mc Capstone

mcChill: IoT Low-Cost Wireless Remote Temperature Monitoring Device for Vaccine Storage and Handling

Abstract

Our product focuses on the development of a low-power, wireless temperature monitoring device designed to ensure vaccine safety during storage and transport. The system is composed of a modular hardware architecture featuring a motherboard and daughterboard, each developed with custom PCBs and integrated NIST traceable temperature sensors. Key design goals include precise temperature tracking, reliable wireless communication, and a one-year battery lifespan at 2–8 °C. A custom PCB antenna was developed and tested to improve signal integrity within cold storage environments. The firmware utilizes an event-driven architecture supporting BLE and UART communication along with low-power sleep cycles. Mechanical development emphasized manufacturability, including injection molding and gasket design for waterproofing. The product addresses technical challenges in antenna performance, asynchronous memory handling, mechanical tolerances, and power optimization while meeting a extremely low manufacturing cost for mass production.

Introduction

Problem

This is not just a project; it is a product.

Due to the specific nature of vaccines, temperature monitoring and recording in storage is required by Alberta Health Services (AHS). These reporting methods must use devices that meet standards set in place by the Alberta College of Pharmacists (ACP). During an audit, AHS may request historic data to ensure temperature deviations of the vaccines did not fall outside acceptable ranges. Devices that meet ACP standards include simple thermocouple-based LCD display thermometers as well as more advanced remote wireless monitoring devices.

Because of the specific nature of the application, these proprietary devices maintain large price tags as well as having non-replaceable batteries. The traditional thermocouple thermometers also require calibration and constant monitoring from employees. While these products and procedures have worked for many years in the industry, pharmacies are looking for easier, more reliable and cost-effective solutions for temperature monitoring and logging. Furthermore, a simple analog thermometer cannot provide real time alerts when temperatures deviates from acceptable ranges and may not allow pharmacists to get control of the situation, causing the pharmacy to have to dispose of their inventory.

Industry Interviews

To better understand current cold storage monitoring practices, our team visited a pharmacy to evaluate existing procedures and industry requirements. Temperature logging is currently done manually twice daily using a thermocouple-based thermometer, with an audible alarm for temperature deviations outside of a set range. This method does not have a remote monitoring or alert system. Vaccines are stored in various form factors, including vials and pre-filled syringes and refrigeration units are usually full, requiring a product that takes space saving into consideration. Key concerns highlighted by the pharmacy manager included battery reliability, ensuring the device does not fail silently (battery capacity tracking and alarm), and maintaining an accurate reading in the 2–8°C range. They also emphasized the importance of ACP and cold-chain certification, and the ability to remotely check temperatures online for real-time monitoring at any time. These insights directly guided our product design, ensuring it meets real-world operational needs.

Proposed Product

Introducing mcChill, a BLE temperature sensor device that periodically collects temperature data from vaccines and forwards it through BLE to a connected LTE gateway external to the fridge. Messages sent from mcChill to a connected mcGateway are forwarded directly to mcCloud. Pharmacists can easily view their temperature data through the mcCloud website. The mcCloud software is capable of sending real time temperature threshold alerts if vaccine temperatures are out of threshold, giving pharmacists plenty of time to save their inventory.

mcChill mcGateway

Industry Competition

A direct competitor for mcChill is sold by BlueRover. Their devices use a much larger form factor and has built in LTE communication to a proprietary cloud, causing it to have a shorter battery life, and requiring a full unit replacement at end of life.

	mcChill	BlueRover
Cost	$15-$20 / Unit at scale ($35-$50 for Gateway)	$500+ / Unit
Expected Lifetime	Minimum 10 Years (with battery replacement)	Less than 1 Year (Unit replacement required)
Battery Life	1-2 Years	Less than 1 Year
Battery QTY.	1 x AAA	6 x Li-Ion
Temperature Update Interval	2 Minutes	1 Hour
Communication Protocol	BLE + LTE	LTE
Size	43mm * 65mm	Comparable to tissue box
Accessibility	Access through mcCloud globally with customizable variables and alerting methods (SMS, email)	Proprietary software – SMS and email availability, only modifiable by company.

