Edge-cloud Blockchain and IoE enabled Quality Management Platform for Perishable Supply Chain Logistics

Chen Yang, Shulin Lan, Zhiheng Zhao, Mengdi Zhang, Wei Wu, and George Q Huang

***Abstract*—In perishable supply chain logistics, even a small departure from the required storage conditions at any distribution link can compromise the quality of transported products, such as food, pharmaceuticals, and other bioproducts, resulting in big losses for the businesses involved or even threats to public health. To enhance quality management and consumer confidence, an edge-cloud blockchain and Internet of Everything(IoE) enabled quality management platform is proposed to achieve low delay and rapid response for sensor data acquisition, authentication, consistency, and transparency in cold supply chain logistics. Then we design an adaptive data smoothing and compression mechanism (ADSC) to reduce IoE data size, analyze and store those data in the edge gateways with limited computation and storage capacity for correctly characterizing logistics operations and transactions. Moreover, to ensure the data integrity during last-mile delivery, the mobile edge gateway is adopted when the goods is temporarily off the communication range of the fixed edge gateway in the truck. Then we propose a synchronization engine with a formal workflow applied at mobile and fixed edge gateways where data blocks are generated, validated and synchronized with the cloud. Finally, a real-life case study on vaccine logistics is introduced to verify our proposed approach with results presented.**

***Index Terms*—Perishable supply chain logistics, edge-cloud blockchain, Internet of Everything(IoE), quality management**

I. Introduction

SUPPLY chain logistics(SCL) is facing challenges in recent years. The Economic Daily has revealed that China's manufacturing industry suffers a direct loss of over 170 billion CNY every year because of quality problems in supply chains [1]. Meanwhile, due to the selfishness of the supply chain members [2], and the information asymmetry in the supply chain [3], [4], the number of serious quality scandals is increasing, while products quality and credibility are in danger.

Moreover, perishable food, such as frozen meat, chilled seafood, and fresh fruit, is a popular item category for sale on e-commerce platforms all over the world [5], which entails more stringent appeal to SCL. Even a small departure such as keeping produce at improper temperatures can compromise the quality of transported products and cause unnecessary loss. Due to the presence of multiple uncontrolled variables in the distribution process, an appropriate temperature and humidity monitoring program is essential to protect the quality of perishable produce and ensure public health safety[6]. The problem demands a prompt solution. An advanced supply chain logistics management platform is required to protect and extend the shelf life of the products within logistics processes, reducing the loss and waste in transportation.

Meanwhile, the stakeholders require a more equal and safer environment. In recent years the increasing number of serious quality scandals has revealed that there are severe drawbacks to be solved. SCL usually suffers from logistics delays, asynchronous data between multiple parties, irregularity in monitoring mechanisms, and the possibility of shared data being concealed [7], which is harmful to downstream manufacturers, putting product quality and credibility in danger. Therefore, downstream buyers in the production process are requiring openness of SCL from the perspective of quality assurance, inventory and logistic optimization, and agile responses to the changing market, while end consumers are demanding access to to the quality related information about products that they bought [8]. The Internet of Everything (IoE) that enables the embedding and interconnection of computing elements and sensors in everyday objects to collect data ubiquitously from surroundings is a promising solution for the quality management of SCL, however, it is always perplexed by poor interoperability, resource constraints of IoE devices, and privacy and security vulnerabilities.

Blockchain attracts considerable attention and demonstrates the characteristics such as trust machine, decentralized governance, and traceable transactions, and can help create trusted transaction environments using the peer-to-peer paradigm. A blockchain is essentially a technology about the distributed ledger. With the decentralized consensus, blockchains can enable a transaction occurring in a mutually distrusted distributed environment without the participation of the trusted third

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party. Unlike the system focused on the major company, every participator is equal, sharing the same rights and same information. Furthermore, each transaction saved in blockchains is immutable because every participator in the network keeps all the committed transactions in the blockchain. Meanwhile, cryptographic mechanisms, including encryption algorithms, digital signature, and hash functions, guarantee the integrity of data blocks in the blockchains, ensuring non-repudiation of transactions [9]. While the Blockchain-based financial systems and services see booming development, Blockchain has tremendous potential in IoE and SCL areas. In addition, the attached timestamp guarantees traceability in blockchains. It is not an exaggeration to say that blockchain is a perfect complement to IoE.

