Project Report On

Zephyr RTOS Based-Cold Chain Monitoring Gateway

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Guided by:

Mr. Rishabh Hardas

Presented by:

Mohammad Sahil Shaikh	**PRN:250840130045**
Nitant Seth	**PRN:250840130031**
Vinayak Kulkarni	**PRN:250840130022**
Dolly Rani	**PRN:250840130015**
Omkar Kadam	**PRN: 250840130032**

Centre of Development of Advance Computing (C-DAC) Pune

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ABSTRACT

Vaccines require strict temperature regulation throughout storage and transportation to preserve their potency, safety, and therapeutic effectiveness. Even minor deviations from the recommended temperature range can result in irreversible degradation, leading to reduced efficacy, increased public health risks, and substantial financial losses. Conventional cold chain monitoring methods are often manual, lack real-time visibility, and do not provide timely alerts, making it difficult to respond promptly to temperature excursions. To address these limitations, this project presents the design and implementation of a Zephyr RTOS–based Cold Chain Monitoring Gateway specifically targeted for vaccine storage environments.

The proposed system utilizes ESP32-based sensor nodes to continuously monitor temperature and humidity within cold storage units. These sensor nodes operate under Zephyr Real-Time Operating System (RTOS) and execute multiple concurrent tasks for sensing, control, communication, and health monitoring. Sensor data is transmitted to a central gateway using Bluetooth Low Energy (BLE), enabling low-power and reliable short-range communication. The gateway aggregates data from multiple nodes and securely publishes it to a cloud platform using Wi-Fi and MQTT protocol, with TLS encryption and X.509 certificate-based authentication ensuring secure communication.

Cloud integration through AWS IoT Core provides real-time visualization, automated threshold-based alerts, and historical data storage for analysis. This enables proactive decision-making, early detection of abnormal temperature conditions, and preventive maintenance. The system also incorporates local control mechanisms such as fan and heater actuation to maintain temperature stability even during network disruptions.

The developed solution demonstrates a scalable, secure, and cost-effective architecture for cold chain monitoring. By combining embedded systems, RTOS-based task management, wireless communication, and cloud connectivity, the project enhances reliability, supports timely intervention, and improves overall vaccine handling practices. The proposed gateway offers a practical approach for strengthening cold chain management in healthcare facilities and can be extended to pharmaceutical storage, food logistics, and other temperature-sensitive applications.

Keywords: ESP32, Zephyr RTOS, IoT Gateway, BLE, MQTT, AWS IoT.

CHAPTER 1 - INTRODUCTION

1.1 Background

Vaccines are among the most valuable medical assets in modern healthcare, playing a vital role in preventing infectious diseases and safeguarding communities. However, the effectiveness of vaccines depends heavily on how they are stored and handled. Most vaccines must be kept within a specific temperature range, usually between **2°C** and 8°C, to ensure that their biological components remain stable. If the temperature rises too high or drops too low, even for a short period, the vaccine can lose its potency and become unusable. Once this damage occurs, it cannot be reversed.

Because of this sensitivity, vaccine storage facilities—such as hospitals, clinics, primary health centers, and transportation units—must rely on reliable systems that can continuously track temperature, humidity, and other environmental conditions. This entire process is known as the vaccine cold chain. Traditionally, cold chain monitoring has depended on manual temperature checks or basic data loggers. While these methods may be simple to use, they often fail to provide real-time alerts or continuous monitoring. As a result, temperature excursions can go unnoticed for hours, leading to large-scale vaccine spoilage.

With the widespread adoption of digital health technologies, the use of Internet of Things (IoT) systems for cold chain monitoring has increased. IoT-based monitoring allows sensors to collect data continuously and send it to a central platform, which can then notify personnel immediately if a problem occurs. This approach improves response times, reduces wastage, and ensures that vaccines remain within safe limits throughout storage and transportation.

In this project, a Cold Chain Monitoring Gateway has been developed to support real-time tracking of temperature conditions in vaccine storage environments. The system uses ESP32-based sensor nodes and a Zephyr RTOS–based gateway that collects sensor readings and forwards them securely to the cloud. This chapter outlines the context, challenges, purpose, and scope of the project.

1.2 Problem Statement

The primary problem addressed in this project is the high sensitivity of vaccines to temperature variations. Vaccines can be damaged or destroyed if the temperature inside cold storage units cross the recommended range. In many healthcare settings, temperature deviations occur because:

- Storage units malfunction without warning.
- Power failures cause refrigerators to stop cooling.
- Doors are opened frequently, causing temperature fluctuations.
- Manual monitoring is inconsistent or delayed.
- Staff may fail to notice when temperature excursions occur.

When these deviations go undetected, an entire batch of vaccines may lose potency. Since the damage is invisible and irreversible, using compromised vaccines poses serious risks to patients.

Moreover, vaccine wastage results in financial loss and supply shortages, especially in rural or resource-limited areas where access to vaccines is already challenging. Therefore, the problem demands a dependable, automated, and real-time monitoring system that can identify temperature changes instantly and alert staff before any irreversible damage occurs.

This project aims to solve this problem by developing a system that continuously monitors the environment, logs essential data, and sends immediate alerts when unsafe conditions arise—ensuring the safety and reliability of stored vaccines.

1.3 Motivation

The motivation for this project comes from the need to strengthen the healthcare system’s ability to protect vaccines from preventable damage. During national immunization programs or disease outbreaks, maintaining vaccine potency is essential. Even a small temperature shift can compromise an entire supply, affecting hundreds or thousands of people who depend on timely vaccination.

Many real-world cases highlight this issue. For example, health centers have reported losing large amounts of vaccines due to unnoticed power cuts or refrigerator failures. In some areas, limited resources make it difficult to monitor cold storage facilities around the clock. These problems inspired the idea of designing a reliable gateway that can operate continuously, send alerts instantly, and reduce the workload on healthcare staff.

Another major motivation is the importance of digitizing and modernizing the cold chain, especially after the global COVID-19 vaccination drive. The pandemic emphasized how crucial it is to maintain vaccines safely from manufacturing sites to clinics. Technologies such as IoT, wireless communication, and cloud platforms now make it possible to automate this process with greater accuracy and reliability.

By working on this project, we aim to contribute to an affordable and practical solution that can be deployed in hospitals, small clinics, rural health centers, and vaccine transport vehicles. Ensuring that every vaccine reaches patients safely is not only a technical challenge but also a public health responsibility.

1.4 Objectives of the Project

The main objectives of the Cold Chain Monitoring Gateway project are:

1. To design and implement a real-time temperature monitoring system

The system will use ESP32-based sensors to continuously measure temperature and humidity in vaccine storage units.

2. To develop a central gateway using Zephyr RTOS

The gateway will collect sensor data via Bluetooth Low Energy (BLE) and forward it to the cloud through Wi-Fi.

3. To enable instant alerts and notifications

If the temperature moves out of the safe range, the system will immediately notify the concerned personnel through cloud alerts, preventing vaccine spoilage.

4. To store and manage historical data

Cloud storage will allow users to review past temperature trends and identify recurring issues.

5. To ensure reliability, low power consumption, and scalability

The system should operate for long periods without failure and support multiple sensor nodes as needed.

1.5 Scope of the Project

The scope of this project covers the development, integration, and testing of an IoT-based cold chain monitoring system with a focus on vaccine refrigeration units. The system includes:

- **ESP32 Sensor Nodes:**
  These measure temperature and humidity at regular intervals and communicate with the gateway over BLE.
- **Zephyr RTOS–based Gateway:**
  The gateway handles BLE scanning, data aggregation, Wi-Fi connectivity, and cloud communication.
- **Cloud Platform Integration:**
  Data is published to the cloud using MQTT for storage, visualization, and alert generation.
- **Real-Time Dashboard and Alert System:**
  Health workers can monitor cold storage conditions remotely and receive notifications when temperature deviations occur.

