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Short Communication

Enhancing Pharmaceutical Supply Chain Efficiency through Smart Contracts: Ensuring Transparency, Traceability, and Security

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Abstract *- This paper introduces a cutting-edge smart logistics solution for Pharma Supply Chain Management (PSCM) by integrating smart contracts, logistics planning, and asset condition monitoring using Internet of Things (IoT) devices. Focused on enhancing accountability, traceability, and liability across the entire supply chain, the proposed model demonstrates real-time visibility as products move from the drug's manufacturer to patients. In the PSCM, a critical concern is the safe and efficient delivery of medicines, particularly in maintaining precise temperature conditions. Addressing this challenge, the solution integrates blockchain, smart contracts, IoT sensors, and gas-efficient implementations. The system employs Radio Frequency (RF) sensors to collect accurately timestamped data, ensuring transparency and reliability in drug movement. Gas-efficient smart contracts streamline processes, revolutionizing pharmaceutical supply chain management and improving patient outcomes through real-time IoT monitoring, countering counterfeit drugs, and ensuring data integrity.*

Keywords *- Blockchain, Smart contract, Internet of Things, Supply chain, Temperature monitoring.*

1. Introduction

In the present busy world, managing the supply chain for the pharmaceutical sector is crucial. Ensuring the safe and efficient delivery of medicines is a complex and critical process, with challenges ranging from asset tracking to maintaining optimal conditions for drug efficiency. PSCM [1] is a highly complicated network involving many stakeholders, like manufacturers, distributors, retailers, healthcare providers, and patients. The movement of a drug from its point of origin to the end-user is filled with challenges, ranging from logistical complexities to the critical requirement of maintaining specific temperature conditions [2]. Traditional supply chain management systems often struggle to provide real-time visibility and accountability, leading to inefficiencies, delays, and, in some cases, compromises in patient safety. In this context, the integration of smart contracts, logistics planning, and IoT-based asset condition monitoring emerges as a convincing solution to address the gaps in PSCM. Smart contracts, as programmable agreements between parties, offer a transparent and tamper-proof mechanism to enforce terms and conditions throughout the supply chain. This ensures accountability and traceability at every step, justifying risks and enhancing overall reliability.

The essential of this proposed solution lies in its use of IoT devices to monitor the condition of pharmaceutical assets in real-time. In the pharmaceutical industry, maintaining precise temperature conditions is not just a logistical challenge but a critical requirement for ensuring the effectiveness and safety of drugs. Temperature-sensitive drugs, such as vaccines and certain medications, demand a continuous, monitored environment to prevent degradation. The pharmaceutical supply chain faces a unique challenge – the need to maintain precise temperature conditions to ensure the efficacy and safety of drugs. Temperature-sensitive pharmaceuticals, including vaccines and biologics, require storage and transportation within specific temperature ranges.

Any deviation from these ranges can compromise the quality and effectiveness of the drugs, actually leading to adverse health outcomes for patients. Traditional temperature monitoring methods in the pharmaceutical supply chain often rely on periodic manual checks and paper-based records. This approach, however, is susceptible to human error, delays in detection, and lack of real-time visibility. Additionally, it falls short of providing a comprehensive and tamper-proof record of temperature conditions throughout the entire supply chain journey. In response to these challenges, our proposed smart logistics solution for PSCM integrates advanced technologies to ensure precise temperature control and monitoring. The collaboration of blockchain [3], smart contracts, IoT sensors, and gas-efficient implementations aims to revolutionize the pharmaceutical supply chain, offering a comprehensive and technologically advanced solution to the persistent challenges in temperature-sensitive drug transportation. Blockchain technology, with its decentralized and immutable ledger, provides an ideal platform for ensuring the integrity and transparency of data in the pharmaceutical supply chain.