Nonetheless, there are still several major challenges when implementing the blockchain in the IoE for SCL quality management. Firstly, IoE end devices usually have limited computation, memory, and storage resources, therefore, vast amounts of sensor data with noise and variance generated poses pressure for data block validation, generation, and storage for blockchain in those devices. As the IoE end devices are usually moving at different speeds during transport, the cloud and network services are not always available, so it is vital to deploy edge computing devices (edge gateways) near the end devices to provide stable IoE data storage and processing services. For an edge gateway which will connect and serve multiple IoE devices, techniques about reducing sensor data size should also be investigated. Secondly, the nature of supply chain logistics determines that related SCL operations and activities are geographically dispersed, so the interconnectivity of SCL things during storage and transport is unstable, which can cause negative effects to the integrity, real-time and visibility of SCL data, such as missing data points on logistics processes especially during transitions between SCL operations. Then the mobile edge computing should be adopted to take the responsibility of connecting IoE devices. The mechanism about the synchronization between fixed edge gateways and mobile gateways should be investigated to keep the integrity of SCL data. Thirdly, for stakeholders of SCL, the acquisition and processing of SCL quality data should follow the principles of immutability and non-repudiation, because data fraud, latency and deferred response to quality issues during any SCL moves can cause economic losses and health risks. Therefore, data block generation and validation should be investigated.

Therefore, this paper aims to propose an Edge-cloud Blockchain and IoE enabled Quality management platform for perishable Supply chain logistics (EBIQS). An Adaptive Data Smoothing and Compression(ADSC) mechanism and spatial temporal analytics are developed for alleviating the pressure of data block validation, generation, and redundancy considering limited storage capacity at the edge side. We design a synchronization engine that can orchestrate edge gateways to realize seamless IoE sensing and data exchange. Moreover, smart quality management(QM) contracts are introduced to regulate data block generation of SCL transactions and report potential quality risks automatically under predefined conditions. A real-life case study of vaccine logistics is conducted to test and verify the effectiveness of the proposed platform.

The rest of this article is organized as follows: Section II presents related work of IoE in SCL and blockchain applications; Section III introduces the architecture of EBIQS including details of ADSC, spatial-temporal analytics and synchronization engine; Section IV describes a case study and discusses related results. Section V presents the conclusion of this article and future works.

II. Related Work

A. Internet of Everything in Supply Chain Logistics

The Internet of Things(IoT) is a new technology paradigm envisioned as a global network of machines and devices capable of interacting with each other [10]. A state-of-the-art and intensive survey is conducted and presented as follows, concerning the existing IoT-based applications in logistics. IoT is forming an ecosystem especially in product status monitoring [11]. The Internet of Everything(IoE) expands the IoT concept by connecting data, people, and business processes [12]. Hsueh *et al*. [13]. proposed a monitoring approach for the application of radio frequency identification (RFID) technology and wireless sensors to ensure the products' quality and traceability along the supply chain. Temperature variations can be detected for stakeholders to take corrective action and prevent further deterioration in food logistics. The products' quality and decay rate are used to schedule the vehicle routing plan. Further work on assessment and decision support for the cold chain quality has been conducted by Wang *et al* [14] and ontology is proposed with sensing layer, network layer, and application layer. The ZigBee coordinator is adopted to acquire readings from cold chain tags and the data is transferred to the hand-held terminal through RS232 protocol. An intelligent tracking system based on ZigBee for the cold chain is proposed by Luo *et al*. [15], data and information is integrated to ensure effective control. However, this research does not consider the reaction to abnormal situations. Tsang *et al*. [16] developed an IoE-based cargo monitoring system to detect any environmental change of environmentally sensitive products in order to ensure their quality throughout the entire cold chain operational environment. Two modules namely storage condition adjustment module and guidance establishment module are proposed. Shanley [17] believed that IoT, advanced analytics, and blockchain solutions promise to give manufacturers more control over products and supply chains. Zhou *et al*. [18] integrated cloud computing with IoT to facilitate information exchange and synergic performance between things and people. Edge computing for resource allocation in IoT is proposed to meet the requirements for real-time decision-making [19]. Francisco *et al*. [20] presented a low-power semi-passive RFID enabled temperature sensor developed for the cold chain management. It can record the temperature in the memory. The active RFID tag was adopted for monitoring the temperature to improve the cold chain responsiveness[21]. The question of how to make the technology work reliably in the highly dynamic environment of logistics operations such as facing the massive IoE data and potential risks, need to be solved.