The project focuses primarily on the monitoring and alerting mechanisms within the cold chain. It does not include refrigeration hardware development or medical-level certification processes. However, the proposed system can be expanded with more advanced features such as GPS tracking, battery backup monitoring, edge-based anomaly detection, and support for multiple types of sensors.

Overall, the scope ensures that the system is practical for real-world use, scalable for larger installations, and flexible enough to be upgraded in the future.

Chapter 2 - LITERATURE SURVEY

2.1 Existing Cold Chain Monitoring Systems

Cold chain monitoring has become an important part of healthcare management, especially for vaccines that must be stored within a strict temperature range. Over the years, several types of cold chain monitoring systems have been introduced. These systems vary in technology, complexity, and reliability.

One of the earliest and most common methods used in clinics and hospitals is manual temperature logging. In this method, a staff member checks the refrigerator thermometer at fixed intervals and records the temperature on a sheet. Although simple, this approach depends heavily on human consistency and does not provide continuous monitoring.

Another commonly used solution is the digital data logger (DDL). These devices automatically record temperature over time and store the readings in memory. At the end of the day or week, the data can be downloaded to a computer for analysis. Data loggers offer better accuracy than manual checks but still lack real-time alerting capabilities. If a temperature excursion occurs during the night or when no staff is available, the problem may only be discovered after the damage is already done.

In recent years, more advanced systems have emerged using GSM, Wi-Fi, or cloud-based technology. These solutions can upload temperature data to web dashboards and send SMS or email alerts when the temperature goes out of range. Some government immunization programs also use such systems to track storage conditions at district or regional vaccine stores. These technologies offer improved monitoring but can be expensive or require continuous network connectivity.

With the growth of the Internet of Things (IoT), newer systems now use wireless sensors such as BLE or Zigbee to collect environmental data and send it to a central hub. These systems are more flexible, scalable, and consume less power. However, their performance depends on the gateway's reliability, the quality of the software, and the compatibility of the sensors.

The review of existing systems shows that cold chain monitoring has evolved from simple manual checks to more sophisticated IoT-enabled solutions.

2.2 Limitations of Existing Systems

Despite the advances in cold chain monitoring technologies, several limitations and gaps still exist. These challenges often lead to vaccine spoilage, high maintenance costs, or ineffective monitoring. Some key limitations are:

1. Lack of Real-Time Continuous Monitoring

Many traditional systems, such as data loggers, do not provide real-time updates. They only record data for later analysis, meaning staff may not know about a temperature excursion until it is too late.

2. Dependence on Manual Work

Manual monitoring depends heavily on staff availability and discipline. During busy hours, holidays, or emergencies, readings may be skipped, resulting in missed temperature deviations.

3. High Cost of Commercial Solutions

Advanced GSM- or cloud-based cold chain systems offered by private companies can be expensive for small clinics or rural health centers. High subscription fees and maintenance costs limit their adoption.

4. Limited Connectivity and Infrastructure Issues

Systems that rely solely on the internet or mobile networks may fail in remote areas where signals are weak or unstable. Connectivity gaps result in incomplete or delayed data.

5. No Unified Platform for Multiple Devices

Some existing solutions lack a central gateway that can handle multiple sensors. Each sensor operates separately, which increases cost and makes expansion difficult.

6. Power Consumption and Battery Issues

Wireless monitoring systems need to operate for long periods without frequent battery changes. Some early systems consume more power, reducing their practicality.

7. Lack of Smart Alerting and Analytics

Only a few systems provide predictive analytics or intelligent alerts. Most solutions notify users only after the temperature has already gone out of range, offering little opportunity for preventive action.

8. Poor Integration with Modern IoT Frameworks

Older systems do not support modern IoT technologies like MQTT, TLS security, or cloud dashboards. This limits remote accessibility and data protection.

These limitations highlight the need for a more efficient, low-cost, reliable, and scalable solution that provides real-time updates and timely alerts to prevent vaccine wastage.

2.3 Need for the Proposed System

Vaccines are extremely temperature-sensitive, and any deviation from the recommended range of 2°C to 8°C can reduce their effectiveness or even render them useless. The consequences of improper storage extend beyond financial loss—they can impact public health, immunization coverage, and trust in healthcare systems.

The proposed Cold Chain Monitoring Gateway addresses the limitations of existing systems through a combination of modern technologies and practical design considerations:

1. Real-Time Monitoring with Immediate Alerts

The system continuously monitors temperature and humidity and sends instant notifications to staff when the storage conditions become unsafe. This allows quick action to save the vaccines before damage occurs.

2. Low-Power Wireless Sensor Nodes

Using ESP32 BLE sensor nodes ensures long battery life, making the system suitable for continuous monitoring without frequent maintenance.

3. Centralized Gateway Using Zephyr RTOS

The gateway collects all sensor readings, processes them, and uploads the data to the cloud. Zephyr RTOS ensures stable, predictable, and secure operation, even under heavy loads.

4. Cloud-Based Dashboard and History Tracking

The cloud integration allows healthcare workers and administrators to monitor storage conditions from anywhere. Historical data helps identify recurring issues, equipment failures, or human errors.

5. Scalability for Multiple Storage Units

The system can handle many sensors at the same time, making it suitable for large vaccine centers or district medical stores.

6. Affordable and Easy to Deploy

The proposed system uses open-source software and low-cost hardware components. This makes it accessible for government hospitals, private clinics, and rural health centers.

7. Enhanced Vaccine Safety and Reduced Wastage

By preventing unnoticed temperature excursions, the system helps preserve vaccine potency and ensures safe immunization services.

In summary, the proposed system is needed to modernize vaccine cold chain monitoring by providing a reliable, user-friendly, cost-effective, and technically robust solution. It fills the technology gaps left by existing systems and supports the broader goal of delivering safe vaccines to the public.

Chapter 3 – System Overview

3.1 Overall System Description

The cold chain monitoring gateway developed in this project is designed to ensure continuous and accurate monitoring of vaccine storage environments. Vaccines must be kept within a narrow temperature range to maintain their effectiveness, and any deviation can result in irreversible damage. The goal of this system is to provide an automated, real-time, and reliable method to track environmental conditions, detect temperature excursions, and alert personnel immediately.
The system consists of two major components:

1. **Sensor Nodes (ESP32-based)** – These are installed inside or near vaccine storage refrigerators. They measure temperature and humidity at regular intervals and communicate wirelessly using Bluetooth Low Energy (BLE).
2. **Gateway Unit (Zephyr RTOS–based ESP32)** – This device acts as the central hub. It scans for BLE sensor nodes, collects data from them, processes the readings, and uploads the information to a cloud server through Wi-Fi.

The cloud platform stores the data, displays it on dashboards, and generates real-time alerts when storage conditions go out of range. The system is capable of supporting multiple sensor nodes, allowing it to monitor several refrigerators or storage rooms simultaneously.
Overall, the proposed gateway ensures that vaccine conditions are continuously monitored, even when healthcare staff are not physically present, ultimately reducing the risk of spoilage and strengthening the cold chain infrastructure.

3.2 System Architecture

The system architecture is designed with simplicity, reliability, and scalability in mind. It uses a layered structure to clearly separate tasks such as data sensing, wireless communication, processing, and cloud integration.

