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Cold Chain Monitoring System

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***Abstract* - The preservation of temperature-sensitive products such as vaccines, pharmaceuticals, dairy items, and frozen foods requires an efficient and reliable cold chain monitoring system. Any deviation from the recommended temperature and humidity range during transportation or storage can result in product degradation, financial loss, and potential health risks. This paper presents the design and development of a low power consumption IoT-based Cold Chain Monitoring System using the ESP32 WROOM microcontroller. This system allows user to set a threshold temperature which should not exceed during the travel. If temperature exceeds in the threshold temperature, system will activate the temperature collection and upload to cloud. This logic is put in place to lower the Power consumption as entire system will not be powered at all time. It will be powered up based on the requirement. The system integrates a DHT11 temperature and humidity sensor for environmental monitoring, a GPS module for real-time location tracking, and a GSM module for instant alert notifications. The ESP32 processes the collected data and uploads it to a cloud platform via Wi-Fi for remote monitoring. The proposed system ensures monitoring, data logging, and improved transparency in cold chain logistics. Experimental results demonstrate reliable performance, low power consumption, and effective alert generation, making the system suitable for pharmaceutical and food supply chain applications.**

Keywords: Cold Chain Monitoring, ESP32, IoT, Temperature Monitoring, GPS Tracking, GSM Alert System, Relay Control, Cloud Monitoring System, Low power consumption.

I. INTRODUCTION

The preservation of temperature-sensitive products throughout storage and transportation is a critical requirement in modern supply chain management. Products such as vaccines, pharmaceuticals, dairy items, seafood, and frozen foods require strict environmental control to maintain their quality, safety, and effectiveness. This controlled supply process is known as the *cold chain*. Any interruption or deviation in temperature and humidity conditions during transit or storage can lead to product spoilage, reduced efficacy, financial losses, and potential public health risks. Therefore, monitoring, and real-time tracking of environmental parameters are essential to ensure cold chain integrity.

Traditional cold chain systems rely heavily on manual monitoring methods or standalone temperature data loggers. These systems often lack real-time alert capabilities and remote accessibility. In many cases, temperature deviations are detected only after delivery, making corrective action impossible. Moreover, the absence of location tracking and automated control mechanisms reduces the efficiency and transparency of the logistics process. With the rapid advancement of the Internet of Things (IoT), smart monitoring solutions have emerged as a reliable alternative to conventional systems.

IoT-based monitoring systems enable real-time data acquisition, remote accessibility, and automated response mechanisms. Microcontrollers with integrated wireless communication capabilities, such as the ESP32 WROOM module, have significantly simplified the implementation of such intelligent systems. The ESP32 offers built-in Wi-Fi and Bluetooth connectivity, low power consumption, and sufficient processing capability, making it suitable for real-time environmental monitoring applications.

In cold chain transportation, temperature and humidity are the most critical parameters. Even a small deviation from the recommended temperature range can compromise vaccine potency or food safety. Therefore, continuous environmental sensing using reliable sensors is necessary. In addition to environmental monitoring, real-time location tracking using GPS technology enhances transparency and ensures that shipments follow designated routes. Furthermore, GSM-based alert systems allow instant notification to responsible authorities whenever abnormal conditions are detected.

This paper presents the design and development of an IoT-based low power consumption Cold Chain Monitoring System using the ESP32 WROOM microcontroller. The system allows user to set a maximum threshold temperature above which products are not supposed to go. If threshold temperature is crossed, the system is initiated which integrates a DHT11 temperature and humidity sensor for environmental monitoring, a GPS module for real-time location tracking, and a GSM module for SMS-based alert notifications. This logic is put in place to lower the Power consumption as entire system will not be powered at all time. It will be powered up based on the requirement. The collected data is displayed locally on an LCD screen and simultaneously transmitted to a cloud platform through Wi-Fi for remote supervision. This ensures proactive intervention and minimizes the risk of product damage.

The proposed system aims to provide a low-cost, reliable, and energy-efficient solution for cold chain logistics. By combining real-time monitoring, automated control, and remote data accessibility, the system enhances supply chain transparency and reduces dependency on manual supervision. It is particularly suitable for vaccine transportation, pharmaceutical distribution, blood banks, and perishable food logistics.

II. LITERATURE REVIEW

In recent years, the integration of Internet of Things (IoT) technologies into cold chain logistics has become a focal point of research due to the increased demand for accurate, real-time environmental monitoring and control during the transportation and storage of perishable goods. Traditional cold chain solutions, largely reliant on manual inspection and offline data logging, are often insufficient for detecting anomalies in time to prevent product degradation. As a result, researchers have shifted toward more intelligent monitoring strategies that combine environmental sensing, connectivity, and automated alert systems.