Currently, there is no proper IoE solution in terms of temperature sensing and data communication to meet the requirement of all-weather quality management especially for the continuous and real-time monitoring of perishable products during in-transit delivery. Moreover, a proper data processing approach is required as the massive IoE data generated poses challenges for edge devices with limited computation and storage capacity.

B. Blockchain

Blockchain is a distributed technology that supports financial operations and helps establish a secure and trustworthy system for product provenance authentication [22]. Fosso Wamba *et al*. [23] evaluate the level of knowledge on Bitcoin, Blockchain, Fintech and their evolution over time. The supply chain decision-making approaches can be developed and optimized based on these technologies. As a perfect complement to IoT with excellent tamper-proofing, traceability, and non-repudiation, blockchain has shown an encouraging future for being a backbone to several IoT applications. Chen *et al*. [1] propose a framework and system architecture for blockchain-based supply chain quality management. The framework and the corresponding 4-layer system architecture can improve the efficiency and profits of enterprises. Dai *et al*. [9] propose the blockchain of things (BCoT), the synthesis of blockchain and IoT. They discuss the opportunities of integrating blockchain with IoT and summarize the applications of BCoT. To preserve data privacy, Shen *et al*. [24] incorporated blockchain into the intelligent edge computing framework. Wan *et al*. [25] build a lightweight decentralized IIoT architecture based on blockchain for a smart factory and a security and privacy model is introduced to help analyze the key aspects of the architecture by setting up a white list mechanism. Feng *et al*. [26] established a blockchain-based multi-sensors monitoring system to collect multi-dimensional quality data and verify captured information for improving the transparency at the cold storage phase. To address limited computing capacity and high latency issue, Wu *et al*. [27] proposed a blockchain-enabled IoT-Edge-Cloud computing architecture. Pan *et al*. [28] prototype an “EdgeChain” framework based on blockchain and smart contracts. The core idea is to integrate a permissioned blockchain and the internal currency or “coin” system to link the edge cloud resource pool with each IoT device’s account and resource usage, and hence behavior of the IoT devices.

Even though there have been some efforts paid to deploy the blockchain in the SCL, there are still several problems. Unlike the cryptocurrency (e.g. Bitcoin, Ethereum) where transactions are carried out with fine network accessibility, the logistics transactions data generated mostly from IoE devices in the edge side where the quality of network cannot be guaranteed. As a result, the data efficacy, traceability, and transparency face challenges. Moreover, in most of the existing frameworks blockchain are deployed on the cloud server, which leaves hidden trouble to edge nodes in terms of the data safety issue. Even there may be work on edge-cloud blockchain,the synchronization mechanism between edge side and cloud side in terms of data collection without communication network and the mechanism of data compression and spatial temporal validation at the edge side deserve more in-depth study.

C. Quality Management of Supply Chain Logistics

Quality management is a standing dish in recent years. As a typical representative of horizontal integration management, supply chain logistics quality management implements information communication, data exchange, and collaborative work between the manufacturer, suppliers, distributors, retails, and final customers. Supply chain logistics has become an effective way for enterprises to global competition in the 21st century. Shi [29] summarizes the characteristic of supply chain logistics quality management and propose an architecture based on e-commerce. Li *et al*. [7] describe a kind of supply chain logistics quality management in the context of the Open Manufacturing (OM) concept and its integration with IIoT and Blockchain. Pal *et al*. [30] introduce the Internet of Perishable Logistics for studying basic relations among the delivered quality of perishable product, transportation efficiency and number of active carries. In response to the food quality issues, retail giant Walmart using blockchain technology to tackle the food supply chain transparency problem. A ”complete end-to-end traceability” is achieved[31]. Haya Hasan *et al*. [32] identified that the warehousing part of the cold supply chain in healthcare has larger temperature disturbance. A triggered notification is required to make quick response. To ensure product quality and boost consumer confidence, consumers and the supervision department are supposed to be concerned, so as the real-time information of transportation and regulation information. The lack of instant response to shareholders about quality issues may cause threats to public health especially circulating to the next steps in SCL.

III. EBIQS: Platform for Edge-cloud Blockchain of IoE enabled Supply Chain Logistics Quality Management

A. Architecture of EBIQS

IoE technology has been pervasively adopted to track and monitor men, machines, and materials in the domain of SCL. However, there are still several special concerns for the cold SCL. First, perishable goods or foods such as pharmaceutical products should be kept within proper temperature or humidity boundaries throughout the supply chain. The accurate, timely and reliable data are of great importance for downstream and upstream partners in the supply chain. Therefore, the timeliness and authenticity of the IoE data generated by continuous monitoring of SCL should be guaranteed. Second, false alarms caused by instant opening and closing of the insulated container or sensor errors lead to the decrease in credibility of quality data. Third, edge devices have limited computing and storage capacity, and data freshness can be significantly affected by overwhelmed IoT data which poses challenges to data block generation and causes data redundancy. Last but not least, missing data points about logistics transactions due to unstable Internet connection may lead to the untrustworthiness among different stakeholders. A continuous sensing and controlling mechanism that can work in the dynamic and harsh environment is urgently needed.