Hardware Investigation

Challenges and Requirements

Accuracy → Implementation of NIST traceable sensors with no calibration to reach 0.1°C accuracy

Low Power → Critical component selection, less than 4uA total quiescent current consumed by hardware

Form Factor → The device's physical size must integrate seamlessly into their existing workspace

Cold Environment Operation → Components and battery chosen to work optimally in a 2-8°C fridge

Wireless Connectivity in Enclosures → Wireless signal strength must be powerful enough to breach a pharmaceutical fridge and reach the LTE gateway

Cost → Hardware cost must not exceed 20% of the competitor's product cost of $500+ to be disruptive

Splitting up the Problem - A Multi-board Solution

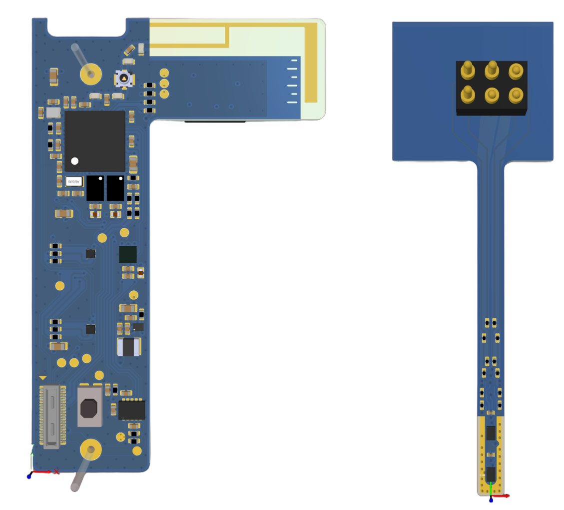
The full functionality of this product is delivered through 3 PCBs working together to deliver the complete solution. Our sensor device contains 2 of the PCBs, a motherboard and daughterboard. The implementation of a multi-board design was done in solution to the complex challenge of thermally coupling the temperature sensor to the metal probe, then to the surrogate glycol solution, all while keeping the device form factor small.

Motherboard: contains all complex circuitry, including the microcontroller, accelerometer, antenna, coulomb counter, and various user interface elements. It facilitates the main functionality to the device.

Daughterboard: contains two TMP117 temperature sensors for verification of accurate measurements. It is driven by the motherboard and is electrically connected to it via an array of 2x3 SMT pogo pins carrying I2C and hardware interrupt signals for temperature threshold alerts.

The intuitive ultrasonic weld design on our enclosure keeps the motherboard and daughterboard in constant electrical connection. All hardware throughout this project was designed without the use of prebuilt modules to keep scale manufacturing costs low.

*The pogo pin interfacing occurs on the opposite side of the motherboard

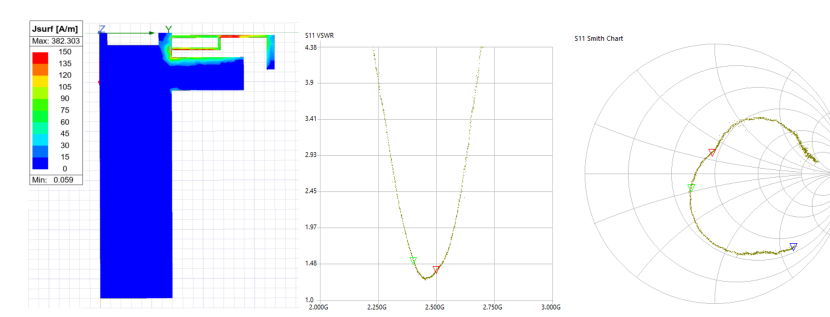


Motherboard Daughterboard

BLE Antenna Design & Testing

The small size and unique shape of the PCB required us to give extra attention to the antenna design. A custom antenna design was required to provide optimal signal transmission. We designed our own antenna using Ansys HFSS to simulate the antenna's performance, efficiency, and radiation pattern. The result is an original design that was tested using a vector network analyzer showing that it was better tuned and had a higher power radiation efficiency than a comparable chip antenna. Another big advantage is that it decreases our manufacturing cost by roughly 10% considering SMT chip antennas of similar performance applicable to our form factor are over $1.00 in volume.

