

A Lightweight IoT and Blockchain-Based Cold Chain Track-and-Trace Prototype for Medical Materials in Resource-Constrained Environments

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Abstract: Transporting and storing temperature-sensitive medical materials requires strict adherence to controlled conditions across multi-actor cold chains to ensure safety and efficacy. This challenge is amplified in resource-constrained environments, where cost-effective and verifiable monitoring solutions are limited. This study presents the design and implementation of a low-cost cold chain track-and-trace system integrating IoT sensors, edge computing, and blockchain technology. Temperature and GPS data are captured via sensors connected to a Raspberry Pi Pico microcontroller, published over Wi-Fi to an MQTT broker, persisted to database and relayed via an API to a Node.js server for persistence on the Polygon blockchain. A web application enables stakeholders to initiate shipment, and track shipment conditions and custody. Evaluation results show average round trip (sensor - MQTT broker - Node.js - blockchain - transaction confirmation) transaction write times of 10 seconds on Ethereum Sepolia, 10.5 seconds on Polygon Amoy, and 0.08 seconds on Ganache. Average transaction fees are approximately 0.05 ETH (Sepolia) and 0.05 POL (Amoy), demonstrating feasibility with cost and latency trade-offs.

Keywords: cold chain logistics, blockchain, internet-of-things, track-and-trace, supply chain transparency, supply chain traceability, resource-constrained environments.

1. Introduction

1.1 Problem Statement

Transportation of medical materials such as biological samples (e.g. blood specimens), vaccines, and medications requires strictly controlled environmental conditions to ensure they are still safe for use or viable at the destination [1]. Failures in maintaining these conditions can compromise material integrity, leading to sample spoilage, reduced efficacy or severe health risks.

However, end-to-end measurement and verification of transportation conditions in resource-constrained environments remains a significant challenge, particularly in multi-stakeholder cold chain environments involving health care facilities, couriers, diagnostic facilities and storage facilities. Firstly, geographic challenges such as limited road networks and mains power access remain a concern in Africa [2]. Further, existing tracking approaches are often fragmented and opaque as data is siloed across actors, which limits

visibility and auditability. In addition, reliance on specialised logistics providers and service providers is often cost-prohibitive. As a result, there is no affordable, tamper-resistant, and universally trusted mechanism for verifying that medical materials have consistently remained within prescribed conditions whilst in transit, especially in resource-constrained environments.

It is against this backdrop that this study explores how smart technologies - specifically internet-of-things (IoT) and blockchain - can enable a cost-effective, secure, and verifiable cold chain tracking solution. The focus is on tracking and validating the temperature, location, and custody of vaccine shipments transported in low-cost polystyrene cooler boxes. Specifically, how actors in a medical materials cold chain track and verify the temperature and location of vaccines delivered from hospitals or pharmacies using smart technologies.

1.2 Study Objectives

The overarching objective of this study is to design and evaluate a cost-effective, secure, and verifiable cold chain tracking system for medical materials using IoT and blockchain technologies. The breakdown of objectives is as follows:

RO1: To design a secure and reliable mechanism for capturing and recording environmental data-specifically temperature-during the transportation of medical materials, with support for offline operation in intermittently connected environments.

RO2: To implement reliable geolocation tracking of medical shipments throughout the delivery lifecycle.

RO3: To establish an immutable and auditable record of custody and transportation conditions, accessible to all stakeholders.

RO4: To evaluate the feasibility and cost-effectiveness of deploying such a system in resource-constrained environments.

1.3 Contribution

This study makes the following contributions:

- i. **Design and Implementation of an Integrated Cold Chain Platform.** A novel system combining a low-cost polystyrene-based smart cooler box, embedded IoT sensors, and supporting web applications to define condition rules and notifications, and monitor and manage cold chain shipments.
- ii. **Hybrid Offline-Capable IoT-Blockchain Architecture for Verifiable Logistics.** The platform records sensor data (temperature, GPS) and shipment metadata both in a traditional database and on a public blockchain, ensuring data integrity, immutability, and transparency. The blockchain integration from the IoT-sensors is via an API to account for offline conditions and limitations on IoT hardware.
- iii. **End-to-End Traceability Model for Multi-Actor Environments.** The system enables stakeholders to trace shipment provenance, including custody, location, and environmental conditions, via a unique shipment identifier, improving accountability across the value chain.
- iv. **Cost-Conscious Approach to Cold Chain Monitoring for Developing Country Contexts.** By leveraging affordable materials (polystyrene) and commodity IoT components, the solution demonstrates a practical and scalable alternative to expensive specialised logistics services.
- v. **Empirical Demonstration of Feasibility.** The study validates that combining IoT and blockchain technologies can provide a trusted, tamper-resistant, and accessible mechanism for verifying cold chain compliance in real-world scenarios.

