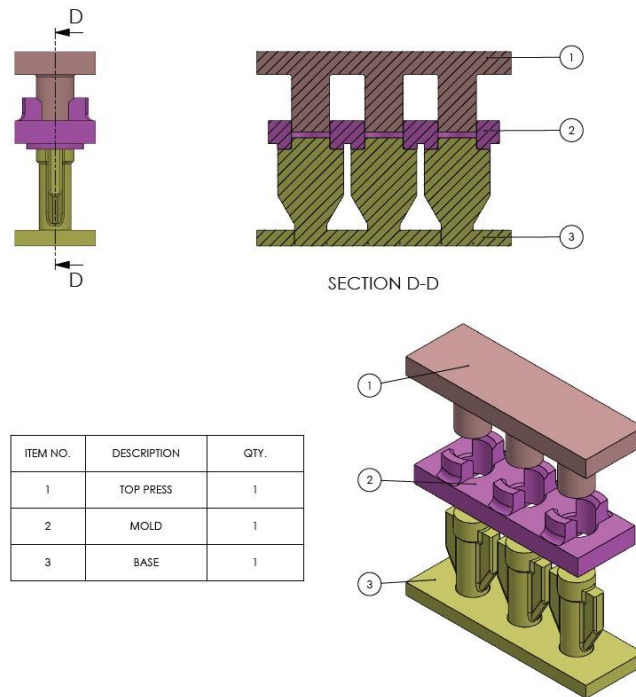


Figure 42: Exploded view BOM of tri-press

Beacon activation (with nRF52832-based PCB) tests were conducted to find the effectiveness of the pallets and measure the decay in voltage after 2 minutes of the initial beacon activation using a DMM. Table 14 shows the test results and indicates that all sensors could activate the beacon, and the average activation time was 39 seconds. After 3 minutes of the initial beacon activation, the average sensor unit voltage was 1.87 volts, which showed an insignificant drop considering the approximate maximum sensor unit OCV of 2 V and was higher than the baseline load test average voltage after 3 minutes (1.8 V).

Table 14: Sensor activation time and voltage after three minutes

Sensor Unit ID	Activation Time (s)	Sensor Unit Voltage after 3 mins. (V)	Sensor Unit ID	Activation Time (s)	Sensor Unit Voltage after 3 mins. (V)
1	31	1.86	11	45	1.89
2	38	1.87	12	26	1.88
3	44	1.87	13	46	1.87
4	54	1.83	14	31	1.84
5	46	1.86	15	39	1.83
6	31	1.88	16	44	1.9
7	61	1.83	17	31	1.86
8	41	1.89	18	28	1.88
9	24	1.85	19	49	1.89
10	30	1.87	20	44	1.89
Average	Activation Time (s) 39		Sensor Unit Voltage after 3 mins. (V) 1.87		

4.3.3 Direct Deposit Mould

Moving towards high-scale production means a simple yet fast process for the palleting is required. A direct deposit mould was designed, 3D printed and tested. Compression was done using the tensile machine; however, a mechanical arbour press was considered for the next iteration to make the process fast and scalable. The controlled parameters in this palleting method were the pallet's thickness and porosity. Controlling the thickness means limiting the top press vertical movement, and controlling the porosity means the same powder weight should be used throughout the palleting procedure.