The use of blockchain in this context addresses several critical issues, including data security, traceability, and accountability. Smart contracts [4], which are self-executing contracts with the terms of the agreement directly written into code, play a pivotal role in enhancing the enforceability and transparency of agreements between different parties in the supply chain. In the pharmaceutical context, these smart contracts can govern various aspects, such as quality assurance processes, compliance checks, and delivery conditions. By use of blockchain and smart contracts, the proposed solution establishes a secure and tamper-resistant framework for recording and verifying transactions and agreements at each stage of the PSCM. This not only ensures data integrity but also creates an auditable and transparent trail that authorized parties can access, thus mitigating the risks associated with data manipulation or unauthorized access. In addition to ensuring data integrity and real-time monitoring, the proposed smart logistics solution incorporates gas-efficient smart contracts [5] to streamline processes within the pharmaceutical supply chain.

Gas in blockchain networks refers to the computational cost required to execute operations on the network. Gas-efficient smart contracts are designed to optimize these costs, making the execution of smart contract functions more economically viable. In the PSCM, where the volume of transactions and agreements can be substantial, the use of gas-efficient smart contracts becomes crucial for maintaining cost-effectiveness. These contracts reduce the computational overhead associated with executing transactions and contribute to the system's overall efficiency. By incorporating gas-efficient smart contracts into the solution, the proposed framework ensures that the benefits of blockchain and smart contract technology are realized without incurring excessive computational costs. This not only makes the system more scalable but also aligns with the practical considerations of implementing such a solution within the complex and high-volume pharmaceutical supply chain.

The proposed smart logistics solution further enhances transparency and reliability in drug movement by incorporating Radio Frequency sensors. These sensors play a crucial role in collecting accurately timestamped data throughout the supply chain journey. RF sensors, being contactless and capable of transmitting data wirelessly, offer a non-intrusive yet highly effective means of monitoring pharmaceutical shipments. The use of RF sensors ensures that the collected data is not only precise but is also transmitted in a secure and timely manner. The timestamped data serves as a comprehensive record of the conditions to which the drugs were exposed at each stage of the supply chain. This not only facilitates compliance with regulatory requirements but also acts as a valuable tool for conducting post-shipment audits and investigations.

The integration of RF sensors adds a layer of visibility and accountability, allowing stakeholders to track the exact journey of pharmaceuticals from the manufacturing facility to the end-user. This granular level of information is instrumental in identifying and addressing any anomalies or deviations in the supply chain, thereby bolstering the overall reliability and trustworthiness of the pharmaceutical distribution process. In this paper, we will outline our approach in three main sections. Section 2 will provide a detailed explanation of our proposed method, emphasizing the essential layers of PSCM and demonstrating its application in monitoring logistics. moving forward to Section 3, we will discuss the results obtained through our methodology. Finally, in Section 4, we will wrap up the paper by presenting our conclusions.

2. Proposed Methodology

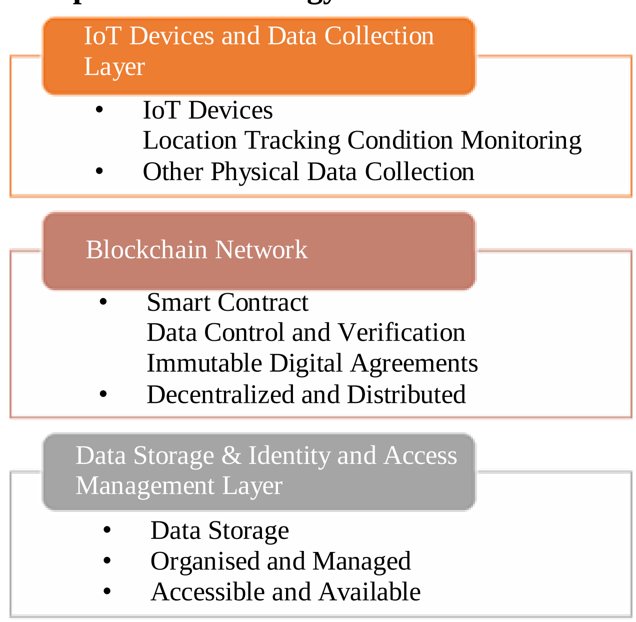

Fig. 1 Key layers in PSCM

The proposed framework, as shown in Figure 1, integrates three essential layers to establish a secure environment for transactions among logistics stakeholders. Its primary goal is to address the challenge of maintaining the safety and privacy of data during logistics operations. The initial layer, known as the "IoT devices and data collection layer", employs specialized IoT devices to gather information regarding the physical aspects of the logistics process. These devices monitor variables such as the location and condition of goods in transit. The second layer, the “Blockchain Network Layer”, utilizes blockchain technology as a highly secure database to safeguard and control vital data from IoT devices [6] and RF sensors through smart contracts. The third layer, “Data Storage & Identity and Access Management”, carefully manages all data from IoT devices and the blockchain, ensuring accessibility and organizational integrity. Through this integration, the framework establishes a robust system and assures logistics stakeholders that their data remains protected and secure throughout the entire process.