1.4 Paper Organisation

The rest of the paper is organised as follows: Section 2 highlights the background and related work; Section 3 discusses the methodology used to model the cold chain supply chain and its key participants; Section 4 highlights the architecture and implementation of the platform and how it works; Section 5 provides an evaluation of the costs and time to write to the blockchain; Section 6 provides a discussion, lessons learnt and future work considerations. Section 7 concludes the study.

2. Background and Related Work

The need for temperature monitoring and control in cold chains is well-established, particularly in developing country contexts. Evidence from the Clinton Health Access Initiative (CHAI) highlights temperature monitoring and control (TMC) devices as a critical intervention to reduce temperature excursions and improve vaccine efficacy [2]. Their work emphasises the transition from manual tools, such as stem thermometers, to continuous monitoring systems with integrated alerting mechanisms via SMS and email notifications.

Early technological approaches focused on low-cost, accessible solutions. For example, [3] propose a mobile phone-based temperature monitoring system using a feature phone add-on (FoneAstra), enabling continuous sensing, SMS-based data transmission over 2G networks, and basic location tagging. While cost-effective and suitable for low-connectivity environments, this system is primarily designed for static storage monitoring rather than in-transit tracking. Furthermore, reliance on centralised web servers introduces risks of data tampering by a system administrator and limited trust across stakeholders.

More recent systems extend monitoring capabilities to transportation contexts. In [1], a real-time cold chain monitoring system captures temperature, humidity, and location data, with alerts triggered via mobile and web applications. The inclusion of tamper detection mechanisms via light sensors inside the packed vaccine box enhances shipment integrity monitoring. However, these systems continue to rely on centralised data storage, assuming trust in system administrators and lacking guarantees of data immutability.

Blockchain-based approaches aim to address these trust limitations. ColdNet [4] integrates IoT devices with Ethereum smart contracts to provide transparent and immutable vaccine tracking across storage and transportation stages. While this improves data integrity and auditability, several limitations remain. These include the absence of GPS-based tracking, limited usability due to reliance on blockchain-native interfaces such as MetaMask (a browser wallet plugin for accessing the blockchain) when interacting with the system as an end-user or administrator, and architectural constraints where IoT devices interact directly with the blockchain, raising concerns around scalability and hardware limitations. Additionally, ColdNet assumes continuous connectivity, which is impractical in resource-constrained or intermittently connected environments.

Overall, prior work demonstrates a clear evolution from low-cost sensor-based monitoring to integrated IoT-blockchain solutions. However, key gaps persist, including: (i) lack of offline-first capabilities for unreliable network environments; (ii) limited usability due to exposure of blockchain complexity to end users; (iii) insufficient integration of location tracking with verifiable storage; and (iv) reliance on either centralised trust models or resource-intensive architectures. This study addresses these gaps by proposing a cost-effective, user-friendly, and hybrid IoT-blockchain architecture designed for real-world deployment in resource-constrained settings.

3. Methodology

3.1 Modelling the Cold Chain

To develop the cold chain track and trace platform, we model a simplified medical materials cold chain for the transportation of vaccines using the resources-events-agents (REA) framework. The REA framework is useful for modelling exchanges of resources in a shared data environment [5]. Its key constructs are (i) resources - the item of interest in the supply chain; (ii) events - an exchange of economic interest; and (iii) agents - the individuals or firms with whom a transaction takes place with [6]. The resulting cold chain consists of three primary agents - the sender, a courier and a receiver; four events - packed, collected, in transit, and delivered; and the resource is the medical material (i.e. vaccine) in the cooler box.