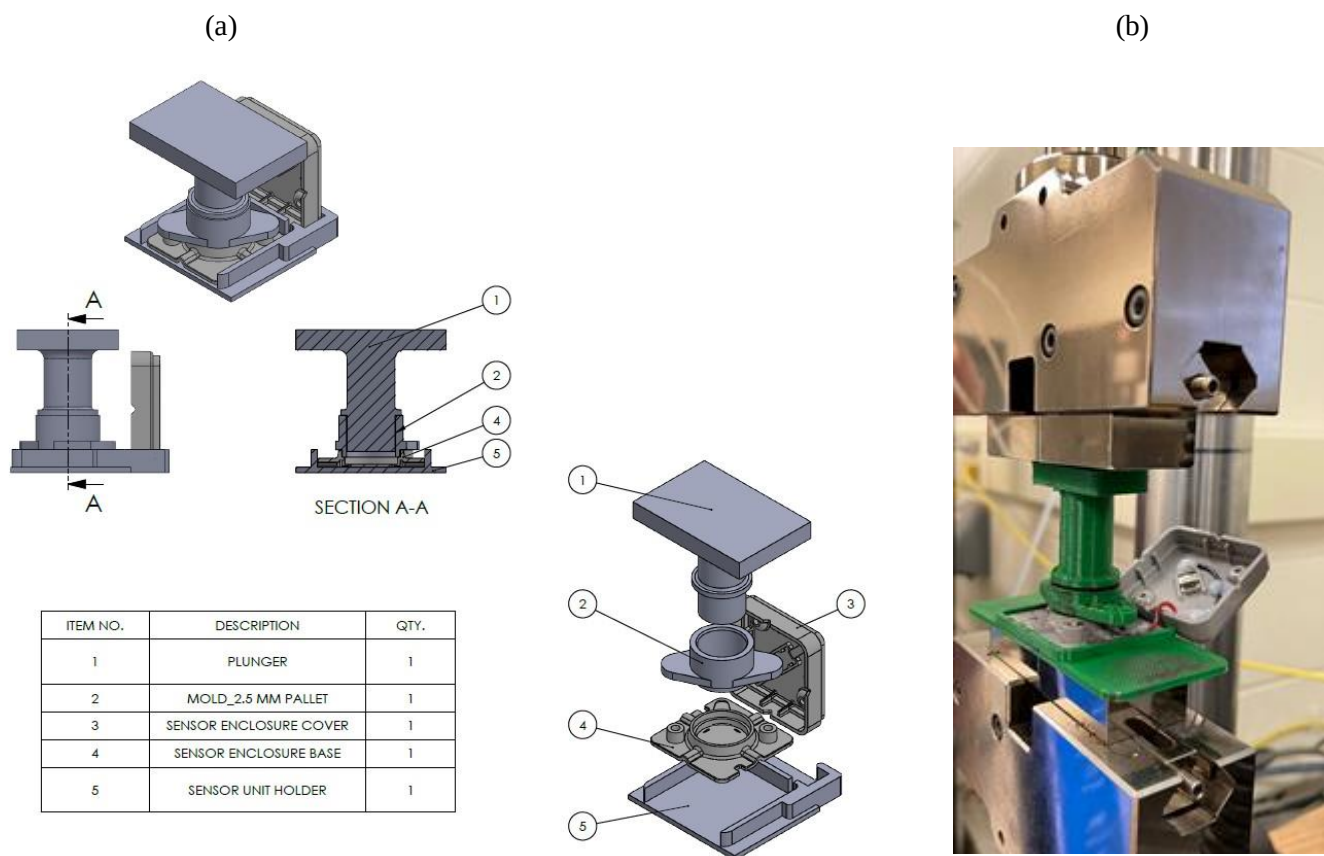


Figure 43: (a) Exploded view BOM of direct deposit mould, and (b) 3D Printed direct deposit mould under tensile machine

The first-round beacon activation (using the AquaSensing IN100 PCB with 220 μ F bulk capacitor) test results were consistent and successful and can be found in Table 15.

Table 15: First round beacon activation tests with AquaSensing IN100-based PCB

Sample No.	Activation Time (s)	Sample No.	Activation Time (s)
1	78	9	60
2	40	10	20
3	65	11	64
4	34	12	52
5	36	13	30
6	60	14	28
7	28	15	37
8	56		
Average (s)	45.8		

After verification of the design concept, the next step was to build a machined version of the direct deposit mould and use an arbour press to speed up the assembly process. A machined version was designed and built by Inertia Manufacturing and was used to carry out some preliminary tests (Figure 44).