2.1. IoT Devices and Data Collection

In the IoT devices and data collection of the PSCM, a pivotal role is played by IoT-driven sensors, particularly low-power smart sensors [7], designed for wireless data collection and transmission. These sensors are involved in monitoring the environmental conditions of drugs during transit. Specifically, they measure parameters such as temperature and humidity, ensuring continuous observation of storage conditions. To strengthen this monitoring capability, Radio Frequency (RF) sensors are integrated with GPS modules during drug transportation. The GPS module provides real-time information on the vehicle’s location, date, and time.

This incorporation of smart sensors and GPS technology enables precise, real-time tracking of the vehicle carrying the drugs, ensuring strict adherence to the designated transportation route. The GPS data not only enhances the security and integrity of the drugs but also offers transparency to stakeholders, such as manufacturers and distributors. These stakeholders gain visibility into the drugs’ location at any given moment, empowering them to take immediate actions if needed to safeguard the products. The collaboration between smart sensors, RF technology, and GPS tracking in the IoT-based data layer significantly elevates the monitoring and control of drug transportation in the supply chain. This integration promotes operational efficiency, enhances security measures, and ensures strict adherence to required environmental conditions, collectively increasing the integrity of the pharmaceutical supply chain.

2.2. Blockchain Network

Blockchain serves as a special kind of database for businesses like those in the PSCM. It works by recording transactions and information in blocks, and each block has a unique code called a cryptographic hash [8] that connects it to the one before it. This makes sure that the information is tamper-proof and secure. In the supply chain, where different Stakeholder work together, they negotiate and agree on terms for their transactions. These terms get turned into something called a smart contract, which is like a digital agreement. This smart contract is then stored on the blockchain.

It is smart because it can automatically check if everything is okay and decide if it should go ahead with the transaction based on the agreed terms. When it comes to keeping data safe in the PSCM, blockchain is like a guard. It makes it hard for anyone to mess with the information. The records cannot be changed, and the smart contracts and the way information is stored make sure that sensitive data stays private. This not only makes everything more transparent and trustworthy but also reduces the chance of data breaches. In a nutshell, using blockchain in the pharmaceutical supply chain makes everything more secure and trustworthy, changing the way businesses make and check transactions.

2.3. Data Storage & Identity and Access Management

As much information is generated in the process of shipment, which is stored on the blockchain, it acts as a decentralized and secure data storage solution for the supply chain. Information related to the manufacturer, shipment, and delivery of products is stored in blocks, and each block is linked to the previous one, ensuring an irreversible and transparent record. Identity and Access Management (IAM) [9] ensures that only authorized participants have access to specific information within the blockchain. Each participant, such as manufacturers, distributors, and retailers, is authenticated, and IAM assigns them roles with corresponding access privileges.

This helps maintain data privacy and controls who can view or modify certain aspects of the supply chain data. Smart contracts, which are self-executing, are employed to automate processes in the supply chain. IAM regulates access to these smart contracts, ensuring that only authorized entities can execute or engage with them. For instance, a manufacturer might have permission to start a smart contract for the manufacturer, while a distributor can activate one for shipment also, IAM enables privacy controls by regulating the level of access participants have to sensitive information. Smart contracts can be designed to share only relevant data with authorized parties, safeguarding confidential details.