Regarding the primary agents:

- **Recipient:** The recipient acts as the starting point in this logistic chain, the primary entity identifying the need for a vaccine sample. The recipient triggers the process by requesting the vaccine sample through a predetermined channel, be it a phone call or another mode of communication. They provide specifications about the vaccine sample, including type, quantity, and any special handling or storage requirements. Once the vaccine sample is delivered, the recipient verifies its condition, ensuring that it has been maintained under stipulated conditions and arrived in a timely fashion.
- **Sender:** The sender is the vaccine packager. The sender acts upon the recipient's request, ensuring that the vaccine sample is appropriately prepared for transportation. Upon receiving the vaccine sample request, the sender acknowledges it, setting the logistics process in motion. The sender ensures the vaccine is in optimal condition and then packages it adhering to any specific handling or storage guidelines. Once the vaccine sample is packed, the sender notifies the courier, handing off the package for transportation.
- **Courier:** The courier is responsible for physically transporting the vaccine sample from the sender to the recipient. Upon notification from the sender, the courier retrieves the vaccine package, ensuring all details match the order. Throughout transportation, the courier is responsible for maintaining the required storage conditions, ensuring the vaccine remains viable. Once at the destination, the courier ensures the vaccine sample is handed over to the authorised recipient, completing the chain.

The simplified medical materials cold chain is illustrated in Figure 1 below.

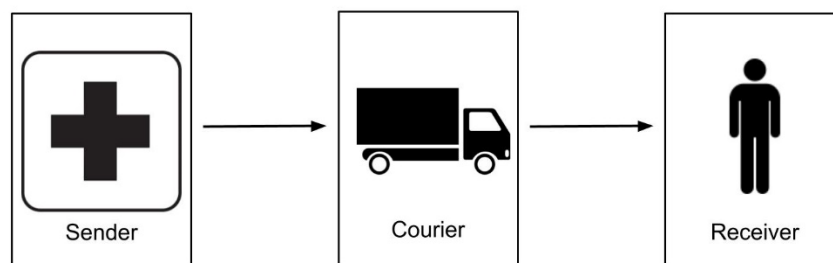


Figure 1: Illustration of a simplified medical materials cold chain. A sender (e.g. a pharmacy) packs a vaccine into a cooler box, and the package is sent to a receiver via a courier. (Source - Authors)

3.2 Requirements

We note the following as requirements for monitoring the state and condition of a packed cooler box:

- i. Recording of temperature and location data along all steps in a cold chain and storage to a local datastore and the blockchain.

- ii. Ability to set temperature ranges for monitoring according to the vaccine needs.
- iii. Dashboards to give information about shipment packages.

Further, we note that for a cooler box to protect the viability and integrity of medical materials being transported, it should be rugged, protect against vibrations, provide an even distribution of temperature within the box, and allow attachment of sensors without distorting its cooling properties. In addition, it must be easy to clean and disinfect, easy to carry and transport, affordable and recyclable.

4. Technology Description

4.1 Architecture

We design a 3-tier architecture which consists of:

- i. **Data collection and logging service:** This service is comprised of a physical temperature sensor and a GPS module. These sensors are connected to a Raspberry Pi Pico W microcontroller edge device, which publishes the data over a wireless internet connection to a message broker in a Node-RED environment.
- ii. **Data monitoring and relay service:** This service consumes sensor data from the MQTT broker and persists it to the time series data store (InfluxDB), and relays it via a POST request to the blockchain and tracking service REST API.
- iii. **Blockchain and tracking service:** This web and REST API service receives data from the Node-RED MQTT client anytime a shipment order is created/delivered or sensor readings for an existing shipment is received and persists this data to a SQL database and the Polygon Proof-of-Stake (POS) blockchain. Once data is added to the blockchain, the transaction hash is stored in alongside the corresponding record in the SQL database, which closes the loop. This allows any user with the shipment package number to view the package's provenance in a timeline view, from creation of the shipment order to the delivery, together with the relevant sensor data.