Afreen and Bajwa (2021) proposed an IoT-based intelligent cold storage monitoring system that continuously records temperature and humidity and triggers real-time alerts when threshold limits are violated. Their design emphasizes the importance of continuous data acquisition and automated notification mechanisms to reduce human intervention and enhance reliability in cold storage conditions [1]. This research highlights the limitations of conventional standalone data loggers and demonstrates the potential of networked sensors in improving cold chain integrity.

Further refinement of cold chain monitoring strategies is demonstrated in the work of Cil et al. (2022), who applied wireless sensor networks (WSNs) for real-time cold container monitoring at port terminals. Their system integrates wireless environmental sensors with gateway communication to enable remote access to condition data. This approach demonstrates scalability and adaptability for larger logistic environments, particularly in port logistics where multiple containers require simultaneous supervision [2].

Beyond temperature and humidity monitoring, location tracking has also emerged as a significant parameter in cold chain research. Studies focusing on GPS-integrated IoT frameworks illustrate that combining environmental sensing with real-time positioning allows stakeholders to view both condition and location of shipments simultaneously. GPS integration is particularly useful in long-distance transportation scenarios, ensuring that data is contextually linked with vehicle routing and logistics planning. This trend underscores the growing need for traceability alongside condition monitoring in modern cold chain management [3].

With the rising adoption of cloud services, recent literature has also emphasized the integration of IoT devices with cloud platforms for remote monitoring and analytics. Cloud-centric frameworks enhance data accessibility, historical logging, and scalable storage solutions. Moreover, real-time cloud dashboards facilitate remote supervision and decision support by presenting live condition data and alert history to users irrespective of geographical location. Researchers have reported improved responsiveness and situational awareness when cloud platforms are incorporated into cold chain architectures [4].

Another active research direction is the use of machine learning and analytics to predict condition deviations and optimize cold chain performance. Adaptive algorithms that interpret sensor data to forecast potential faults or temperature excursions are gaining attention, indicating a move beyond reactive alerting systems toward predictive and preventive control strategies. Such models are particularly valuable in contexts where proactive intervention can prevent spoilage and reduce operational costs [5].

Despite these advancements, several challenges remain. Network reliability, sensor accuracy, and scalability in diverse logistic environments are frequently cited as primary barriers to large-scale IoT adoption. Additionally, issues related to power management in sensor nodes and compliance with regulatory standards for temperature-sensitive goods continue to influence implementation decisions in real-world systems. Addressing these challenges is critical to ensuring robust and sustainable cold chain monitoring solutions [6].

In summary, recent research shows a clear evolution from basic temperature logging systems toward advanced IoT-enabled monitoring frameworks that incorporate real-time alerts, GPS tracking, cloud integration, and intelligent analytics. These developments collectively aim to enhance transparency, reliability, and decision support in cold chain operations.

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III. GAP ANALYSIS

Although recent studies have demonstrated significant advancements in IoT-based cold chain monitoring systems, several critical gaps remain in existing research and implementations. Most proposed systems focus primarily on real-time temperature and humidity monitoring with cloud-based visualization and alert mechanisms. However, many of these solutions either lack integrated automatic control mechanisms (such as relay-based cooling activation) or rely solely on notification-based responses, which still depend on human intervention to take corrective action. This limitation reduces the effectiveness of real-time monitoring in preventing product spoilage.

Furthermore, while some research incorporates GPS tracking for shipment traceability, integration between environmental monitoring, location tracking, and automated decision-making is often implemented as separate modules rather than a unified, low-cost embedded solution. Many existing frameworks are designed for large-scale industrial deployments and may not be economically feasible for small and medium-scale distributors, rural healthcare supply chains, or small logistics operators.

Another significant gap lies in power optimization and system portability. Several studies emphasize cloud-based analytics and advanced predictive models but overlook practical implementation challenges such as power consumption, network dependency, and hardware simplicity required for field-level deployment. Additionally, limited research provides a complete prototype-level validation that combines IoT connectivity, GSM-based alerts, GPS tracking, and automatic relay control within a single compact architecture.

Therefore, there is a need for a cost-effective, integrated, and energy-efficient cold chain monitoring system that combines real-time environmental sensing, GPS tracking, cloud connectivity, automated cooling control, and instant GSM alerting in a unified embedded platform. The proposed system aims to address these gaps by developing a practical ESP32-based solution suitable for real-world transportation and storage applications.