The 2 charts on the right are actual measured data collected by a network analyzer during our antenna tuning procedure. Our antenna was tuned in the enclosure to account for the plastic dielectric and negate effects of frequency shifts



Current distribution S11 VSWR S11 Smith Chart

Component Selection + Manufacturing

Component selection was foundational to achieving high accuracy and low power consumption for our product. It laid the groundwork for the software team to further improve through firmware updates.

Microcontroller nRF52840: Rx/Tx currents ~35mA, Tx power of 8dBm, sleep mode down to ~1-2uA. Facilitates all wired/wireless communication, the brain of the device

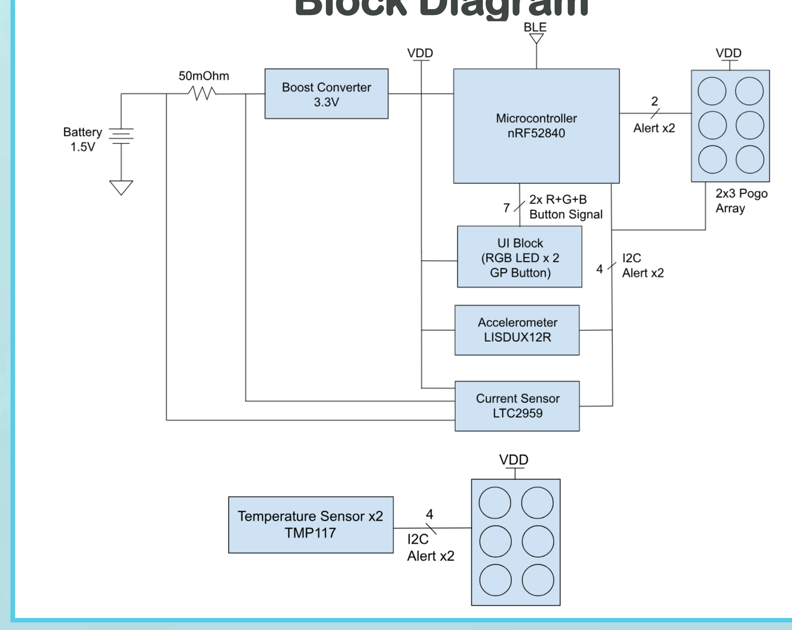
Temp Sensor TMP117: +-0.05°C between -20 to +50°C, resolution of 0.0078°C/LSB, 3.5uA sampling current, 15nA sleep current in a tiny, NIST traceable BGA package. Perfect for fitting into the probe tip in our enclosure

Accelerometer LIS2DUX12: 6 axis, 2.7uA sampling current @ 1Hz update frequency, 10nA sleep mode. Will let us know if our device is in motion

Other components: two RGB LEDs and a button for UI, an onboard high accuracy coulomb counter for power consumption monitoring and battery lifetime alerts, and two flash modules for downloading updates over the air. Li/FeS_2 battery chemistry was chosen for its good performance at cold temperatures and low RF impact.

The result is a hardware device with a theoretical floor current consumption of **less than 4uA** with optimized firmware. We've exceeded our cost goal by developing a product that can be manufactured at scale for **~$11.03 at scale** including the estimated labor cost of assembly.

Block Diagram



Mechanical Design

Requirements

Prioritizing affordability → By using existing mechanical components, costs can be minimized

Simple assembly → Assembly process heavily influenced modeling of design

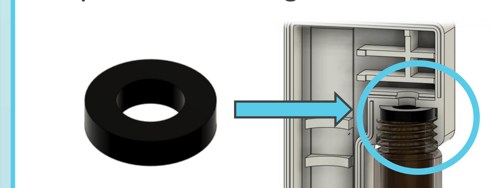
Avoid Undercuts → Undercuts lead to larger moulding costs and would result in an unachievable start-up cost

Watertight→ Ultrasonic weld design combined with rubber gasket ensure no surrogate solution contamination

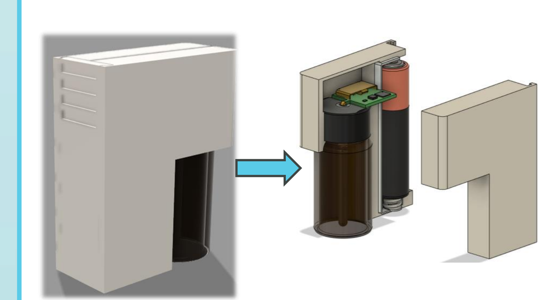
Replaceable Battery→ Device can be used for many years without replacement.