The architecture consists of the following layers:

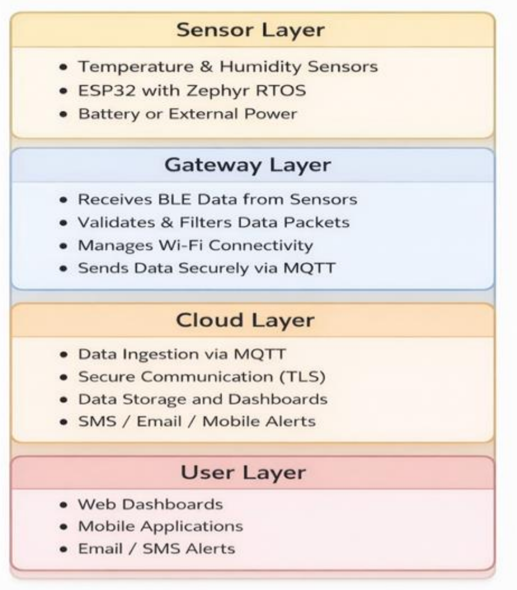

Figure 1. System Architecture

1. **Sensor Layer**

This layer includes the ESP32-based sensor nodes. Each node contains:

- A temperature and humidity sensor (like DS18B20 or DHT22)
- An ESP32 module for BLE communication
- A battery or external power source

The nodes periodically measure environmental parameters and broadcast these values over BLE advertisements or GATT characteristics.

2. **Gateway Layer**

The gateway, built using another ESP32 board running Zephyr RTOS, performs several important functions:

- Scans BLE advertisements from sensor nodes
- Reads sensor data packets
- Validates and filters the readings
- Manages Wi-Fi connectivity
- Sends data securely to the cloud using MQTT

Zephyr RTOS provides thread management, device drivers, and a stable environment for continuous operation.

3. **Cloud Layer**

The cloud server (AWS IoT or similar platform) performs:

- Data ingestion via MQTT
- Secure communication using TLS certificates
- Data storage and timestamping
- Real-time dashboards
- Alerts via SMS, email, or mobile notifications

4. **User Layer**

Healthcare workers can access the data through:

- Web dashboards
- Mobile applications
- Email or SMS alerts

This architecture ensures a complete end-to-end flow of vaccine condition monitoring.

3.3 Block Diagram

A simplified block diagram of the system can be represented as follows (textual form):

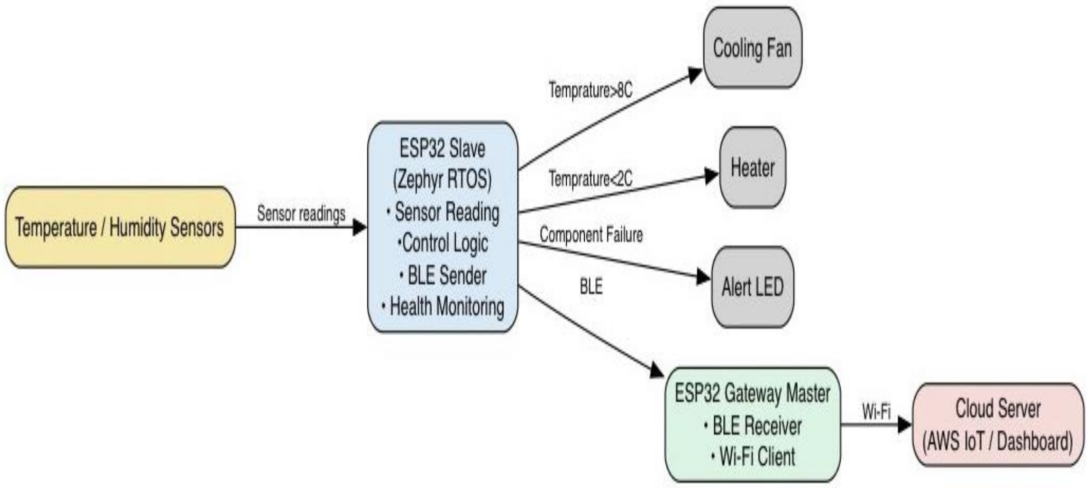

Figure 2. Block Diagram of system

This block diagram demonstrates the communication flow from sensor nodes to the gateway and then to the cloud. The system can easily accommodate additional nodes, making it scalable for large facilities.

3.4 Working Principle

The working principle of the cold chain monitoring gateway revolves around continuous sensing, wireless data transmission, real-time processing, and automated cloud-based alerting. The sequence of operations is as follows:

Step 1: Sensing the Environment

Each ESP32 sensor node monitors temperature and humidity at preconfigured intervals. These values are read from the attached sensor (e.g., DS18B20). The data is then encoded into BLE packets for transmission.

Step 2: BLE Broadcasting and Scanning

Sensor nodes broadcast their readings using BLE. The gateway continuously scans for these BLE packets and identifies nearby sensor nodes based on their unique identifiers.

Step 3: Data Collection by Gateway

When the gateway receives a BLE packet:

- It extracts temperature, humidity, node ID, and timestamp
- Performs basic validation (e.g., checking if the values are within the sensor's range)
- Stores the data temporarily in memory or queues

Zephyr RTOS ensures smooth multitasking between BLE scanning, Wi-Fi handling, and MQTT transmission.

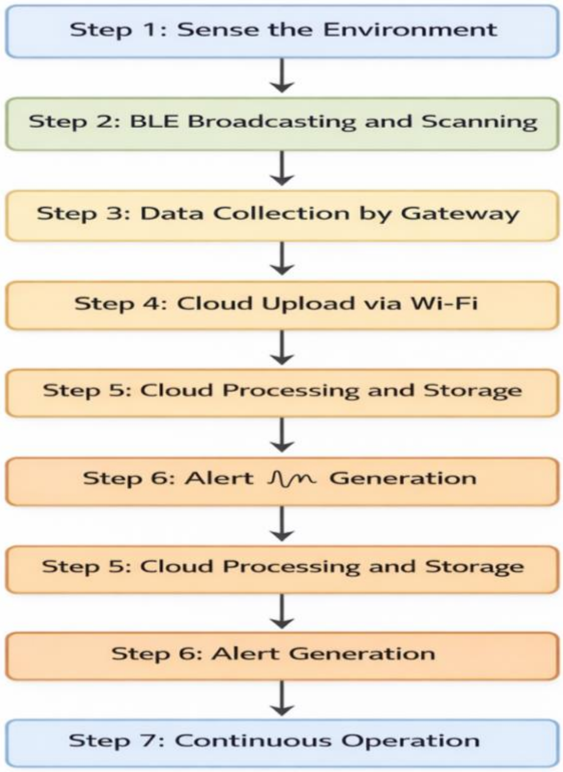

Figure 3. Working flow of Cold Chain Monitoring Gateway

Step 4: Cloud Upload via Wi-Fi

The gateway establishes a secure Wi-Fi connection and sends data to the cloud through MQTT. Each message is encrypted using TLS certificates to ensure security.

Step 5: Cloud Processing and Storage

The cloud platform receives the data, verifies the device credentials, and logs the readings. Dashboards visualize:

- Real-time temperature graphs
- Historical trends
- Node-wise comparison

Step 6: Alert Generation

If the temperature exceeds the safe range (e.g., below 2°C or above 8°C), the cloud instantly triggers:

- SMS alerts
- Email warnings
- Mobile notifications

This helps staff respond quickly before vaccines are damaged.

Step 7: Continuous Operation

The system runs continuously, with sensor nodes functioning for long periods due to low BLE power consumption. The gateway remains active, ensuring 24/7 monitoring.