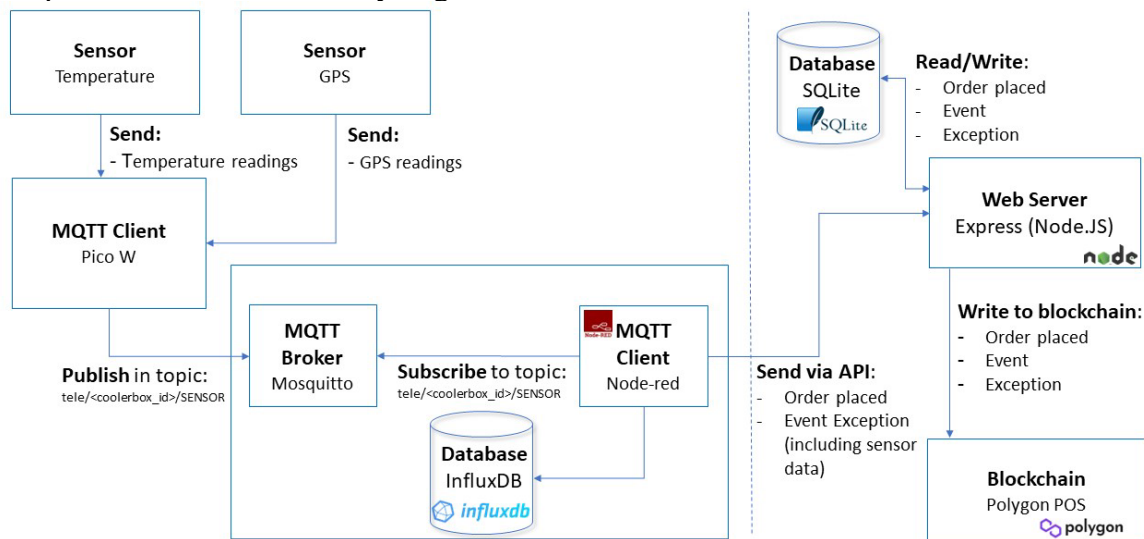


Figure 2: Architecture diagram for the cold chain track and trace platform, which consists of (i) a data collection and logging service that captures temperature and GPS data from sensors connected to a microcontroller (Raspberry Pi Pico W) and transmits them via MQTT to an edge device running Node-RED; a data monitoring and relay service which consumes data from within the Node-RED environment, stores the data in a time-series database and concurrently relays it via a REST API to the blockchain and tracking service; and (iii) a blockchain and tracking service which is a web API that receives data from the monitoring and logging service, and writes it to the blockchain. (Source - Authors)

4.2 Implementation

The prototype platform we develop to satisfy **RO1**, **RO2** and **RO3**, comprises a sensor box, the data collection and logging service, data monitoring and relay service, and the blockchain and tracking service. These are described below.

- i. **Sensor box:** This device, shown in Figure 3, comprises a Raspberry Pi Pico W microcontroller, a PT1000 temperature sensor and a Ublox NEO-6M GPS module. It attaches to polystyrene cooler boxes, continuously monitors the internal temperature of the cooler box and tracks its geographical location whilst in transit. The sensor box addresses **RO1** and **RO2**.



Figure 3: Illustration of the cold chain track and trace sensor box and a polystyrene cooler box in the backseat of the car, during the field testing of our implementation. A temperature and GPS antenna are attached to the sensor box. (Source: Authors)

- ii. **Data collection and logging service:** The Raspberry Pi Pico W microcontroller reads the temperature and GPS location values every 30 seconds and publishes them to an MQTT broker on an edge server. The microcontroller is programmed to cache data locally in the case it does not have Wi-Fi connectivity to reach the Node-RED environment. The microcontroller is powered by a 5V USB solar power bank. This service addresses **RO1** and **RO2**.
- iii. **Data monitoring and relay service:** This service, within the Node-RED environment, consumes the temperature and GPS data from the MQTT broker and logs it into an Influx time-series database. It also sends the shipment package's corresponding order, event or exception data to the blockchain and tracking service. An order is a data payload with shipment details, including the order number, cooler box identifier, and sender and receiver details. An event is a data payload that is created when a change in status, such as custodian, is recorded and includes shipment details, the custodian and the sensor readings (temperature and GPS data). An exception is similar to an event, except it is created when a temperature reading is detected to be outside of the acceptable range that is predefined at the time of creating the shipment order. The service also addresses **RO1**, **RO2**, and **RO3**.
- iv. **Blockchain and tracking service:** This service receives order, event or exception data from the data monitoring and logging service. Once data is added to the blockchain, the corresponding transaction hash is stored alongside the corresponding record in the SQL database, ensuring traceability with just the shipment package identifier. The use of blockchain technology, which [7] defines as a digital, decentralised and distributed ledger in which transactions are logged and added in chronological order

with the goal of creating permanent and tamper-proof records, provides enhanced traceability and a trust foundation in the cold chain.