Waterproofing

To prevent liquid from leaking out of the vial, a standard rubber gasket was integrated into the design, providing a secure and reliable seal. A resistant two-part epoxy was used to further seal the enclosure, aiding in durability in all external conditions. Additionally, the probe was potted with a thermal compound to maintain accurate thermal transfer and ensure reliable temperature readings.



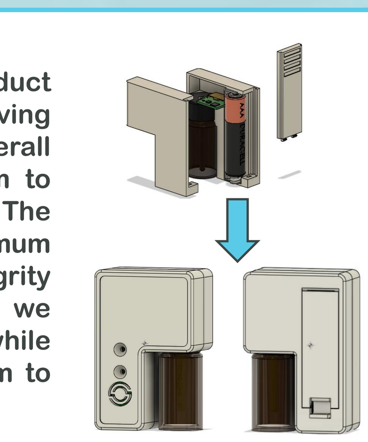
Prototyping



This design offers several benefits, including ease of manufacturing, a replaceable battery, and improved stability. While it uses more material compared to initial designs, we ultimately chose this design due to its larger size, which better accommodates internal components, as well as the convenience of the replaceable battery and its significantly greater physical stability.

Progression

The progression from our initial prototype to the final product involved several key design refinements aimed at improving manufacturability and functionality. We adjusted the overall dimensions and redesigned the removable lid mechanism to eliminate undercuts and simplify the production process. The average wall thickness was also modified to meet the minimum requirements for injection molding, ensuring structural integrity while maintaining manufacturability. For prototyping, we optimized tolerances to support a reliable snap-fit design, while for production, we incorporated an energy director system to enable efficient ultrasonic welding.



Testing Procedure

To validate the durability and functionality of our design, we conducted several tests, including tip-over tests, drop tests from a small height, and leak tests. The tip-over and drop tests helped assess the physical stability and robustness of the enclosure, ensuring it could withstand minor impacts without damage. Additionally, we performed leak tests and noted no leakage.

Software/Firmware Investigation

Challenges and requirements

Multiple Connections → Implementation that supports up to 20 concurrent BLE connections while managing and forwarding data to the cloud.

Low Power Code → The code has been tailored to ensure long battery life through minimum power consumption.

Store & Forward Messaging → If no Gateway is available for the Sensor(s) then the Sensor will store the data and time, forwarding it to the gateway upon the next available connection.

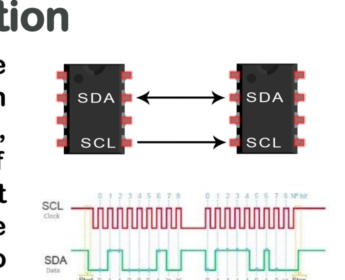
Accurate Time Keeping → When no gateway connection is available, our sensors keep track of time to associate with the measurements.

Secure Connections → All Communication is encrypted using AES128 with on-device encryption keys.

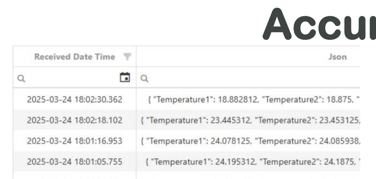
Compatibility → All firmware must be compatible to predefined mcThings standards and protocols.

Sensor Communication

To communicate with the sensors, we are using the inter integrated circuit (i2c) protocol. In addition to the physical and practical benefits i2c provides, using i2c also enables us a high degree of customization for these sensors such as one-shot mode. Because of this, we were able to fine tune how and when the sensors measured data to ensure minimal on time, and current consumption. Output was verified with nRF logs and RTT viewer.