2.4. Blockchain and IoT-Based Pharma Supply Chain Management

To begin, an IoT device registers in the blockchain by creating a unique signature using its ID and its private key. This ensures authenticity and ownership. Once registered, the device can post verified transactions, which a smart contract can verify. By integrating the TTGO T-Beam v1.1 ESP32 LORA board [10] with the u-blox*9 NEO-6M GPS module [11], DHT22 temperature and humidity sensors [12] and RF power sensor as shown in Figure 2, and coupling this setup with smart contract blockchain technology, a highly efficient tracking and monitoring system can be established for logistics. This system will enable real-time data collection, secure storage, and automated actions, ultimately enhancing transparency, security, and efficiency throughout the supply chain.

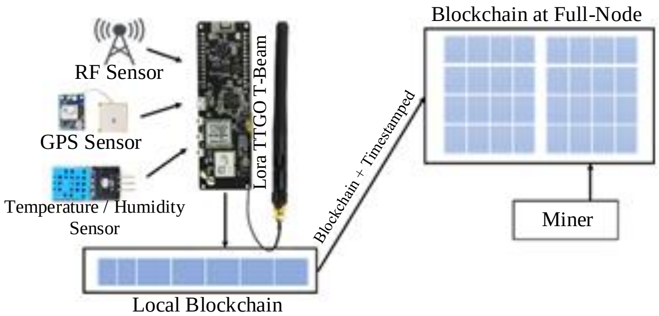

Fig. 2 Tracking and monitoring setup with smart contract blockchain

When drugs are being transported from one place to another, sensor nodes gather data over time, such as temperature readings. This data is organized into blocks locally. Each block is marked with a timestamp, indicating when the data within that block was collected. This timestamp ensures the data's accuracy and order, making it difficult to tamper with. These timestamped blocks are sent to a blockchain network full node. Within the blockchain, specific actions, especially those involving smart contracts (self-executing code on the blockchain), require large computational resources.

This is where gas as a fee is used, which is required for executing actions or smart contracts on the blockchain. However, we can increase efficiency and cost savings in blockchain technology by a strategic approach that minimizes Gas expenditure. This optimization is achieved by refraining from sending individual data fragments as separate transactions, which would otherwise result in elevated Gas costs attributed to transaction overhead. Instead, the practice of consolidating data into timestamped blocks serves to curtail the volume of transactions and, consequently, associated Gas fees. So, the implementation of gas in this process involves using gas efficiently by sending batches of data (timestamped blocks) to the blockchain, reducing costs, preventing network congestion, and promoting the creation of optimized and cost-effective smart contracts. This approach is precious in supply chain applications where real-time data monitoring and cost savings are crucial. Inside the container, there is a unique sensor that monitors temperature and humidity.

If these conditions go beyond safe limits, it could harm the quality of medical drugs and affect patients. The sensor provides temperature in Celsius and humidity as a Percentage. We compare these values with predefined safe ranges. If they deviate, we notify everyone involved in transportation to take corrective action. To find a location, GPS is used, and to generate a location signature, we use RF power sensor value, which is the signal strength of each value of RF bands available in that locality, as shown in Figure 3. Re-computation parameters of a hash tree signature infrastructure generate this digital signature. Then, it is submitted as a transaction on a blockchain where blockchain serves as a tamper-proof ledger where this information is stored. This is done to establish proof of the device's presence at a particular location at a specific time.

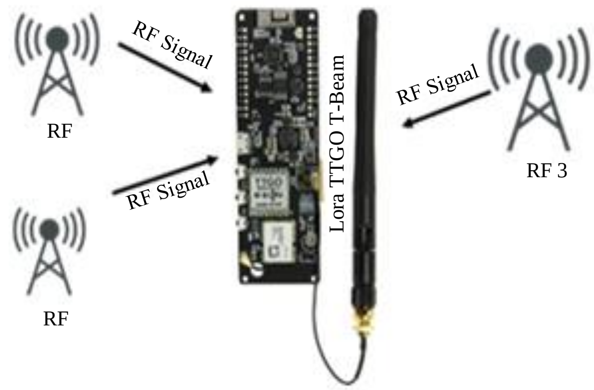

Fig. 3 Data collection from RF sensor

2.4.1. Algorithm Steps to Generate Location Signature

Collect RF Power Sensor Data

Collect RF power sensor data from the device, measuring signal strength from nearby RF bands.