Therefore, we propose the architecture of EBIQS (shown in Fig. 1), which consists of four layers.

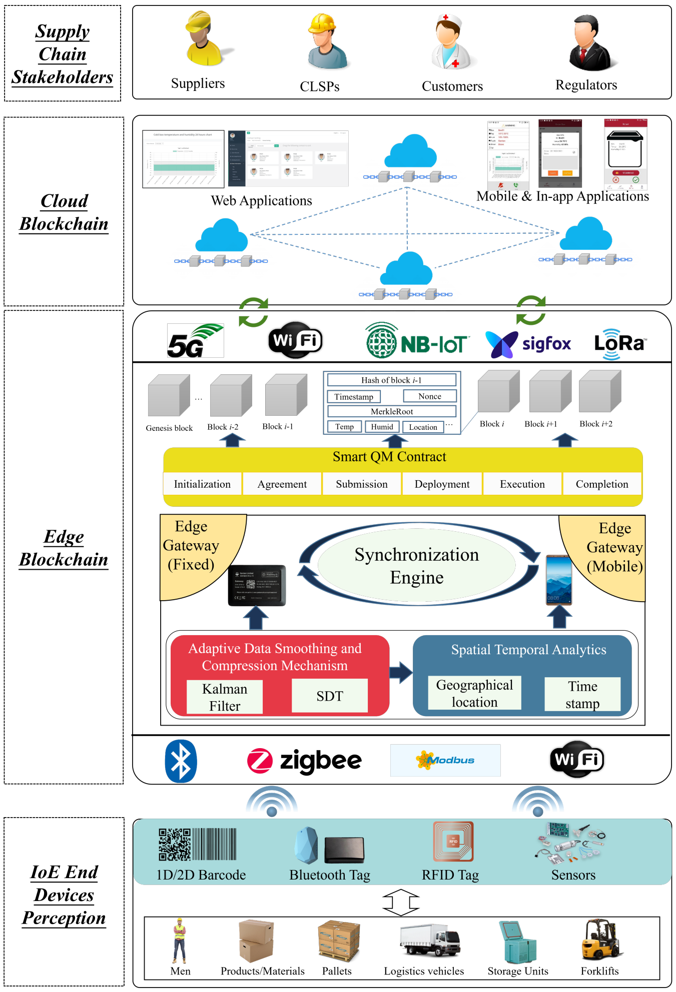

Fig. 1. Architecture of EBIQS.

(1). *IoE Devices Perception*: In this layer, logistics assets including men, products, pallets, and vehicles that relate to SCL operations are equipped with IoE devices to have the ability of being identified, sensed, communicated, controlled, and monitored. Passive 1D/2D barcodes and RFID tags contribute to the identification of logistics assets. An active Bluetooth tag consists of the communication module, sensors, microprocessor, and batteries and enables the whole process of data provenance from data creation (sensing) to data transmission. Temperature and humidity sensors such as SHT3X and DHT series can perceive changes on indexes of the surrounding environment in real-time while the calibration-free technologies ensure the long-time use of smart sensors. The IoE devices, therefore, can represent the physical entities to participate the future games. Other communication technologies such as Zigbee, Modbus, and WiFi are also options with different advantages and disadvantages to connect men, machines and things.

(2). *Edge blockchain*: Although cloud-based solutions centralize various computing resources to resolve problems, massive IoE data generated are geographically dispersed. The high latency of data transmission between IoE nodes and the cloud server and cloud based computation time leads to the slow response for assets' requests, especially in large-scale scenarios. The thriving of edge computing supports alleviating the central pressure and makes the best use of edge devices such as mobile phones and IoE devices. Two types of edge gateways are proposed, namely fixed edge gateway (FEG) and mobile edge gateway (MEG). Both kinds of gateways consist of computation modules and communication modules such as GPS, cellular network, and Bluetooth. Downward communications technologies are also implemented to collect data from the IoE devices. Gateways perform the main functions of IoE (data collection, filtering, and transmission) and blockchain (validation, data block generation). Those edge devices have limited computation, storage and bandwidth capacity to host and exchange holistic blockchains in an effective manner. Therefore, the edge devices only hold the local events related to blockchain and store limited historical data blocks during communication. These data blocks in edge devices are referred to as edge blockchain.