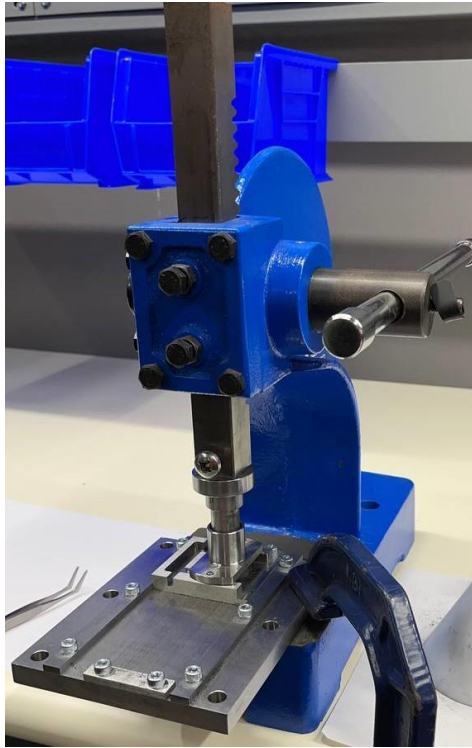


Figure 44: Machined direct deposit mould clamped to arbour press

The repeatability test conditions were identical to the repeatability performance tests conducted in the previous chapter. The testing was carried on by using the IN100-based PCB along with the sensor units assembled with the direct deposit mould (Table 16). The average activation time saw an increase when compared to the results for the IN100-based PCB using the tri-press mould assembly in the previous chapter. In addition, although for the sensors assembled using the tri-press mould, up to ten rounds of repeatability were conducted without any failure; in this case, the first failure was spotted in round seven. However, overall, considering the manufacturability of the sensor unit using the direct deposit method compared to the tri-press mould assembly method, the average activation time and six rounds of repeatability without failure were acceptable.

Table 16: Repeatability for sensor units assembled with direct deposit mould and connected to the IN100-based PCB

Sample #	Activation Time (s)						
	Round #1	Round #2	Round #3	Round #4	Round #5	Round #6	Round #7
1	32	73	64	77	64	53	56
2	29	80	75	64	61	49	63
3	30	58	58	60	58	54	62
4	33	55	55	51	45	47	52
5	30	58	51	73	50	63	48
6	Load Test	85	64	63	57	51	58
7	Load Test	73	74	68	41	67	45
8	Load Test	60	66	66	52	37	58
9	Load Test	45	49	52	36	51	FAIL
10	Load Test	65	60	56	44	49	43
Average (s)	30.8	65.2	61.6	63	50.8	52.1	53.8

4.4 1000-Unit Production

This batch was produced using the direct deposit method and with the machined mould. The process, assembly procedure and AQL load tests were carried out in Inertia's facility located in Toronto.

4.4.1 Acceptance Quality Limit (AQL) Testing

The Acceptance Quality Limit (AQL) provides the necessary baselines for deciding if a batch of assembled/manufactured parts is declared acceptable regarding the quality guidelines set. The inputs required to determine the number of units needed for sampling are the total units produced, the inspection level and the AQL level.

The inspection level (I, II, III) is usually determined based on the industry of the product. As the inspection level increases, the number of samples required for batch verification increases, meaning more confidence is associated with the results. As a starting point for large-scale production, an AQL level of 2.5 was chosen, which means that 2.5 failures out of 100 samples are accepted as the worst tolerable quality level. Also, an inspection level of II was chosen.

Based on AQL, the number of samples required for testing is 80, and up to five defects are acceptable; however, if six defects are found, the batch does not pass the acceptance quality limit criteria. The determined criteria for finding defective samples are described in the test procedure.

4.4.1.1 Load Test

The load test is independent of the type of electronics unit used; therefore, it gives a good standpoint for the performance of sensor units. A constant current load of 50 μA is used for the load test, and the voltage drop is monitored after three minutes of water exposure. The two determined criteria for failure in the load test are the following (Both must be true for the test result to be a failure):

1. The maximum voltage is less than 1.9 V for fresh samples &
2. The drop in voltage with the load applied results in a voltage of less than 1.8 V after three minutes of the test

As shown in Figure 45, out of the 80 tested samples, three are coloured in red, meaning that they are the failed units. This batch can be accepted considering AQL metrics because the number of failed units is less than six.