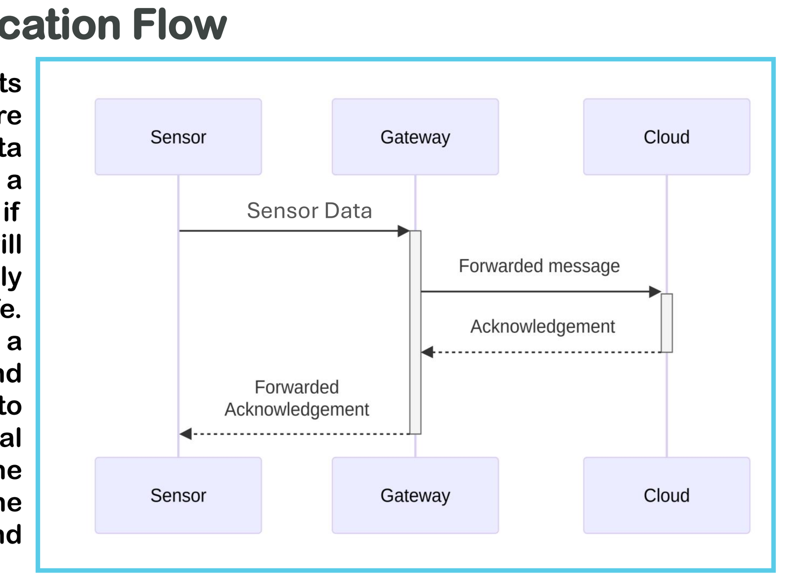
Accurate time keeping



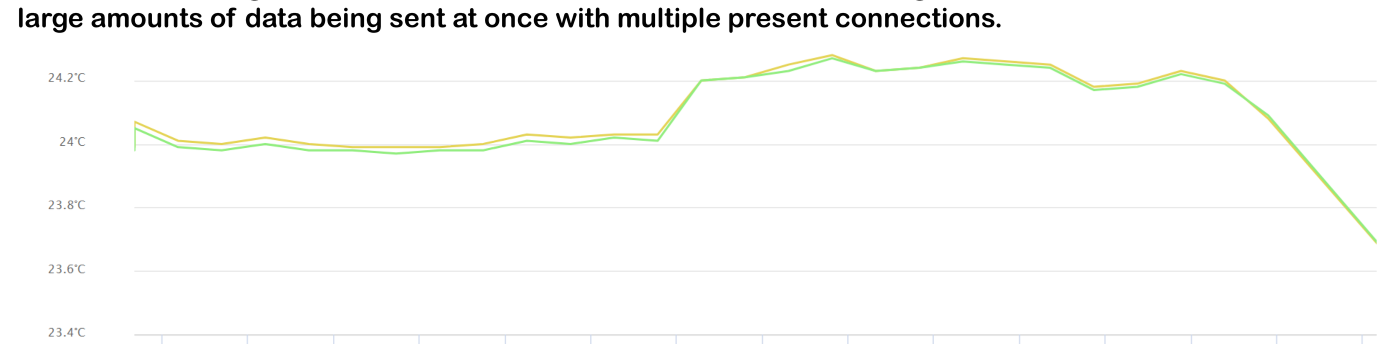
It is imperative to track time as the sensor data needs to be associated with a time for meaningful statistics and event information. Given that the Sensors won't always be connected to the Gateway, and therefore the cloud, we implement a "relative" time for offline time keeping. The Sensor counts the elapsed time since startup and upon a successful connection to the Gateway, the Gateway forwards the current time to the Sensor. With both the relative and absolute time, the Sensor can accurately determine the absolute time for measurements, preserving time integrity.

Communication Flow

The communication flow involves three parts working together. First, the sensor must measure some data and store it in flash to ensure the data is not lost. The sensor then searches for a gateway over Bluetooth Low Energy (BLE) and if it cannot find one within a specified time, it will go into sleep mode where it exhibits extremely low quiescent current to preserve battery life. Once the sensor successfully connects to a gateway, it will then forward all its data over and the gateway will immediately send that data to the LTE portion of the device over universal asynchronous receiver transmitter (UART). The data is then sent over LTE to the cloud where the user is able to view specific data points and trends.