IV. METHODOLOGY

The proposed Cold Chain Monitoring System is designed to provide environmental monitoring, automated control, and real-time data communication during transportation and storage of temperature-sensitive products. The methodology comprises system architecture design, hardware integration, software implementation, communication framework development, and experimental validation.

A. System Architecture

The overall architecture of the proposed system is illustrated in Fig. 1. The system consists of sensing, processing, communication, display, and control modules integrated into a unified embedded platform.

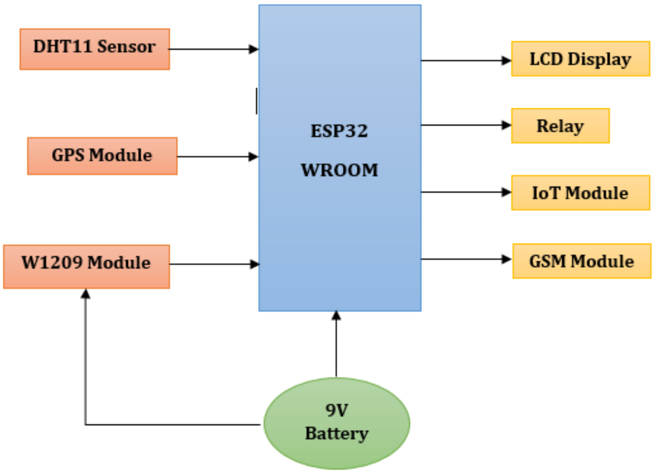

Figure 1: Block Diagram of Proposed Cold Chain Monitoring System

As shown in Fig. 1, the W1209 Module continuously measures temperature and humidity inside the storage chamber. If temperature goes above a threshold set by user, supply is given to ESP32 WROOM microcontroller unit. The DHT11 sensor periodically measures temperature and humidity and the collected data is transmitted to the ESP32 WROOM microcontroller, which serves as the central processing unit. The ESP32 performs data acquisition, threshold comparison, and control decision-making.

The system integrates:

- **W1209 Module** acts as temperature-controlled relay
- **GPS Module** for real-time location tracking
- **GSM Module** for SMS-based alert notifications
- **LCD Display** for local parameter visualization
- **IoT Cloud Connectivity** via Wi-Fi for remote monitoring

B. Hardware Implementation

The hardware setup is configured to ensure reliable field-level deployment. W1209 Module acts as temperature-controlled relay. If temperature goes beyond set threshold, then only supply is given to the rest of the system. This implementation is done to lower the Power consumption as entire system will not be powered at all time. It will be powered up based on the requirement. Once the entire system is supplied power, the DHT11 sensor periodically measures temperature and humidity and transmits digital signals to the

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ESP32. The GPS module provides latitude and longitude coordinates through serial communication. The GSM module is interfaced using UART protocol for sending alert messages.

A 16×2 LCD display is used for local visualization of environmental parameters and system status. The relay module is connected to the cooling mechanism (fan/compressor) to maintain temperature within the required range. The system is powered using a regulated 9V rechargeable battery supply to ensure stable operation.

C. Software Algorithm

The system software is developed using the Arduino IDE environment for the ESP32 microcontroller. The operational algorithm follows these steps:

1. Initialize the system with connecting charged 9V battery.
2. Read a set threshold temperature on the W1209 module. If temperature exceeds the threshold limit:
   a. Activate the relay to provide battery supply to rest of the system.
3. Provide supply to Microcontroller, sensors, Wi-Fi, GSM, GPS, and LCD modules.
4. Establish Wi-Fi connection with IoT cloud server.
5. Acquire temperature and humidity readings at fixed sampling intervals through DHT11 Sensor.
6. Retrieve GPS location data.
7. Compare temperature readings with preset threshold limits.Send SMS alert through GSM module.
8. Upload environmental and location data to the cloud platform.
9. Display current readings on LCD.
10. Repeat the monitoring cycle continuously.

This closed-loop monitoring and control mechanism ensures minimal human intervention.

D. Communication Framework

The communication framework employs dual-mode connectivity:

- Wi-Fi-based IoT communication for cloud monitoring and data logging.
- GSM-based alert mechanism to ensure reliable notification in case of internet unavailability.

Cloud integration enables remote access to live data, historical analysis, and condition verification. GPS data enhances shipment traceability and logistics transparency.

E. Experimental Validation

The system performance is evaluated under simulated temperature variation conditions. Key performance parameters assessed include:

- Sensor response accuracy
- Alert generation time
- Relay switching response
- Data transmission reliability
- System stability under continuous operation

The obtained results validate the system's ability to maintain temperature within acceptable limits and provide timely notifications.