This blockchain data can be viewed in a timeline view from the blockchain and tracking service. Further, the choice to develop on the Polygon POS blockchain, which is a layer-2 Ethereum Virtual Machine (EVM) compatible blockchain, significantly cheaper transaction costs as compared with the widely adopted Ethereum blockchain, and the wide availability of cheap transactions and the maturity of tools to develop on EVM compatible blockchains. This service completes **RO3**.

4.3 How it Works

The cold chain track and trace platform works as follows:

- i. **The sender initiates the shipment order.** Sender accesses a sender-specific Node-RED dashboard and enters their information, the recipient's details, vaccine details and the sensor box number. Once the sender creates the order, QR tracking codes are generated to be placed on the cooler box. The order is packed, and the order placed event is added to the blockchain, which includes the temperature and GPS location readings. Once packed. The temperature and GPS location readings are recorded every thirty seconds, although not logged to the blockchain unless an out-of-range reading is detected or a change in custody occurs.
- ii. **The courier collects the package.** The courier accesses a courier-specific Node-RED dashboard where they scan the QR code on the box (generated at initiation by the sender) to see the receiver details, and this also triggers a change in custody, which is tracked on the blockchain as a collected event. This event includes the temperature and GPS location readings.
- iii. **The receiver receives the package.** To take delivery of the shipment, the recipient accesses a receiver-specific Node-RED dashboard and scans the cooler box QR code. This displays the receiver details, a list of exceptions and their corresponding timestamps and sensor readings, if any. In addition, a map with GPS markers is displayed to show the route travelled by courier with the "smart" cooler box. Each marker has information about the temperature recorded at that point. Scanning the QR code by the receiver also triggers a change in custody, for which a delivered event is logged to the blockchain.

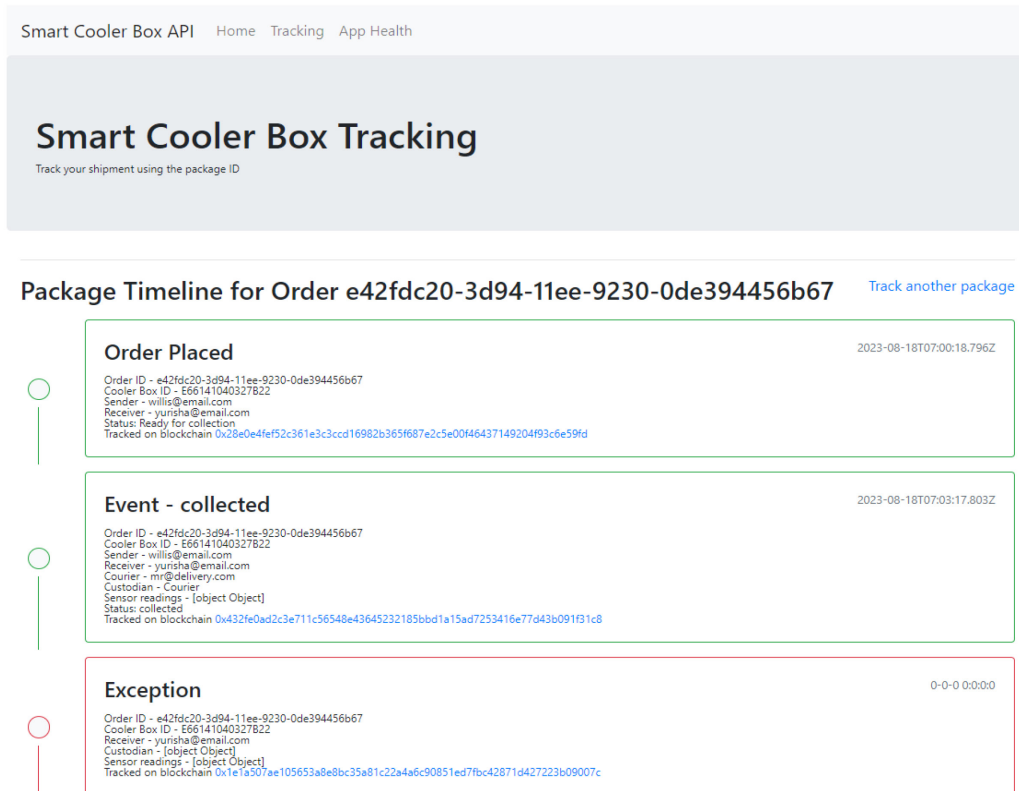


Figure 4: The provenance of a shipment displayed in a timeline view.