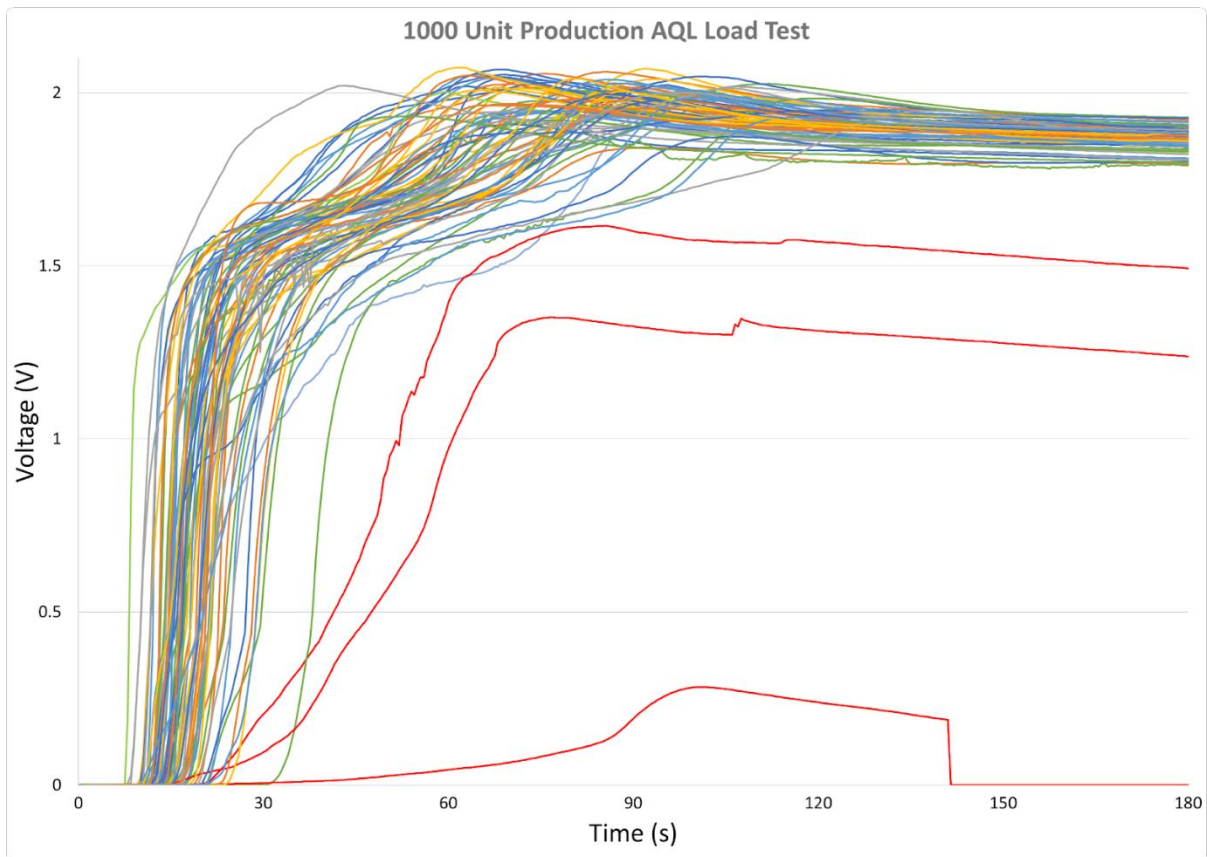


Figure 45: AQL load testing for 1000 sensor unit production using direct deposit mould

4.4.2 Beacon Activation

In order to verify the results of the load test with another test setup, the beacon activation test was conducted using the IN100-based PCB. Twenty samples were chosen randomly throughout the 1000 units. The maximum activation time for the fresh samples should be 5 minutes, and if a sensor activates after 5 minutes, it is considered a failed unit. One sample failed to activate the beacon in 5 minutes. The results can be seen in Table 17.

Table 17: Beacon activation test for twenty random samples out of the 1000-Unit batch

Sensor Unit ID	Activation Time (s)	Sensor Unit ID	Activation Time (s)
0334	34	0714	30
0354	43	0738	26
0420	31	0751	39
0451	48	0815	38
0535	45	0823	31
0562	43	0837	34
0581	57	0850	48
0668	37	0913	39
0684	FAIL	0914	44
0690	36	0929	42
Average (s)		39.2	

While the beacon was connected to the sensor unit, the sensor voltages were recorded using an oscilloscope, indicating that the failed sample (0684) experienced a sudden voltage drop and could not rise after that. Figure 46 shows the average voltage of the sensors which passed the beacon activation test in green and the voltage for the failed sample (0684) in red.