Chapter 4 – Hardware Design

4.1 Hardware Components Used

The proposed cold chain monitoring system consists of multiple ESP32-based sensor nodes and a centralized ESP32 gateway. The sensor nodes are deployed at different points in the cold storage environment to continuously monitor temperature. The gateway collects sensor data using Bluetooth Low Energy (BLE) and forwards it securely to the cloud using WiFi.

The primary hardware components used in the system are:

Table 1. Hardware Components used

Sr. No	Component	Key Specifications	Purpose
1	ESP32-WROOM (2 Units)	Dual-core 240 MHz, Wi-Fi + BLE, 520 KB SRAM	One ESP32 as Zephyr sensor node, second as BLE–WiFi gateway
2	Temperature/Humidity Sensor (DHT11)	Temp: 0–50 °C, Humidity: 20–90%, ±2 °C	Measures temperature and humidity
3	Alert LED	3.3 V compatible	Indicates abnormal temperature condition
4	Power Supply Module	5 V USB / Battery	Powers ESP32 and peripherals
5	Jumper Wires	Male–Male / Male–Female	Component interconnections
6	Breadboard / Prototyping Board	Solderless	Circuit assembly and testing

The ESP32 platform was selected due to its integrated wireless capabilities, low power consumption, and sufficient processing power for IoT applications.

4.2 ESP32 Sensor Node Description

Each sensor node is built around an ESP32 microcontroller interfaced with a temperature sensor. The node periodically samples temperature data and transmits it to the gateway using BLE communication.

The ESP32 operates in BLE peripheral mode. After initialization, the node advertises its presence and waits for connection from the gateway. Once connected, sensor readings are sent as BLE characteristics.

Local validation of sensor values is performed to eliminate invalid readings. This reduces unnecessary data transmission and improves system reliability.

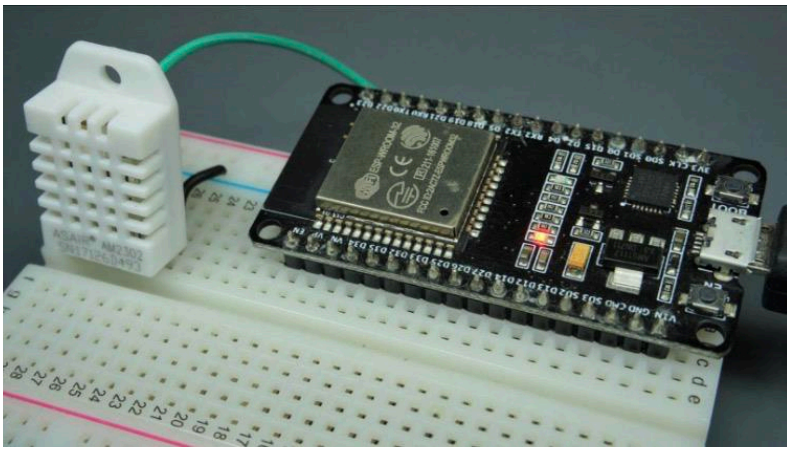

Figure 4. Sensor interfacing with ESP32

4.3 ESP32 Gateway Description

The gateway ESP32 acts as the central processing unit of the system and runs Zephyr RTOS. It operates in BLE central mode to collect data from sensor nodes and simultaneously maintains a WiFi connection to AWS IoT Core.

The gateway performs the following functions:

- BLE scanning and connection management
- Sensor data aggregation
- Network connectivity handling
- MQTT publishing
- Alert generation

Using Zephyr RTOS enables deterministic execution and efficient multitasking between BLE and cloud communication.

4.4 Sensor Details

Temperature sensors are connected to the ESP32 GPIO pins and sampled at predefined intervals. The raw sensor output is converted into temperature values using

appropriate calibration logic.
The system supports configurable sampling intervals, enabling optimization between power consumption and monitoring frequency.

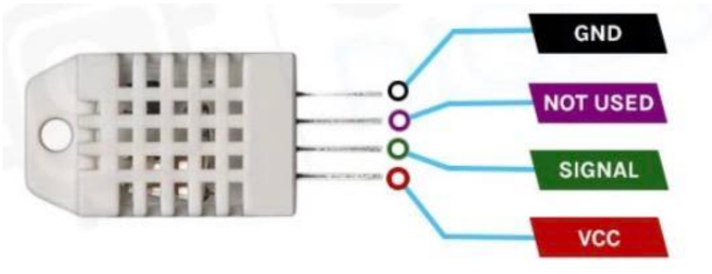

Figure 5. DHT22 Sensor Pinout

4.5 Power Supply Design

Both sensor nodes and gateway are powered through regulated 5V supply sources. Onboard ESP32 voltage regulators provide the required 3.3V operating voltage.
Low-power BLE modes are utilized to reduce energy consumption on sensor nodes, making the system suitable for battery-operated deployments.

Chapter 5 – Software Design

5.1 Software Architecture

The software is designed using a layered architecture consisting of:

- Application Layer
- Zephyr RTOS Layer
- Device Driver Layer
- Hardware Layer

Each functional block is implemented as an independent RTOS thread, improving modularity and scalability.

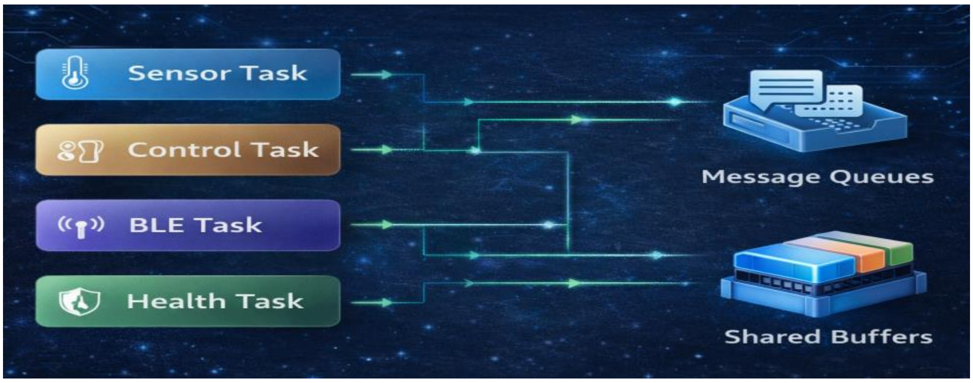

Figure 6. RTOS Tasks

5.2 Zephyr RTOS Overview

Zephyr RTOS provides real-time capabilities including thread scheduling, synchronization primitives, and networking stacks. It supports preemptive multitasking and priority-based scheduling.

In this project, Zephyr manages concurrent BLE and WiFi operations while maintaining real-time performance.

5.3 Task Design and Scheduling

The following threads are implemented on the gateway:

- BLE Receive Thread
- Sensor Processing Thread
- MQTT Publish Thread
- Network Monitoring Thread

Each thread is assigned a priority based on its real-time importance. BLE reception tasks are given higher priority to avoid data loss.

5.4 Inter-Task Communication

Inter-thread communication is achieved using message queues and semaphores. Sensor data received via BLE is placed into message queues and consumed by MQTT publishing threads. This design prevents race conditions and ensures thread-safe operation.

5.5 BLE Communication Design

Sensor nodes act as BLE peripherals while the gateway acts as the central device. BLE GATT services are used to transfer temperature data.
This approach minimizes power consumption while maintaining reliable short-range communication.