Additionally, to view the provenance of a shipment, an interested party with the unique shipment order identifier can access a timeline shown in Figure 4, as well as the blockchain explorer entry by clicking on the Tracked on blockchain hexadecimal link¹.

Based on this workflow, we show that the study objectives and identified requirements are satisfied.

5. Evaluation

5.1 Setup

To satisfy **RO4**, we compare write speed to the blockchain and transaction costs on a server with the following specifications: *Ubuntu 22.04, 11th Gen Intel(R) Core(TM) i9-11950H @ 2.60GHz and 32 GB RAM*. The benchmarking uses the following synthetic data to call the respective endpoints:

- Create order - `{ "sender_email": "test@gmail.com", "recipient_email": "recipient@gmail.com", "order_id": "PERF001", "coolerbox_id": "I", "order_datetime": "2023-07-25T14:30:00" }`
- Log event - `{ "sender_email": "test@gmail.com", "recipient_email": "recipient@gmail.com", "courier_email": "courier@gmail.com", "coolerbox_id": "I", "sensor_data": {"temperature": 25, "latitude": 40.7128, "longitude": -74.0060, "gps_timestamp": "2023-07-25T14:30:00"}, "agent_type": "courier", "agent_status": "in_transit", "order_id": "PERF001", "event_datetime": "2023-07-25T14:30:00" }`
- Log exception - `{ "recipient_email": "recipient@gmail.com", "agent": {"type": "Courier", "status": "in_transit", "email": "courier@gmail.com"}, "coolerbox_id": "I", "sensor_data":`

¹ Example blockchain explorer record for a cold chain track and trace event

<https://mumbai.polygonscan.com/address/0x51a7d5b11d9efa3b6c6740dcf7d6cbe853f9df31>

```
{\"temperature\":45,\"latitude\":40.7128,\"longitude\":-74.0060,\"gps_timestamp\":\"2023-07-25T14:35:00\"},    \"order_id\":    \"PERF001\", \"exception_datetime\": \"2023-07-25T14:35:00\" }
```

The comparisons are conducted across three different blockchain environments, a local blockchain environment (Ganache), the Ethereum TestNet (Sepolia) and the Polygon TestNet (Polygon Amoy). The configurations in Table 1 are used for the Ethereum TestNet and Polygon TestNet, where we make use of the same node provider for consistency and assume the underlying hardware for the TestNet nodes are identical.

Table 1: Parameters for benchmarking the platform on the Ethereum and Polygon TestNets.

TestNet	Parameter	Value
Sepolia	gas	gas: 1000000
Sepolia	gasprice	gasPrice: '200000000000'
Sepolia	RPC endpoint	https://11155111.rpc.thirdweb.com
Sepolia	Contract Address	https://sepolia.etherscan.io/address/0x371160bb6117cDa0Fa1E850Ea5015bc68192f5D9
Polygon Amoy	gas	gas: 1000000
Polygon Amoy	gasprice	gasPrice: '200000000000'
Polygon Amoy	RPC endpoint	https://80002.rpc.thirdweb.com
Polygon Amoy	Contract Address	https://amoy.polygonscan.com/address/0x25D455cE561dCA6018037AB1E767bB60a6Cb2B

5.2 Blockchain Write Time Analysis

The results of the time to write to blockchain are shown in Table 2. The write times to the Ganache blockchain environment are fastest because it a local environment and there is no network interface induced delays, whilst the Sepolia and Polygon Amoy are in similar write time ranges.

Table 2: Benchmarking of time to write to the blockchain on the Ganache (local), Sepolia (Ethereum) and Polygon Amoy TestNets.