(3). *Cloud blockchain*: Cold SCL business systems for daily operations are deployed at cloud servers. The data blocks generated on the edge side are received by multiple load balancing cloud servers. Each cloud has a dedicated interface to accept the blockchain data offloaded by edge gateways. The cloud storage capacity and bandwidth among cloud servers can satisfy the requirements of low-delay transmission and long-term storage of blockchain data, thus the holistic blockchain is safely deposited at the cloud servers which are referred to as the cloud chain. The cloud blockchain synchronize the edge blockchain data to avoid concurrency conflict.

B. Adaptive Data Smoothing and Compression Mechanism

At the *Edge Blockchain* layer, after a period of time for data collection, temperature/humidity/other sensors (embedded in IoE devices) may generate noisy data that disturbs observations. The false alarm also occurs when the cold box is opened and closed during the whole delivery process. Moreover, considering limited storage resources at edge blockchain, the sensor data collection method of fixed acquisition frequency will lead to two situations: when the time interval is set too small, a large amount of redundant data is collected with high power consumption and will run out of edge storage space quickly; when the time interval is set too large, rapid state changes of storage conditions cannot be captured accurately in time. Therefore, this research intends to introduce an adaptive data smoothing and compression mechanism including Kalman Filter and swing door trending algorithm(SDT)[33]. The Kalman filter is adopted to denoise the readings generated by the measurement and eliminate the false alarm during instant opening and closing event of the cold box. It is a state estimator that makes an estimation of some unobserved variables based on noisy data. The following equation illustrates the basic problem statement. SDT dynamically adjusts the acquisition time interval according to the changing degree of the acquisition data. The SDT is a relatively fast linear fitting algorithm for data compression. For the SDT, the more the data can be blanketed, the longer the compressed data segment is, and the smoother the data changes; If the data cannot be blanketed, the shorter the compressed data segment is, the more drastic the data changes. Therefore, the SDT can be used to determine the magnitude of data change, and the result of the judgment can be used to reduce or increase the data acquisition time interval, so that the time interval can be quickly reduced to avoid losing important data when the data changes drastically, and vice versa.

Kalman Filter is one of the most widely used methods for data de-noising.

$$x_t = F_t\ x_{(t-1)} + B_t\ u_t + w_t \tag{1}$$

where the current state x_t is the vector containing the attributes of interest for the system. F_t is the transition matrix that applies the effect on state parameters at time $t-1$ on the system state at time t. B_t is the control input matrix that applies the effect on each control input u. The w_t denotes the process noise caused by the system itself. We acquire a series of temperature readings from sensor tags in the cold boxes. In this case study, it is a one-dimensional Kalman filter for de-noising temperature data. Hence, the system equations take the form:

$$x_t = x_{(t-1)} + w_t \tag{2}$$

Analogously, the measurement observation model is as follows.

$$z_t = x_t + v_t \tag{3}$$

The v_t is the measurement noise caused by the sensor part. The initial value of x_0 of systematic error can be assumed to be 0. The Kalman filter algorithm involves two stages, the prediction and measurement update. The simplified Kalman filter equations are as follows:

Time update equations,

$$\bar{\mu}_t = \mu_{(t-1)} \tag{4}$$

$$\bar{E}_t = E_{(t-1)} + Q \tag{5}$$

Measurement update equations,

$$K_t = \bar{E}_t(\bar{E}_t + R)^{-1} \tag{6}$$

$$\mu_t = \mu_t + K_t(z_t - \bar{\mu}_t) \tag{7}$$

$$E_t = (1 - K_t)\bar{E}_t \tag{8}$$

where μ_t describes the prediction value of temperature at time t and $\bar{\mu}_t$ denotes that the measurement information has not been incorporated. E_t is the estimate of error variance. Q and R are the process noise and the measurement noise respectively. Considering the equations do not have process noise, we assume that Q is 0.008 and R = 3. K_t is the Kalman gain, which is used as a weighting function between the certainty of the estimate and the certainty of the measurement.