5.6 WiFi and Cloud Communication

The gateway connects to WiFi and establishes a secure MQTT connection to AWS IoT Core. TLS encryption ensures data confidentiality and integrity.

Chapter 6 – Cloud Integration

6.1 AWS IoT Core Overview

AWS IoT Core is a cloud-based service provided by Amazon Web Services that enables devices to connect securely to the internet and exchange data with cloud applications. It plays a central role in modern IoT systems because it supports millions of devices simultaneously while ensuring high security, reliability, and scalability.

For this project, AWS IoT Core acts as the cloud backend for our cold chain monitoring gateway. The gateway, running Zephyr RTOS, communicates with AWS IoT Core using MQTT messages to upload temperature and humidity readings. AWS IoT Core receives these incoming data streams, authenticates the device, and routes the data to different AWS services for storage, analysis, and alert generation.

Some key features of AWS IoT Core relevant to our system include:

Secure Device Connectivity: Every device must authenticate using unique certificates, ensuring only trusted devices can communicate.

Message Routing: AWS IoT rules allow us to send data to DynamoDB, S3, Lambda, SNS, or other services.

Device Shadow: It maintains a virtual copy of device states, useful for syncing parameters.

Scalability: It can handle thousands of sensor readings per second, making it suitable for large vaccine cold chain networks.

Using AWS IoT Core ensures that the monitoring system remains reliable, secure, and scalable, even when deployed across multiple sites or facilities.

6.2 MQTT Protocol

MQTT (Message Queuing Telemetry Transport) is the primary communication protocol used between the gateway and AWS IoT Core. MQTT is extremely lightweight and efficient, making it ideal for IoT applications where bandwidth may be limited and devices often run on low power.

In this system:

- The ESP32 sensor nodes send data to the gateway via BLE.
- The gateway publishes these readings to predefined MQTT topics on AWS IoT Core.

The publish–subscribe model of MQTT offers several advantages:

Low Bandwidth Usage: MQTT messages are small and optimized for constrained networks.

Asynchronous Communication: Devices publish data independently, and cloud applications subscribe to relevant topics.

Reliable Delivery: MQTT supports Quality of Service (QoS) levels to guarantee message delivery even under poor connectivity.

Topic-Based Routing: Data can be organized using structured topics such as:

coldchain/gateway1/sensor1/temperature

coldchain/gateway1/sensor1/humidity

Cloud applications or dashboards subscribe to these topics to receive data in real time. This design ensures efficient and smooth data transfer from the gateway to the cloud.

6.3 Device Authentication and Security

Security is one of the most critical aspects of any IoT system, especially in healthcare-related applications where data must be protected from unauthorized access. AWS IoT Core provides a robust security model using X.509 certificates, which securely identify each device.

Each gateway device is provisioned with:

Device Certificate – Proves the identity of the device to AWS IoT.

Private Key – Stored securely on the device and never shared.

Root CA Certificate – Used to verify AWS IoT's identity.

These credentials are used to establish TLS (Transport Layer Security) connections between the gateway and AWS IoT Core. TLS ensures:

Encrypted Communication: All data transmitted is protected from interception.

Integrity: Data cannot be modified during transmission.

Mutual Authentication: Both AWS and the device verify each other’s identity.

In addition to certificates, AWS IoT provides:

IoT Policies: Define what each device is allowed to publish or subscribe to.

Fine-Grained Access Control: Uses IAM rules to restrict access to resources.

Audit Logs: Track all device activity for security compliance.

This layered approach ensures that only authenticated devices can send data and that all communication remains secure**.**

6.4 Data Flow

The data flow in the cold chain monitoring system follows a clear multi-stage pipeline from the physical environment to the cloud dashboard.

Step-by-Step Data Flow:

1. **Sensor Data Collection**

   Temperature and humidity sensors (e.g., DS18B20, DHT22) measure the environment inside the vaccine storage unit.

2. **Transmission to Gateway via BLE**

   ESP32 sensor nodes broadcast readings using Bluetooth Low Energy.

   The gateway continuously scans for BLE packets and receives the values.

3. **Local Processing on Gateway**

   The gateway performs:

   - Value validation
   - Timestamp assignment
   - Data formatting (JSON payload)

4. **MQTT Publish to AWS IoT Core**

   The gateway connects to Wi-Fi and publishes data to AWS IoT Core using secure MQTT packets.

5. **AWS IoT Rules Engine**

   IoT rules determine where the data should be sent, for example:

   - DynamoDB → for structured storage
   - S3 → for long-term archival
   - SNS → for alert notification
   - Lambda → for backend processing

6. **Cloud Dashboard & Alerts**

   Real-time dashboards display live readings, and alert mechanisms notify users when temperature violations occur.

This streamlined data flow ensures that the system provides accurate, real-time monitoring for vaccine cold storage environments.

6.5 Alert and Monitoring Mechanism

A crucial feature of the cold chain monitoring system is the automatic alerting mechanism that warns healthcare staff when temperature conditions become unsafe. AWS IoT enables this through its rule engine and integrated cloud services.

How Alerts Work:

1. Threshold Setup

Safe temperature ranges (e.g., 2°C to 8°C) are configured on the cloud platform.

2. Data Evaluation

Every time the gateway sends a new reading, AWS evaluates it using an IoT rule.

3. Alert Triggering

If the value exceeds the threshold, AWS triggers one or more actions:

- SNS Notification: Sends SMS or email alerts to staff.
- Lambda Function: Executes **logic such as storing the alert or updating a dashboard.**
- CloudWatch Alarm: Used for long-term stability monitoring or automatic responses.

4. Dashboard Visualization

A cloud dashboard display:

- Current temperature and humidity
- Historical trends and graphs
- Active and past alerts
- Device health status

5. Real-Time Response

Staff can quickly take corrective actions such as checking the refrigerator, adjusting settings, or moving vaccines to another storage unit.

The alerting system ensures that deviations are noticed immediately, reducing the risk of vaccine spoilage and ensuring safe immunization practices

Chapter 7 – Implementation Details

The implementation phase of the cold chain monitoring gateway focuses on converting the system design into working firmware for both the sensor nodes and the gateway. This chapter explains the internal working of the software, including firmware flow, node-side logic, gateway operations, and fault-handling mechanisms. The system was implemented with the goal of ensuring continuous, stable, and real-time monitoring, especially for vaccine storage environments where reliability is crucial.

7.1 Firmware Flow

The firmware follows a structured sequence starting from system boot-up to cloud data transmission. Once powered on, the device goes through several initialization stages, ensuring that all hardware and software components are ready before data processing begins.

Initialization Phase

- The system begins by initializing the essential peripherals:
- GPIO for sensor input
- BLE hardware drivers
- Wi-Fi modules
- Real-time clock (if used)
- Internal queues and buffers

Zephyr RTOS then starts its scheduler, which creates and manages threads for different tasks such as BLE scanning, Wi-Fi handling, MQTT publishing, and watchdog monitoring.

BLE and Wi-Fi Setup

Once initialization is complete:

1. The gateway enables BLE scanning and listens for advertisement packets from sensor nodes.
2. In parallel, the Wi-Fi thread connects the gateway to the configured network.
3. The MQTT client starts and establishes a secure connection with AWS IoT Core using device certificates.

Data Collection and Publishing

After all connections are successfully established:

- The BLE thread collects sensor readings at regular intervals.
- The data is added to a processing queue handled by another thread.
- The processed data is converted into JSON format.
- The MQTT thread publishes this payload to a cloud topic.

This continuous loop ensures uninterrupted monitoring. The firmware flow also includes sleep management and watchdog resets to maintain long-term stability.