Environment	Endpoint	Run 1 (ms)	Run 2 (ms)	Run 3 (ms)	Run 4 (ms)	Run 5 (ms)	Run 6 (ms)	Run 7 (ms)	Run 8 (ms)	Run 9 (ms)	Run 10 (ms)	AvgMs	AvgS
Sepolia	Create order	26 877	16510	16311	11059	11485	14523	13495	7519	9431	5401	13261.1	13.2611
Sepolia	Log event	7509	7543	9548	9400	3376	12515	5431	4386	12477	13504	8568.9	8.5689
Sepolia	Log exception	10112	10570	10965	13504	4143	3447	10388	10569	13466	10712	9787.6	9.7876
Ganache	Create order	140	72	71	74	78	65	89	78	80	81	82.8	0.0828
Ganache	Log event	69	78	79	87	72	75	62	67	89	79	75.7	0.0757
Ganache	Log exception	74	74	92	75	87	76	88	77	146	64	85.3	0.0853
Polygon Amoy	Create order	7611	9868	5522	7952	6595	8622	7533	11765	12057	20082	9760.7	9.7607
Polygon Amoy	Log event	9785	3428	7535	13484	13205	12038	11029	9330	16500	8400	10473.4	10.4734
Polygon Amoy	Log exception	13492	11515	60440	20911	12311	2466	2336	3230	2522	3293	13251.6	13.2516

5.3 Blockchain Cost Analysis

The results of the cost comparison are shown in Table 3 below.

Table 3: Benchmarking of average transaction fees when writing data to the Sepolia (Ethereum) and Polygon Amoy TestNets.

Environment	Endpoint	Run 1 Fee	Run 2 Fee	Run 3 Fee	Run 4 Fee	Run 5 Fee	Run 6 Fee	Run 7 Fee	Run 8 Fee	Run 9 Fee	Run 10 Fee	Avg Fee
Polygon Amoy	Create Order	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.0298286	0.029829
Polygon Amoy	Log Event	0.082675	0.079255	0.079255	0.079255	0.079255	0.079255	0.079255	0.079255	0.079255	0.0792554	0.079597
Polygon Amoy	Log Exception	0.069143	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.0657226	0.066065
Sepolia	Create Order	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.029829	0.0298286	0.029829
Sepolia	Log Event	0.079231	0.079231	0.079231	0.079231	0.079231	0.079231	0.079231	0.079231	0.079231	0.0792314	0.079231
Sepolia	Log Exception	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.065723	0.0657226	0.065723

The cost for Sepolia TestNet (Ethereum) is in ETH-the native currency on the Ethereum blockchain, and the cost for the Polygon Amoy TestNet is in POL-the native currency on the Polygon blockchain. The conversion between POL and ETH is 1 POL = 0.000044 ETH as of November 2025. The ETH currency is stronger than the POL currency, and as we can see, it is therefore cheaper to write transactions to the Polygon Amoy blockchain, which is

as expected for a Layer 2 blockchain, and why the viability of the cold chain track and trace platform is best on the Polygon blockchain or a cheaper alternative which is not Ethereum.

6. Discussion

6.1 Benefits

The proposed cold chain tracking proof-of-concept delivers several key benefits over existing solutions. First, it supports an offline-first architecture, enabling reliable operation in environments with intermittent or unreliable connectivity. Second, it improves usability by abstracting underlying blockchain complexity, allowing end users to interact with the system without requiring specialised knowledge. Third, it provides integrated tracking and verifiable storage, combining location and environmental data with immutable records to enhance end-to-end traceability. Finally, the hybrid IoT-blockchain design reduces dependence on centralised trust models while avoiding the overhead of resource-intensive architectures, resulting in a cost-effective and practical solution for deployment in resource-constrained environments.

6.2 Lessons Learned

This study yielded several practical and architectural insights relevant to the design and deployment of cold chain monitoring systems in resource-constrained environments. These include:

- i. **Hardware Design and Durability.** The prototype sensor enclosure used during laboratory testing was not suitable for operational deployment. In practice, the sensor module should be compact, portable, and reusable to support efficient use across multiple shipments. Furthermore, the cooler box must be rugged, waterproof, and leak-proof to ensure reliability under real-world transportation conditions.
- ii. **Data Reliability and Offline Capability.** Field testing over a ~5 km route revealed intermittent network connectivity, a condition expected to be more pronounced in real deployment environments. The implemented offline-first architecture, where sensor readings are persisted locally on the edge device (the Raspberry Pi Pico W can persist data across power cycles and resets) before being transmitted over the network to a Node-RED environment for processing and posting via an API to the blockchain, proved to be robust. This approach effectively mitigates connectivity disruptions and power instability, ensuring data continuity and preventing loss during outages.
- iii. **System Integration and Usability.** Unique shipment identifiers should be encoded as QR codes that can be easily generated, printed, and affixed to cooler boxes, enabling seamless tracking and user interaction across stakeholders.
- iv. **Blockchain Interaction and Cost Optimisation.** Blockchain writes should be asynchronous to prevent failures caused by network/blockchain gateway throttling, particularly when devices reconnect and attempt bulk data submission - an issue we experienced during our testing. Furthermore, hash-based data anchoring strategies should be employed to reduce transaction costs while preserving data integrity.
- v. **Deployment and Scalability Considerations.** Future work should focus on pilot deployments with public healthcare facilities, logistics partners and diagnostic facilities as this is where there is most need for such a solution based on our initial engagements with the relevant stakeholders. In addition, further hardware miniaturisation of the sensor box. Practical considerations such as use of preloaded data SIM cards for microcontroller connectivity are also critical for reliable field operation.
- vi. **Commercialisation Potential.** A structured market analysis is necessary to evaluate pathways for scaling and commercial deployment of the solution.

6.3 Assumptions and Limitations

This study operates under several simplifying assumptions. First, it assumes that cold chain participants act in good faith; specifically, once a shipment is packed, couriers do not intentionally tamper with the medical material or embedded sensors. Second, the sensor module is assumed to be securely affixed to the cooler box and cannot be removed or bypassed during transit. These assumptions limit the system's ability to detect physical tampering or adversarial behaviour, as the focus of this work is on verifying environmental conditions and shipment traceability rather than enforcing physical security.

Additional limitations include the absence of a formal battery life analysis for the sensor box and the lack of a detailed cost analysis for materials and electronics, although all components were selected from readily available commodity hardware. We also do not discuss the initiation of the shipment, and QR codes which is triggered in from the Node-RED environment via a dashboard.

In terms of design constraints, the prototype utilises a polystyrene cooler box due to its lightweight, insulating, shock-absorbing, and cost-effective properties. While suitable for low-cost deployments, this choice may not fully reflect the durability or performance characteristics of industrial-grade cold chain containers.

6.4 Future Work

Future work will focus on strengthening both the physical security and data integrity of the system, and miniaturisation of the sensor box. This includes the integration of a smart locking mechanism to make shipments tamper-evident or tamper-resistant once packed. Additional sensors, such as light sensors to detect unauthorised opening and vibration sensors to monitor handling conditions, can further enhance shipment integrity and provide richer contextual data.

From a data and usability perspective, future enhancements will explore developing a user-friendly web interface for triggering shipments and managing QR codes, privacy-preserving techniques for blockchain storage, ensuring that sensitive shipment information is protected while maintaining verifiability. This may include approaches such as data hashing, selective disclosure, or off-chain storage with on-chain proofs.

Together, these improvements aim to advance the system toward a more secure, robust, and production-ready cold chain solution.

7. Conclusion

This study presents the design and implementation of a low-cost IoT-blockchain-based cold chain track-and-trace platform for transportation of temperature-sensitive medical materials such as vaccines. The system captures temperature and GPS data from sensors connected to a microcontroller (Raspberry Pi Pico W) and transmits them via Wi-Fi using MQTT to an edge device running Node-RED. Within Node-RED, the data are persisted in a time-series database and concurrently forwarded via a REST API to a backend service, which records the data on the Polygon PoS TestNet through a smart contract. This architecture enables end-to-end visibility of shipment conditions and custody, supporting continuous monitoring during packing, transit, and delivery, as well as real-time detection of deviations from predefined thresholds.

By anchoring sensor data on blockchain, the system establishes a transparent and tamper-resistant trust layer among cold chain participants, including senders, couriers, and receivers. Evaluation results demonstrate that while public test networks such as Polygon Amoy and Ethereum Sepolia exhibit comparable latency, Polygon Amoy offers a more cost-effective option for deployment.

Overall, the proposed solution demonstrates the feasibility of combining IoT and blockchain technologies to deliver a trusted, scalable, and accessible cold chain monitoring system for resource-constrained environments.

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Declaration of use of content generated by Artificial Intelligence (AI) (including but not limited to Generative-AI) in the paper

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The authors reviewed and take full responsibility for the final content.

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