RF_{data}=[RF_1, RF_2…. RF_n]

Generate Digital Signature

Use the RF power sensor data to generate a digital signature. Re-compute parameters of the hash tree signature infrastructure to create a unique signature tied to the RF data.

Signature = GenerateSignature(RF_{data})

Location Identification & Blockchain Transaction Submission

Analyze the digital signature based on its connectivity to RF sensors and submit the digital signature on the blockchain.

Location=IdentifyLocation (Signature)

Blockchain.SubmitTransaction(Signature)

Blockchain record confirmation and tamper-proof record

Wait for validation of the transaction on the blockchain to ensure it is recorded in the ledger, and once confirmed, it becomes a tamper-proof record on the blockchain, which includes a digital signature and time stamp.

Confirmation=Blockchain.WaitForConfirmation()

$Record_{blockchain}$ = [Signature, Timestamp].

Proof of Presence

The logged data on the blockchain serves as proof of the device's existence at a specific location at a particular time.

$$Proof_{presence}=Record_{blockchain}$$

The procedure results in proof of the device's presence at a particular location and time, securely recorded on the blockchain: $Proof_{presence}$, which is accessible for various verification and auditing purposes. This helps supply chain managers plan effectively and ensures smooth transportation.

It also enhances efficiency and transparency in cross-border transactions. By using these technologies and storing the data in a smart contract, we ensure that the drugs are transported safely and arrive in good condition for the patients who need them.

3. Results and Discussion

The proposed system is used to track the movement of drugs in real time, as shown in Figure 4, providing visibility to all stakeholders in the supply chain. This can help to improve efficiency and prevent delays.

Fig. 4 Sensor data log

While the container is being shipped, the temperature should stay between 0°C to 5°C. However, if the temperature goes above this range, the system will automatically send email notifications to alert people, as shown in Figure 5. This is done to make sure that the drugs in the vehicle, especially vaccines, stay at the right temperature during the journey.

By using Google Maps and the email notification system, everyone can keep track of the vehicle's location, temperature, and humidity status in real-time, making it easier to monitor the shipment and take quick action if needed. As per the Ethereum blockchain, gas cost ranges- from 0.00042 ETH to 0.00105 ETH per transaction on smart contract; we are creating a batch of 12 transactions, so gas cost is reduced from 0.01260 ETH to 0.0015 ETH.

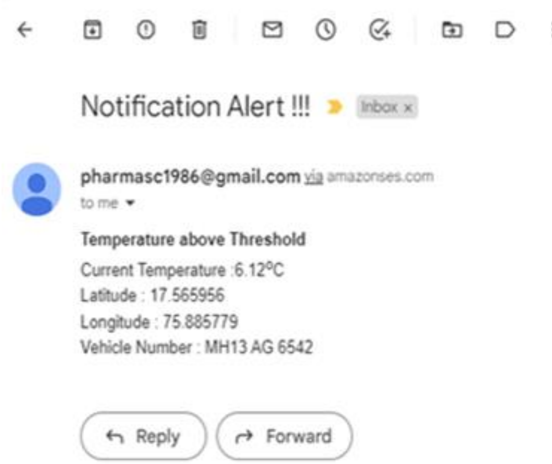

Fig. 5 Email notification

4. Conclusion

In conclusion, this paper presents a nontraditional smart logistics solution for PSCM by integrating blockchain, smart contracts, and Internet of Things devices. The proposed model addresses critical challenges in the pharmaceutical supply chain, such as ensuring precise temperature conditions during transportation, enhancing accountability, and countering counterfeit drugs.

By employing gas-efficient smart contracts, the system optimizes computational costs, ensuring scalability within the high-volume pharmaceutical supply chain. The integration of RF sensors provides real-time, clean monitoring, contributing to transparency and reliability. The three-layered framework, comprising IoT devices, blockchain, and data storage with Identity and Access Management, establishes a secure and transparent environment for stakeholders.

The setup demonstrates the effectiveness of the solution in real-time tracking and monitoring, offering stakeholders visibility into the entire supply chain process. This innovative approach has the potential to revolutionize pharmaceutical supply chain management, ensuring the safe and efficient delivery of medicines while maintaining data integrity and security.

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