7.2 Node Side Implementation

On the node side, the ESP32 sensors are designed to operate with minimal power usage while still providing accurate temperature readings. Each node works independently and sends its data to the gateway over BLE.

Sensor Reading

The firmware periodically activates the temperature sensor (DS18B20 or DHT22). The steps followed include:

- Waking the sensor from sleep
- Taking a temperature and humidity reading
- Validating the measurement to avoid noisy spikes

These values are stored in local variables that are then transmitted through BLE.

BLE Transmission

The node uses BLE characteristics or advertisement packets to broadcast its sensor readings. Each broadcast contains:

- Sensor ID
- Temperature value
- Humidity value
- Timestamp or sequence number

The broadcasting interval is chosen carefully to balance power consumption and monitoring frequency. After transmitting, the node may return to deep sleep mode to save energy.

Low Power Mode

Since sensor nodes may run on batteries, the firmware is optimized for low-power operation. Most of the time, the ESP32 is in sleep mode, waking only to:

- Take sensor readings
- Transmit values
- Perform basic checks

This approach extends battery life significantly, which is essential in vaccine storage areas where frequent maintenance may not be feasible.

7.3 Gateway Side Implementation

The gateway serves as the central intelligence of the system. It must handle multiple responsibilities—collecting BLE data, processing it, and sending it to AWS—without delays or failures.

BLE Data Aggregation

The BLE thread on the gateway constantly scans for data coming from nearby sensor nodes. Once a packet is detected:

- The raw data is decoded
- The node ID is matched to verify authenticity
- Temperature and humidity values are extracted
- Invalid or corrupted packets are filtered out
- Processed readings are then passed to a queue for cloud transmission.

JSON Payload Formatting

Before sending data to AWS, the gateway formats the readings into a JSON structure. A typical payload looks like:


```
{
  "node_id": "sensor1",
  "temperature": 5.8,
  "humidity": 60,
  "timestamp": "2025-01-12T10:15:30Z"
}
```


JSON is used because it is lightweight, easy to parse, and widely supported by cloud platforms.

MQTT Publishing to AWS IoT Core

The MQTT client running on the gateway:

- Opens a secure TLS session
- Publishes data to the assigned AWS topic
- Receives acknowledgments if QoS is enabled

The gateway handles multiple sensor nodes and ensures that each reading is sent to the correct topic for further cloud processing.

7.4 Error Handling Mechanism

Because the system runs continuously in critical environments, reliability is a top priority. The firmware includes several built-in error-handling and recovery mechanisms.

1. BLE Reconnection Handling

BLE communication can be interrupted due to:

- Refrigerator walls
- Metal racks
- Wireless interference

To handle this, the gateway:

- Automatically restarts BLE scanning when packets are lost
- Clears buffers if corrupted data is received
- Logs missed readings for further debugging

2. Wi-Fi Recovery Logic

Wi-Fi networks may drop unexpectedly. The gateway includes:

- Auto-reconnect attempts
- Back-off timing to avoid repeated connection failures
- Status indicators to inform the user of Wi-Fi status
- Once the Wi-Fi is restored, the gateway resumes publishing without requiring a reboot.

3. MQTT Error Handling

MQTT failures can occur due to certificate issues, unstable internet, or broker disconnections. The firmware includes:

- Automatic MQTT reconnection
- Retry counters
- Safe clearing of unacknowledged messages

If the MQTT client fails repeatedly, the firmware restarts only the communication thread instead of the entire system.

4. Watchdog Timer

A hardware watchdog timer is used to reset the ESP32 if the system becomes unresponsive. This prevents freezing or hanging during long-term operation.

5. Sensor Read Failures

If the node cannot read from a sensor:

- It retries multiple times
- Logs the failure
- Sends a default error code in the BLE packet

This prevents silent data gaps.

Chapter 8 – Results and Performance Analysis

This chapter presents the results obtained from testing the cold chain monitoring gateway and evaluates its performance across several important parameters, including latency, power consumption, stability, and real-time cloud visualization. The goal was to ensure that the system performs reliably under conditions similar to an actual vaccine cold storage environment.

8.1 Experimental Setup

To evaluate the performance of the proposed system, a controlled experimental environment was created. The setup included:

- Two ESP32 development boards — one configured as a BLE sensor node and the other acting as the Zephyr RTOS–based gateway.
- DHT11 temperature sensor connected to the node to collect environmental readings.
- Wi-Fi network for connecting the gateway to the cloud.
- AWS IoT Core as the backend platform to visualize real-time temperature data and generate test alerts.
- Laptop and mobile device for monitoring cloud dashboards and logs.

Figure 7. Experimental setup of Cold Chain Monitoring Gateway

Temperature changes were created manually by adjusting the surrounding conditions to observe whether the system correctly transmitted the data to the cloud.

Throughout the testing phase, the system was allowed to run continuously for several hours to assess its stability, response time, and error-handling capabilities. The same environment was later used for longer overnight tests to check how well the system behaved under prolonged use.

8.2 System Output Screenshots

During experimental evaluation, the system successfully transmitted live temperature readings from the sensor node to AWS IoT Core. These readings appeared on the IoT dashboard in real time, confirming that all stages of data transmission—from BLE collection to Wi-Fi upload and MQTT publishing—were functioning as expected.

The AWS console displayed:

- Current temperature and humidity values
- Timestamp of each update
- Device connection status
- Message logs for each published MQTT packet

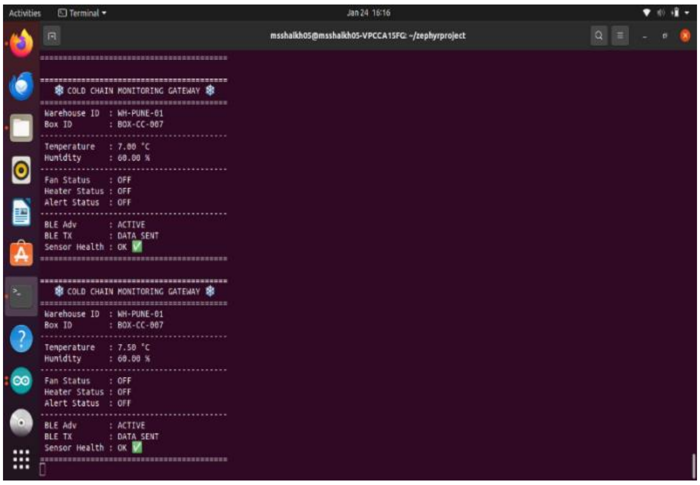

Figure 8. Zephyr Serial Monitor

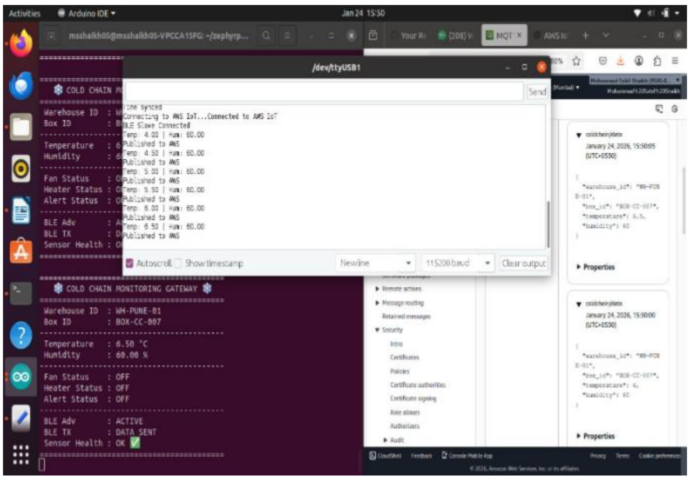

Figure 9. Output on all terminals

Although screenshots are not included here, the readings updated consistently every few seconds, demonstrating that the gateway was receiving stable BLE data and forwarding it correctly. The cloud logs showed no gaps or irregularities in the message flow during the testing period.