The proposed methodology integrates sensing, automated control, and dual-mode communication into a compact embedded platform. The system ensures continuous monitoring, immediate corrective action, and remote supervision, thereby improving the reliability and transparency of cold chain logistics.

V. RESULT AND DISCUSSIONS

The proposed IoT-based Cold Chain Monitoring System was experimentally evaluated under controlled environmental conditions to analyse its monitoring accuracy, alert response time, cloud communication reliability, and automatic cooling performance. The system was tested inside a closed chamber where temperature variations were artificially introduced to simulate real transportation scenarios.

A. Prototype Operation

The developed hardware prototype is shown in Fig. 2. The system integrates W1209 module, ESP32, DHT11 sensor, GSM module, GPS module, relay control, and LCD display within a compact embedded setup.

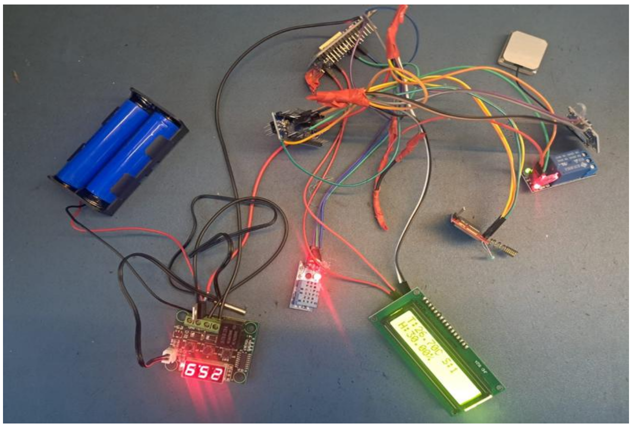

Figure 2: Experimental prototype of the cold chain monitoring system during operation

As shown in Fig. 3, the LCD continuously displays real-time temperature and humidity readings. The system remains in monitoring mode under normal temperature conditions and automatically switches to control mode when threshold values are exceeded.

B. Temperature Monitoring and Control Performance

The system was tested with a predefined temperature threshold of 25°C. When the temperature exceeded this limit, the relay was automatically activated. The operational condition during threshold violation is illustrated in Fig. 3.

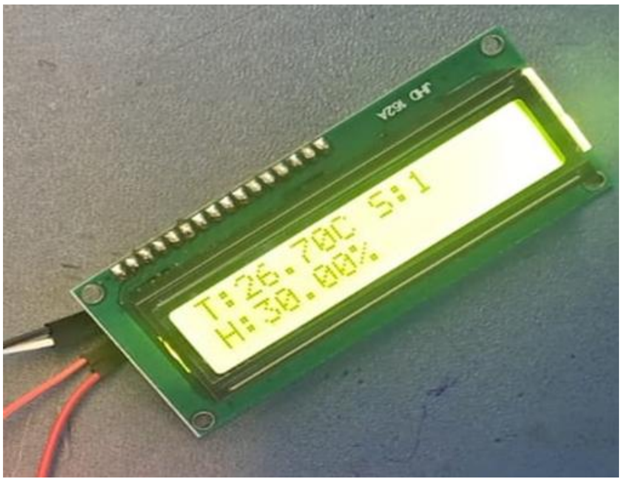

Figure 3: System response during temperature threshold violation

The recorded performance parameters are as follows:

- Threshold detection time: < 2 seconds
- Relay activation delay: ~1 second
- Measurement deviation: ±1.5°C

The results confirm that the closed-loop control mechanism effectively measures the temperature and humidity without manual intervention.

C. GSM Alert Performance

Upon exceeding the preset temperature limit, the GSM module transmitted an SMS alert to the authorized user. The average SMS delivery time ranged between 5–8 seconds depending on network conditions.

This ensures that stakeholders are immediately notified of abnormal conditions during transportation.

D. Cloud Monitoring and Data Logging

The IoT cloud platform successfully displayed real-time environmental data. The dashboard screenshot is shown in Fig. 4.