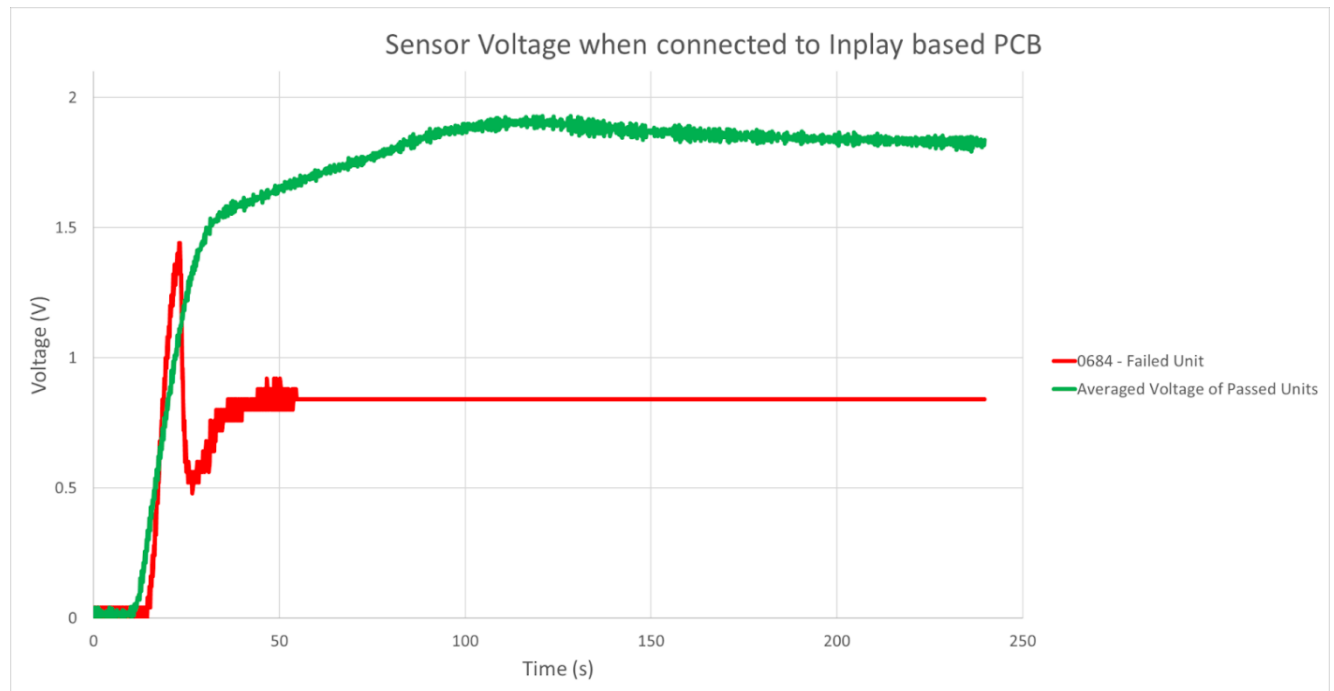


Figure 46: Sensor voltage during beacon activation test, indicating the averaged voltage of passed units in green and the failed unit in red

4.5 Summary of Chapter 4

This chapter's first goal was to investigate some sources of inconsistency in the sensor performance. It was found that an incorrect method of metallic sheet sanding can significantly impact the device performance by lowering the peak OCV and causing fast decay in voltage during load tests. A modified work instruction was generated for processing (sanding and punching) of the metallic sheets to prevent the inconsistencies spotted. Furthermore, i) oxidation on the top surface of the metallic disk and ii) spring contacts with lower than normal deflections can lead to poor connection (high resistance) between the spring contact and the metallic disk, creating a non-stable power output. In order to block these failure modes, a QC step was added for pulling the spring contacts with a tweezer to increase the deflection. The brittle characteristic of the powdered pallet was investigated in shipping conditions, and statistical analysis on activation time revealed inconsistencies in drop tests.

The second goal was refining the manufacturing process by changing the powder depositing method into the sensor enclosures. Moving from a single mould palleting design to a tri-press and finally to a direct-deposit method, along with sanding the metallic sheets instead of each disk one by one, led to reducing the cycle time of the process by 110 seconds (Process shown in Figure 47). Table 18 shows the breakdown of the cycle time for the sensors using the modified procedure. After moving from the tri-press to the direct deposit mould, the repeatability count was reduced from over ten rounds to six rounds of successful beacon activation (with the Inplay PCB). However, this new process is acceptable considering our requirement of 3 rounds (One-time factory testing, one-time on-field leak, and one round of contingency).

Finally, instructions were provided to a local vendor to evaluate the feasibility of production using this manufacturing process. They produced 1000 sensor units in 7 working days (with a single assembly worker), verifying that the manufacturing procedure was simple enough to be carried on by an assembly worker. Successful AQL tests using load test setup verified that the 1000-unit batch quality was in line with the standards set before testing and thus were acceptable.