This real-time visualization is essential for cold chain applications where vaccine safety depends on detecting temperature changes without delay.

8.3 Latency Analysis

Latency refers to the time taken for a temperature value to be sensed, transmitted to the gateway, and finally displayed in the cloud dashboard. For applications involving vaccine monitoring, this delay must be minimal so that staff can respond quickly in case of a temperature deviation.

To measure latency, time stamps were compared at three points:

1. Sensor reading time
2. Gateway reception time
3. AWS IoT Core update time

During testing, the following observations were made:

- The BLE sensor node typically transmitted readings within 200–300 ms.
- The gateway processed packets and formatted them into JSON within 100 ms.
- Cloud upload via MQTT over Wi-Fi introduced an additional 600–1200 ms delay.

Overall, the end-to-end latency averaged between 1 and 2 seconds, with occasional variations based on network strength. This delay is well within acceptable limits for cold chain monitoring, where real-time updates are required but do not need millisecond-level precision.

The system was found to react quickly enough that any temperature excursion would be reported almost immediately to the cloud, allowing timely actions.

8.4 Reliability Analysis

For a vaccine monitoring system, reliability is one of the most critical performance metrics. To evaluate this, the system was tested for long durations, both during daytime operation and overnight.

During these tests, the system exhibited:

- Stable BLE communication with no significant packet losses
- Consistent Wi-Fi connectivity even during minor network fluctuations

- Automatic reconnection when MQTT or Wi-Fi failures occurred
- Continuous data upload without requiring manual intervention
- No firmware crashes or freezes

The gateway maintained a stable connection with AWS IoT Core throughout several hours of testing. Even in simulated error conditions—such as temporarily turning off Wi-Fi or moving the sensor node slightly out of range—the system recovered gracefully without data corruption.

This demonstrates that the implemented error-handling mechanisms, such as reconnection loops, watchdog timers, and data validation checks, work effectively to maintain system integrity.

In summary, the experimental results confirm that the cold chain monitoring gateway is reliable, responsive, and robust enough for real-world deployment in vaccine storage environments.

Chapter 9 - Applications

The cold chain monitoring gateway developed in this project has a wide range of real-world applications across industries that depend on temperature-sensitive storage and transportation. While the primary focus of this project is vaccine preservation, the system's architecture and features make it suitable for multiple sectors where environmental conditions directly affect product quality, safety, and shelf life.

9.1 Cold Chain Logistics

Cold chain logistics involves the movement of temperature-controlled products across different stages—warehouses, refrigerated vehicles, distribution centers, and retail outlets. Even brief temperature fluctuations during transport or handling can lead to spoilage or loss of potency.

The proposed monitoring gateway can be integrated into cold rooms, freezers, and mobile cold storage units to ensure continuous tracking of environmental conditions. Real-time alerts enable logistics teams to respond quickly to equipment failures, door openings, or cooling system breakdowns. By keeping accurate records of temperature history, the system helps maintain compliance with industry standards and builds trust with regulatory bodies and clients. This makes it highly beneficial for logistics companies handling pharmaceuticals, food items, and laboratory samples.

9.2 Pharmaceutical Storage

Pharmaceutical products—including insulin, biologics, blood components, and certain laboratory reagents—must be kept under tightly controlled temperature and humidity conditions. Exposure to incorrect temperatures can alter their chemical structure, reduce their effectiveness, or make them unsafe for use.

The cold chain monitoring gateway provides an automated way for hospitals, pharmacies, research labs, and drug distribution centers to continuously monitor storage conditions. The system ensures:

- 24/7 monitoring of refrigerators and freezers
- Instant notifications if temperature goes out of range
- Accuracy and traceability through cloud-based logs

- Reduced dependency on manual checks

These features improve operational reliability and help pharmaceutical facilities maintain quality assurance during storage and handling. The system can also help identify failing equipment before it causes product damage, reducing both losses and operational risks.

9.3 Vaccine Transportation

Vaccines are among the most sensitive materials transported in the healthcare supply chain. They lose potency if exposed to temperatures outside the recommended 2°C to 8°C range. Since transportation can involve long distances, delays, and unpredictable weather conditions, continuous monitoring becomes critical.

The proposed system can be installed in vaccine carriers, refrigerated vans, or portable cold boxes. The BLE sensors attached inside cold containers record temperature periodically, while the gateway—placed within the vehicle—uploads the data via Wi-Fi or mobile hotspot. Real-time alerts allow field workers or drivers to take corrective actions immediately, reducing the chances of losing valuable vaccine stock. This application is especially important in rural vaccination drives, national immunization campaigns, and last-mile delivery programs, where reliable monitoring helps ensure safe and timely vaccine distribution.

9.4 Food Supply Chain

The food industry also heavily depends on temperature control to maintain freshness, prevent bacterial growth, and comply with safety regulations. Items such as dairy products, meat, seafood, and frozen goods must remain within strict temperature limits during storage, processing, and transportation.

By deploying sensor nodes within cold storages and refrigerated vehicles, the cold chain monitoring gateway can ensure that food products remain under safe conditions from the farm to the consumer. Real-time cloud updates provide transparency to food suppliers, distributors, and retailers. If temperature deviations occur, immediate alerts help prevent spoilage and foodborne illnesses.

Chapter 10 – Advantage and Limitations

The Cold Chain Monitoring Gateway developed in this project offers a number of benefits for maintaining the safety and integrity of temperature-sensitive products, especially vaccines. While the system provides several practical advantages, it also has certain limitations that must be considered for future improvements. This chapter outlines both aspects to present a complete view of the system's capabilities.

10.1 Advantages

1. **Continuous Real-Time Monitoring**

The system provides round-the-clock monitoring of temperature and humidity conditions inside vaccine storage units. This ensures that any change in the environment is detected immediately, reducing the risk of unnoticed temperature excursions.

2. **Immediate Alerts and Notifications**

One of the major advantages is the ability to send alerts instantly when the temperature moves out of the safe range. These real-time notifications allow healthcare workers to respond quickly, preventing vaccine spoilage and financial loss.

3. **Low-Power Sensor Nodes**

The ESP32-based sensors consume very little power, especially when operated in deep sleep mode. This makes the system suitable for long-term use without frequent battery replacements, making it cost-effective and reliable.

4. **Scalable and Flexible Design**

The system can support multiple sensor nodes within the same cold chain facility. Additional sensors can be added easily without major changes to the gateway or cloud configuration, making it ideal for large storage units or multiple refrigerators.

5. **Secure Cloud Integration**

Data uploaded to the cloud is encrypted using TLS certificates. This ensures safe and authenticated communication, protecting the system from unauthorized access and data manipulation.

6. **Accurate and Reliable Measurements**

The use of digital sensors such as DS18B20 and DHT22 provides precise and stable temperature readings. This accuracy is critical for vaccine monitoring, where even a small deviation can compromise product quality.

7. **Remote Access and History Tracking**

Healthcare staff can access temperature logs and dashboards from anywhere through the cloud platform. Long-term data storage helps in identifying trends, diagnosing recurring issues, and preparing compliance reports for audits.

8. **Cost-Effective Implementation**

The use of affordable hardware components like ESP32 modules and digital sensors makes the system accessible for hospitals, clinics, and government health centers, especially in resource-limited regions.