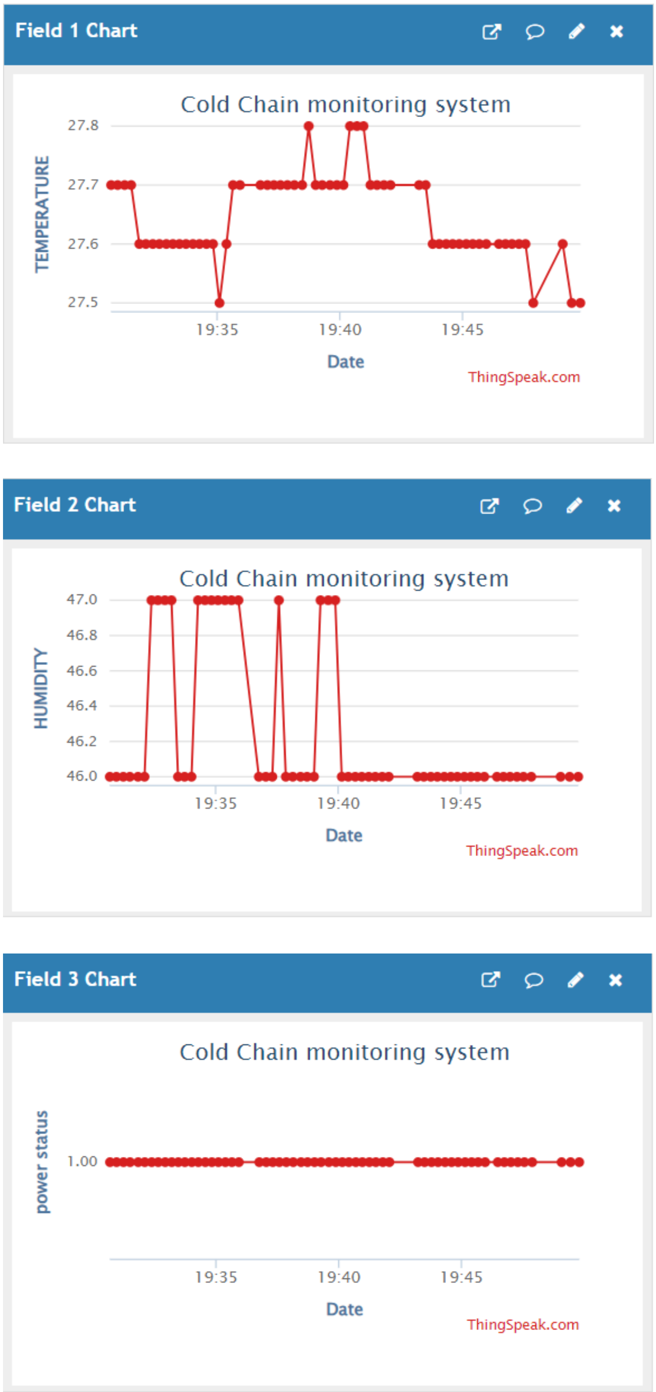

Figure 4: IoT cloud dashboard displaying temperature, humidity, and relay status

The cloud interface provided:

- Live temperature and humidity updates
- Historical data visualization
- Relay status monitoring

The average cloud data update delay was approximately 2–4 seconds under stable Wi-Fi connectivity. No significant packet loss was observed during testing.

E. Performance Summary and Comparative Analysis

Compared to traditional manual cold chain monitoring systems, the proposed system provides:

Feature	Traditional System	Proposed System
Real-time Monitoring	No	Yes
SMS Alerts	No	Yes
Cloud Data Logging	Limited	Yes

The results demonstrate significant improvements in automation, response time, and transparency.

The experimental validation confirms that the proposed Cold Chain Monitoring System effectively integrates environmental sensing, automated control, GSM-based alerting, GPS tracking, and IoT cloud monitoring within a single embedded platform. The system demonstrates reliable performance, fast response time, and stable communication, making it suitable for pharmaceutical and food cold chain applications. Further improvements can be achieved by integrating higher precision sensors and optimizing power consumption for extended deployment.

VI. CONCLUSION

This paper presented the design and implementation of low power consumption IoT-based Cold Chain Monitoring System using the ESP32 microcontroller for real-time environmental monitoring and automated temperature control. The proposed system integrates temperature and humidity sensing, GPS-based location tracking, GSM-based alert notification, and cloud-based remote monitoring within a unified embedded architecture.

Experimental results demonstrate that the system effectively monitors temperature variations. It is a low power consumption system as it activates the entire system based on temperature threshold violation and generates timely alerts to authorized personnel. The integration of IoT connectivity enables continuous remote supervision and historical data logging, thereby enhancing transparency and reliability in cold chain logistics. The GPS module further improves shipment traceability, making the system suitable for transportation applications.

Compared to traditional manual monitoring systems, the proposed solution significantly reduces human intervention, minimizes response time during abnormal conditions, and improves operational efficiency. The prototype validation confirms that the system operates reliably under simulated cold storage conditions with acceptable accuracy and communication performance.

Overall, the developed system provides low power consumption, cost-effective, scalable, and practical solution for pharmaceutical, vaccine, dairy, and perishable food supply chains. Its modular design allows easy customization and further enhancement based on application-specific requirements.

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