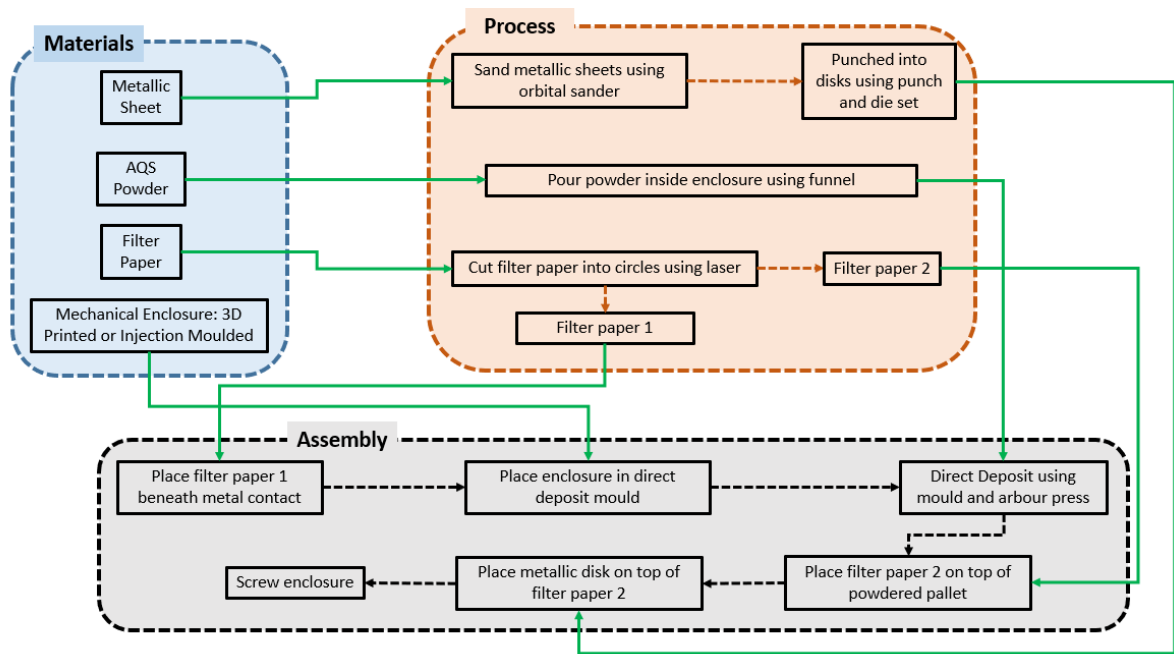


Figure 47: Modified manufacturing/production process of battery-free water leak sensor

Table 18: Cycle time, takt time and total time for sensor fabrication using modified procedure

Step No.	Type	Task	Time (s)
1	Process	Powdered pallet preparation with direct deposit mould	60
2	Process	Sanding each metallic disk	4
3	Process	Laser Cutting filter paper	5
4	Assembly	Opening and closing screws + Assembly of metallic disk	35
5	Assembly	Placing powdered pallet inside enclosure	0
6	Assembly	Placing filter papers inside enclosure	70
Cycle Time (s)			165
Takt Time (s)			16.5
Total Time (s)			181.5

Chapter 5

Conclusions, Recommendations, and Future Work

5.1 Conclusions

1. IoT water leak sensors depend on an external power source (majorly batteries), resulting in functional flaws. The significant effect that environmental parameters (such as very low temperatures) can cause on the lifetime of batteries is a significant problem. Due to batteries, water leak detectors in the market are unsuitable for long-term deployment or in hard-to-reach spots, as they will need a battery replacement in a few years. The maintenance time and cost of swapping batteries in leak detectors can be a major logistical issue. This issue will be even more of a flaw for buildings with hundreds of leak detectors deployed and some in difficult-to-reach locations. These issues can be solved using a leak detector based on a passive water-induced power generator.
2. An energy harvesting scheme is described, which is used for storing and utilizing power to send wireless signals. The work included finding the power generation capacity through electrical tests, then integrating the sensor with an actual BLE chipset for advertising Bluetooth data. The initial design was a two-board design, including an EHB and BLE board; however, it was simplified to a single-board design for simplicity and reducing costs. In order to use the single board design, along with the new BLE chipset (IN100), the current consumption patterns of the Inplay BLE chipset were found. The repeatability was enhanced from 4 successful consecutive rounds for the two-board design (nRF52832-based) to over ten successful consecutive rounds for the single-board (IN100-based) design.
3. The failure modes of the power generating unit (sensor unit) were investigated. It was found that shipping/handling can alter the device performance and cause a statistically variant activation time. Therefore, a standard packaging protocol was developed to reduce the inconsistencies in results. Furthermore, it was seen that the oxidation of the metal disk could increase electrical resistance, resulting in poor electrical performance of the device. In order to prevent this failure mode, it was found that as the force exerted on the spring contact increases, resistance drops. Therefore, the spring contacts should be deflected with a tweezer in the manufacturing facility before assembly into the enclosure. Finally, it was found that the sanding

method of the metal sheets/disks affects the device's performance. Therefore, external work instructions were created for the future processing of this material.