Fig. 2 illustates the SDT compression. The SDT algorithm is a linear trend compression algorithm. In essence, it replaces a series of continuous data points with a straight line determined by the start and end points. Assuming that the vertical axis in the coordinate system is temperature($Temp$) and the horizontal axis is time(t). After the application of the SDT, data from t_0 to t_4 covered by the blanket 1 can be compressed and in blanket 2, only data from t_4 to t_7 can be compressed since the data in t_8 falls outside the blanket 2. The ideal and safe range of temperature for keeping perishable products is defined as $< TEMPmin, TEMPmax >$ which is collected from the smart contract, and the compression deviation is $\Delta E = (TEMPmax - TEMPmin)/2$. The range of data acquisition interval is $< INTVmin, INTVmax >$. The current and new acquisition interval is $Interval\_cur$ and $Interval\_new$ respectively. ADD refers to the step size of each increase of acquisition interval, and MULT refers to the multiplier adopted to reduce the data acquisition interval . The range of the MULT is (0, 1). Generally, MULT can be set to 0.5. Then the gradient of the SDT upper gate can be defined as:

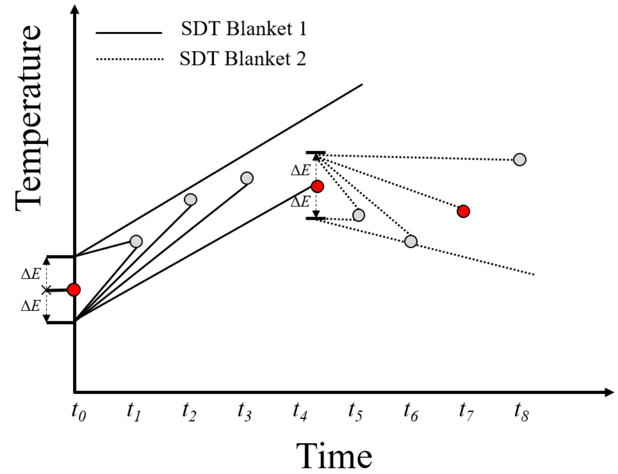

Fig. 2. SDT compression.

$$up\_grdt = \frac{Temp[end] - Temp[start] - \Delta E}{Time[end] - Time[start]} \tag{9}$$

and the gradient of the SDT down gate can be calculated as:

$$down\_grdt = \frac{Temp[end] - Temp[start] + \Delta E}{Time[end] - Time[start]} \tag{10}$$

The gradient of current upper gate and down gate are denoted as $current\_up\_grdt$ and $current\_down\_grdt$ respectively. The maximum gradient of upper gate and down gate are max_up_grdt and min_down_grdt. $Temp[start]$, $Time[start]$ and $Temp[end]$, $Time[end]$ are the starting point and the ending point of the compression segment including time and temperature. The following algorithm introduces an adaptive SDT for sensor data collection. The data acquisition interval is reduced when the collected data changes drastically and if the trend remains much the same, then the data acquisition interval can be increased. The compression ratio (CR) refers to the ratio of the number of data points in the compressed data to the number of data points in the original data. The larger the CR becomes, the more storage space it saves.

$$CR = \frac{n}{m} \tag{11}$$

Algorithm 1 Adaptive SDT algorithm for sensor data collection

set parameters for SDT: $max\_up\_grdt \leftarrow -\infty$, $max\_down\_grdt \leftarrow +\infty$, stored point [start]
loop
  collect new data point [end] and calculate $current\_up\_grdt$, $current\_down\_grdt$
  if $current\_up\_grdt > max\_up\_grdt$ **then**
    $max\_up\_grdt \leftarrow current\_up\_grdt$
  end if
  if $current\_down\_grdt < min\_down\_grdt$ **then**
    $min\_down\_grdt \leftarrow current\_down\_grdt$
  end if
  if $max\_up\_grdt > min\_down\_grdt$ **then** ▷ when the trend changes a lot, decrease the Interval
    point [start] ← point [end-1]
    $Interval\_new \leftarrow MAX(Interval\_cur * MULT, INTVmin)$
  else ▷ when the trend remains much the same, increase the Interval
    $Interval\_new \leftarrow MIN(Interval\_cur + ADD, INTVmax)$ ▷ $MULT \in (0, 1)$
  end if
end loop

C. Workflow of Synchronization Engine

At the *Edge blockchain* layer, the edge gateway is usually deployed at fixed location while the mobile gateway is carried by a person to run the business application of daily SCL operations. These two kinds of gateways have similar functions, but the synchronization is highly needed because when a target object is out of the communication range of fixed gateways, the mobile gateways should take responsibility for seamless connecting the target object to ensure data acquisition and data integrity.