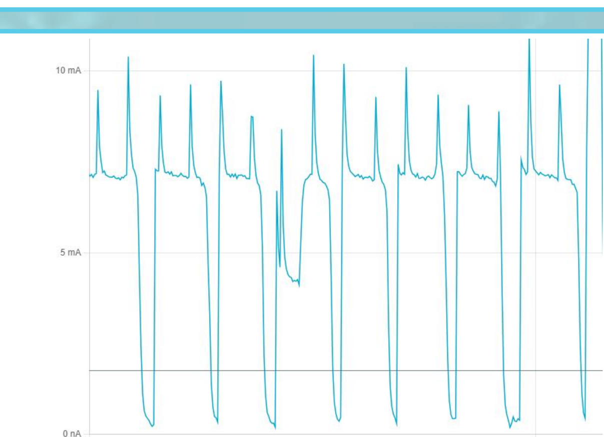


To ensure messages are received without data loss, we implement acknowledgments (ACKs) at every step. When the Sensor sends data to the Gateway, the Gateway will ACK the data, notifying the Sensor of successful data reception. On the Gateway, ACKs and a cyclic redundancy check (CRC) are used to ensure reliable communication over UART. If something is corrupted in transmission no ACK will be received, and the message will be resent with a maximum of three retries before giving up. Lastly, when sending data over LTE, no data will be acknowledged by the Cloud unless the format is exactly as expected. When an ACK is sent, we can be sure the data is correct, and the Cloud has received and stored the message. In addition to ACKs and CRC's, we utilize a large UART data buffer to handle the large amounts of data being sent at once with multiple present connections.



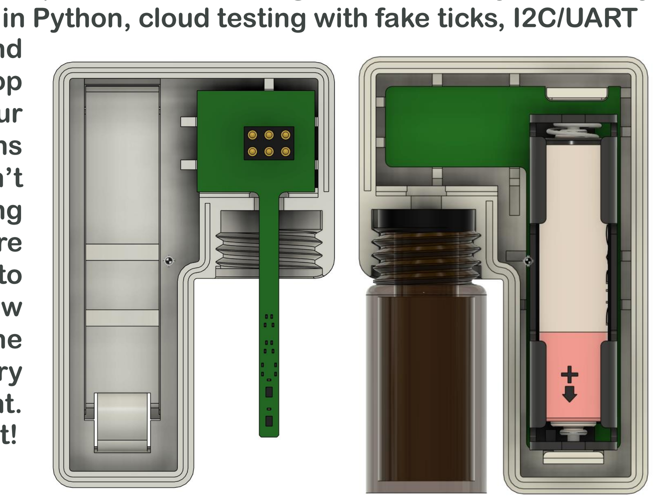
Low power optimization

To guarantee a long battery life, it is not enough to have low quiescent current components. The firmware is optimized to make the device sleep for most of the time, and only to wake up when necessary. The sensor will periodically wake up to search for a gateway and if one is found, it will forward its data then go back to sleep. The sleep mode of the device ensures only essential features are left on, like the timer, which guarantees low power consumption under normal operation.



Conclusion

Our goal was to develop a reliable low-cost and low-power alternative to current vaccine cold chain monitoring devices. mcChill successfully addresses these proven industry issues by integrating custom multi-board hardware, NIST-traceable temperature sensors and low-power encrypted BLE communication, all into an existing mcCloud infrastructure. We've been able to successfully achieve this through calculated component selection, custom BLE antenna design, careful attention to manufacturability, and a smart low-power messaging format. Our product Is fully scalable, well exceeding manufacturing cost goals. A replaceable battery solution with a projected year-long lifespan ensures the device is sustainable, reducing long term electronics waste compared to competitors. mcChill has been thoroughly tested across hardware (antenna, boost regulation, battery chemistry testing), firmware (UART buffer overflow in Python, cloud testing with fake ticks, I2C/UART functionality test with logic analyzer), and mechanical (watertight, assembly, drop testing) domains. Considering our development timeline was only 8-months long, suggested improvements we didn't have time to implement include: optimizing low power firmware, reducing hardware UI complexity, and adding draft angles to the enclosure. We are thrilled to know mcThings will move forward with the development of mcChill, and we're very happy to be part of its early development. Thank you for your interest in our product!



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