4. The sensor unit material assembly previously used a lab-based approach unsuitable for high-scale production. Therefore, a direct deposit assembly fixture was designed, 3D printed, verified, and machined. The modified assembly procedure reduces the cycle time from 302.5 seconds per sensor to 181.5 seconds. In other words, the lab-based assembly cycle time has been reduced by 40%. The performance shows we can have six successful consecutive repeatability rounds with the new sensor unit assembly method and the IN100-based single-board circuit.
5. The device hardware cost dropped from ~28 CAD to ~15 CAD. Therefore, there is an approximate 46% decrease in hardware costs of the leak detector device.

5.2 Recommendations and Future Work

1. Battery aging tests with extreme environmental conditions, such as very low temperatures, can be an excellent standpoint for comparisons and showing the benefits of a power source not affected by environmental conditions.
2. A new enclosure design iteration can be beneficial at this point, thus knowing the failure modes and the points of improvement required. In the new iteration of the enclosure design, electrical components should be replaced according to the feature requirements of the design (The concept design can be found in the appendix). The main features of the new enclosure design should consist of the following:
 - a. Filter paper legs elimination, without affecting the sensitivity and reliability of the device. This goal is possible through an optimized water channel geometry design for effective water capillary action through the enclosure.
 - b. Eliminating wires within the sensor unit enclosure, in order to simplify and reduce the failure modes associated with the connection of the wires within the sensor unit.
 - c. Eliminating hot glue as the mounting method of the contacts within the sensor unit enclosure, because it is not a stable and reliable mounting technique.
 - d. Decreasing overall height of device for easy install in tight spaces.
3. Attempt towards replacing the AQS powder material to a non-powder material which can allow easier manufacturing and possibly reduce variability in device performance.
4. The output voltage on the sensor unit is at a considerable level (1.8 – 2 V), however, the current limits the use of the device to ultra low power wireless protocols. Therefore, if the materials could be enhanced for generating higher currents, the overall device range and performance would increase.

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Appendix

A.1. Leak Detector Concept Re-Design

The re-design process consists of several steps before reaching the final product. The procedure can be seen in the flowchart of Figure 48. The issues of the current leak detector have been identified, and in the next step, the concept 3D design of the new leak detector was prepared in Solidworks.

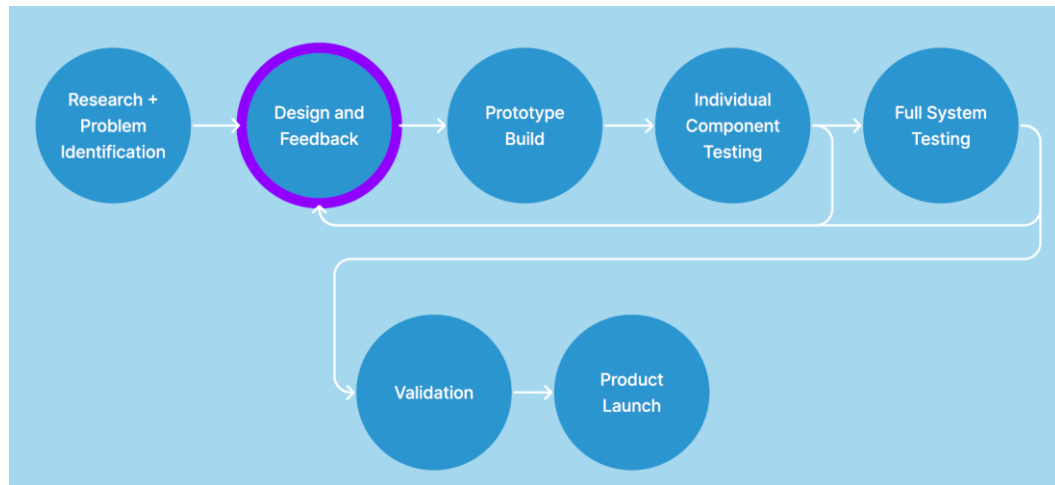


Figure 48: Leak detector re-design flowchart

The significant improvements of the concept re-design of the leak detector consist of the following:

1. No filter paper legs
2. Reduced the wired connections to a single connection within the sensor unit
3. Eliminated hot glue as a mounting method
4. Smaller (reduced dimensions) and low-profile design
5. Eliminated sensor unit male header
6. Eliminated electronics unit female header
7. Eliminated screws in the sensor unit; a snap-fit fastening method was acquired
8. Direct connection from PCB to sensor unit electrodes

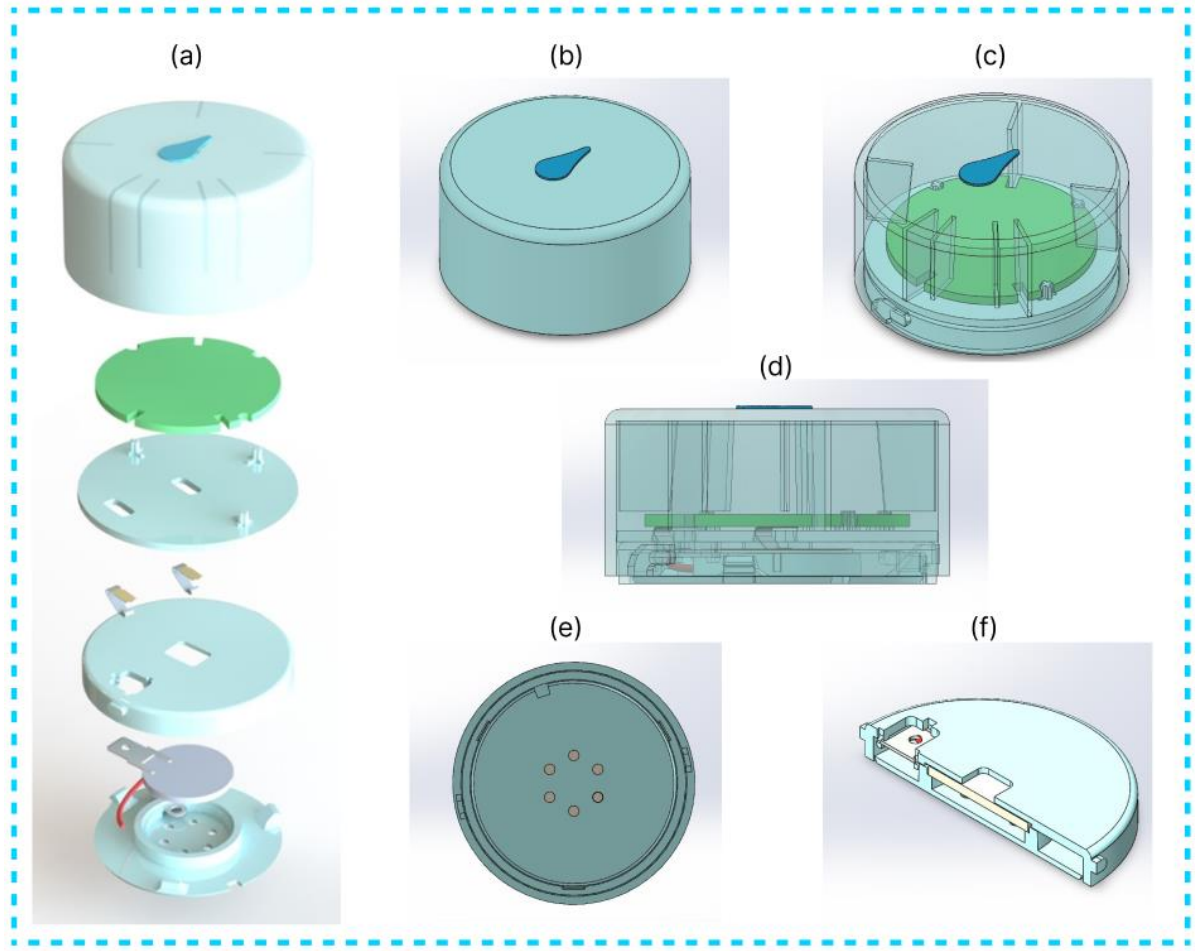


Figure 49: (a) Exploded view of the leak detector concept re-design along with the electrical components, (b) Isometric view of the assembled leak detector, (c) Isometric transparent view of the leak detector, (d) Transparent front view of the leak detector, (e) Bottom view of the sensor unit enclosure, and (f) Section view of the sensor unit