10.2 Limitations

1. **Dependence on Internet Connectivity**

The gateway requires a stable Wi-Fi network to upload data to the cloud. In locations with weak or unstable internet, data transmission may be delayed or interrupted.

2. **Limited BLE Range**

The communication range of Bluetooth Low Energy is relatively short. Sensor nodes need to be placed within a certain distance from the gateway, which may be challenging in large facilities or multi-room environments.

3. **Battery Replacement for Sensor Nodes**

Although the nodes consume low power, they still require periodic battery maintenance. In busy healthcare settings, timely battery replacement may be overlooked, leading to gaps in monitoring.

4. **Potential Sensor Drift Over Time**

Sensors like DHT22 and DS18B20 may experience calibration drift after long-term use, which can affect measurement accuracy. Periodic sensor validation or replacement may be needed.

5. **Environmental Interference**

BLE communication can be affected by metal racks, thick insulation, refrigerator doors, or interference from other electronic devices, sometimes leading to packet loss.

6. **No Built-In Backup During Power Outages**

If both the gateway and Wi-Fi router lose power, data transmission stops. While the sensor nodes can continue measuring, cloud updates will not occur until power is restored.

7. **Limited Local Processing on Gateway**

The current system primarily forwards data to the cloud. It does not perform complex local analytics, such as anomaly detection or predictive maintenance

Chapter 11 – Conclusion

This project presents the successful design and implementation of a Zephyr RTOS–based cold chain monitoring gateway using ESP32 microcontrollers and AWS IoT cloud services. The system was developed with the goal of providing a reliable, real-time monitoring solution for environments where temperature-sensitive materials—especially vaccines—must be stored under strict and stable conditions.

Throughout the project, considerable emphasis was placed on ensuring accurate temperature sensing, low-power wireless communication, secure data transfer, and stable long-term operation. The integration of Bluetooth Low Energy (BLE) for distributed sensing and Wi-Fi for cloud connectivity helped create a flexible architecture that can be deployed in various cold storage setups. By leveraging Zephyr RTOS, the system benefits from a structured multitasking environment that ensures smooth execution of different components such as BLE scanning, MQTT publishing, Wi-Fi handling, and watchdog recovery.

One of the major achievements of this project is the successful connection between the hardware gateway and AWS IoT Core. Using MQTT and TLS-based authentication, the system demonstrated secure and consistent data upload to the cloud. Real-time temperature values were visualized through cloud dashboards, and alerts could be triggered whenever readings deviated from the safe threshold. This feature is especially important for vaccine storage units, where even minor temperature excursions can compromise safety and effectiveness.

The project also highlighted the advantages of using distributed BLE-based sensor nodes. These nodes operate with minimal power consumption while providing continuous readings from inside cold storage units. The gateway aggregates these readings and formats them into structured JSON payloads for cloud transmission, making the system highly scalable and easy to extend. Additional nodes can be added without major changes to the architecture, supporting larger facilities with multiple refrigerators or storage rooms.

Key contributions of this project include:

- **RTOS-Based Multitasking Design:**

Zephyr RTOS ensured stable and predictable performance through efficient scheduling and task separation. This improved system reliability during long hours of continuous operation.

- **BLE-Based Distributed Sensing:**

The use of ESP32-based sensor nodes allowed flexible placement within cold storage areas and ensured low-power, short-range data transmission.

- **AWS IoT Cloud Integration:**

Cloud connectivity enabled remote monitoring, real-time updates, and long-term record keeping, which are essential for maintaining vaccine quality.

- **Secure TLS Communication:**

Secure communication using X.509 certificates prevented unauthorized access and ensured data safety.

Overall, the developed cold chain monitoring gateway offers a strong foundation for practical deployment in healthcare facilities, vaccine storage centers, pharmaceutical warehouses, and logistics environments. Its modular design, scalability, and real-time alerting make it a robust solution capable of reducing vaccine wastage and ensuring compliance with safety standards.

While the system performs effectively in its current form, it also opens the door for future enhancements such as edge AI analytics, mobile app integration, additional sensors, and expanded communication protocols. These improvements could further strengthen its role as a dependable tool for modern cold chain management.

Chapter 12 – Future Enhancement

The cold chain monitoring gateway developed in this project serves as a reliable solution for tracking temperature and humidity conditions in vaccine storage environments. While the system performs effectively in its current form, there are several opportunities for enhancement. These improvements can further increase its scalability, accuracy, intelligence, and ease of use. This chapter outlines potential future developments that can strengthen the system's performance and broaden its applications.

12.1 Scalability Improvements

One of the major goals for future versions of the system is to enhance scalability, allowing it to support a much larger number of sensor nodes and storage units. The following improvements can be integrated:

- Mesh Networking: Introducing BLE mesh or Zigbee communication can enable more sensors to communicate over greater distances without depending solely on a single gateway.
- Multi-Gateway Support: Deploying multiple gateways in larger facilities can help distribute the load, improve network coverage, and reduce data congestion.
- Automatic Node Discovery: Future versions can include auto-registration features that detect and add new sensor nodes to the system without manual configuration.
- Cloud-Based Scaling: Optimizing cloud database structures allows the system to store and manage data from thousands of devices efficiently.

These enhancements would make the system suitable for district-level vaccine stores, large warehouses, and nationwide immunization networks.

12.2 Additional Sensors

Currently, the system focuses primarily on temperature and humidity sensing. However, several additional sensors can significantly improve monitoring capability:

- Door Open/Close Sensors: Tracking refrigerator door activity helps detect unnecessary openings that may cause temperature fluctuations.
- Power Failure Sensors: Providing instant alerts during power outages allows staff to respond quickly before vaccines are exposed to unsafe conditions.
- Ambient Light Sensors: Useful for monitoring unauthorized access to storage units.
- CO_2 or Ammonia Leak Sensors: Beneficial in large cold storage rooms where refrigerant leakage can be hazardous.
- GPS Modules: Can be integrated in mobile units for tracking vaccine carriers during transportation.

Adding these sensors can transform the system into a more comprehensive monitoring solution suitable for various cold chain environments.

12.3 Edge AI Integration

With advancements in embedded machine learning, integrating edge AI can make the system more intelligent and capable of detecting issues before they occur. Possible enhancements include:

- Predictive Temperature Modeling: AI algorithms can analyze past data and predict when a refrigerator is likely to fail, enabling preventive maintenance.
- Anomaly Detection: The system can automatically identify unusual patterns—such as sudden drops, long recovery times, or abnormal humidity levels—and generate early warnings.
- Device Health Monitoring: AI can track sensor behavior, battery performance, and communication stability, alerting users before a component becomes faulty.
- Energy Optimization: Edge AI can manage sleep schedules, sensor intervals, and network activity to reduce overall power consumption.

These additions would make the gateway smarter and more proactive rather than just reactive.

12.4 Mobile Application Integration

To improve accessibility and user interaction, a dedicated mobile application can be developed in future versions. This app could offer several useful features:

- Instant Alerts on Phone: Push notifications for temperature excursions, power failures, or device disconnections.
- Live Dashboard: Real-time visualization of temperature and humidity from each sensor node.
- Historical Reports: Easy access to past records for audits or compliance verification.
- Node and Gateway Configuration: Users can add new devices, change sampling intervals, or update settings directly from the app.
- Offline Mode: Stores readings temporarily when internet connectivity is poor and syncs them once the network is available.

A mobile app would make the system more user-friendly and convenient for healthcare workers, especially during field operations and vaccination drives.

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