The *synchronization engine* is designed to avoid missing data points due to unstable connection, through the seamless collaboration between FEG and MEG. Fig. 3 depicts the workflow of the synchronization engine. These two kinds of gateways are intelligent agents which have the proactive capability of knowing where they are and connecting nearby gateways. The MEG stays idle until the mobile gateway loses the connection with the FEG (e.g. couriers leave the truck for last-mile delivery to the customer), and automatically carries out the holistic functions of the gateway. Nonrepudiation spatial temporal analytics is adopted to ensure IoE data security and reliability. Every SCL transaction with spatial temporal stamp (STS) including timestamp and location information is required to be submitted. If the SCL transaction violates the geographical rules, it may fail the validation. For example, the sensor data of temperature and humidity in transit must contain geographical and time data. Consecutive time and location information can exhibit a conjunction feature that validates the effectiveness of collected data. The incoherent and fallacious spatial-temporal information cannot pass the validation test. The edge blockchain follows the standard rule of forming the data block including hash functions, Merkle tree, and necessary private and public keys. Data blocks are generated and validated in edge devices. Due to limited edge storage capacity and latency issues, the edge blockchain will upload created data blocks to the cloud side if the delivery is finished.

D. Smart Quality Management(QM) Contracts

The smart QM contracts are proposed based on the "smart contracts" conception in blockchain research. The smart QM contracts regulate various cold chain logistics requirements and provide actions once against the rules. It is initialized by suppliers, reviewed by SCL service providers, deployed and executed in the gateways for fast local decisions without the help of the cloud. The upward communications including 5G and low-power wide-area networks such as sigfox and NB-IoT contribute to transferring the data blocks to the cloud blockchain where the business systems are deployed. The addressable smart contracts are self-executing scripts that reside on the blockchain[34]. The edge node transfers logistics and environmental input data to invoke the smart QM contract. The smart QM contract acts as an intelligent agent and deals with these data under predefined conditions. The SCL transactions will be validated only if the certain conditions are satisfied. They can be thought of as being roughly analogous to cryptocurrency transactions in Bitcoin when predefined conditions are triggered. Algorithm 2 presents the smart QM contract. First, the STSs including geographical location information and timestamp will be plotted on a 2D diagram to investigate the data continuity and rationality by considering the vehicle speed and route information. The logistics transactions data blocks cannot be generated if the data fails spatial temporal analytics. The smart QM contract also regulates the temperature and humidity range and alarms will be activated and sent to the cloud if preconditions are satisfied.

Algorithm 2 Smart QM Contracts Conditions

Input: *Spatial temporal stamp, ADSC data, Temperature/Humidity range*
Plot the spatial temporal stamp to 2D diagram.
if Spatial temporal stamp comply with continuity **then**
  if Temperature/Humidity in ADSC within Temperature/humidity range **then**
    Accept the logistics transactions data.
  else
    Accept the logistics transactions data & alarm to cloud blockchain.
  end if
else
  Reject the logistics transactions data.
end if

IV. Case Study

A. Background

The collaborating company is a cold-chain logistics service provider located in Hong Kong. Temperature and humidity

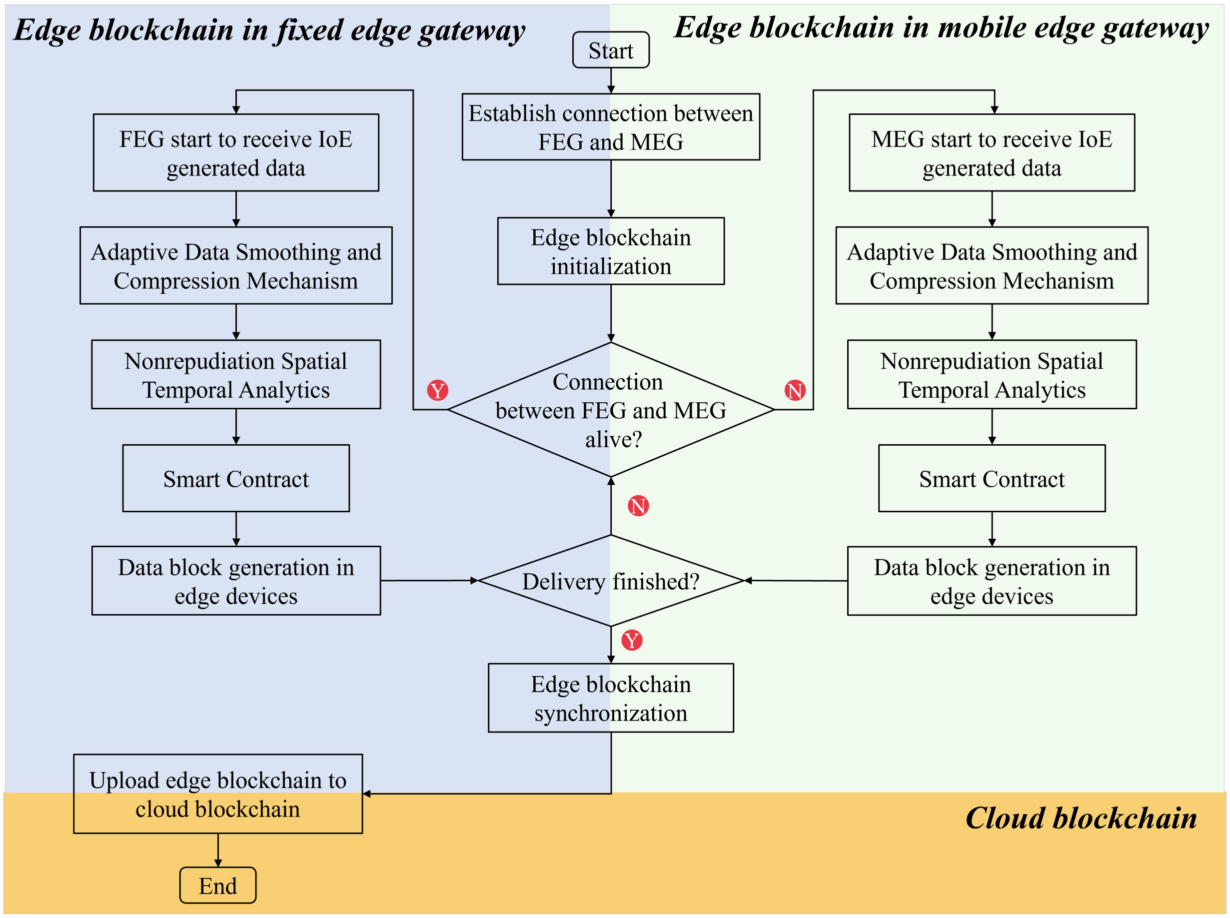

Fig. 3. Workflow of synchronization engine.

sensitive vaccines are the deliverables from the manufacturer's point of origin (the cold storage warehouse) to the point of vaccination (usually hospitals and clinics). Vaccines are biological preparations. Cold storage and transport are a must to make sure that vaccines arrive safely. They have limited lifespans before degrade. Storage and transport in improper temperatures that are too hot or too cold as well as exposure to ultraviolet light can degraded or even destroyed them . These cases are commonly referred to as "cold chain break". The cold storage warehouse is less worried since the centralized temperature control system can guarantee the effectiveness of the vaccines within the proper range of temperature and humidity and an alert will be triggered once the temperature or humidity is out of the specified range. However, during transport, vaccines are usually temporarily stored and covered by ice plates in different cold boxes. With good insulation capability of the cold box, the vaccines can be maintained at normal status ideally. However, the frequent open and close of the cold box when the driver takes out some vaccines to customers, and the reduced sealing effect (or even cold chain equipment failures) caused by the vehicle bumping and long transit time during transport may lead to the cold chain breaks [35]. Globally, cold chain breaks are responsible for the loss of 15-25% of purchased doses and cause threats to healthcare if immediate actions are not taken[36]. Millions of dollars are wasted due to the lack of trustable traceability. The collaborating company has concluded the following requirements.

(1). Real-time temperature and humidity monitoring for vaccines in the cold box.

(2). Alert immediately managers to take corrective action when the cold chain breaks, but false alarms are not allowed.

(3). Temperature and humidity ranges can be customized according to requirements of different kinds of vaccines.

(4). All data should be immutable, non-repudiation, documented and shared among different stakeholders.

These requirements from the healthcare and logistics industry are also the main motivation of this research. Simply adopting IoT technologies can satisfy the first three requirements, however, the limitations such as data privacy and security vulnerability still pose challenges to this project. Therefore, the research team proposed the IoE and edge-cloud blockchain-based quality control architecture. The application of our research is elaborated as the following.

B. Deployment of EBIQS

Five steps are included in the deployment of the proposed solution in Fig. 4.

Step 1: Packaging

The warehouse operators put the vaccines in the cold box according to customer orders and at the same time, prepare

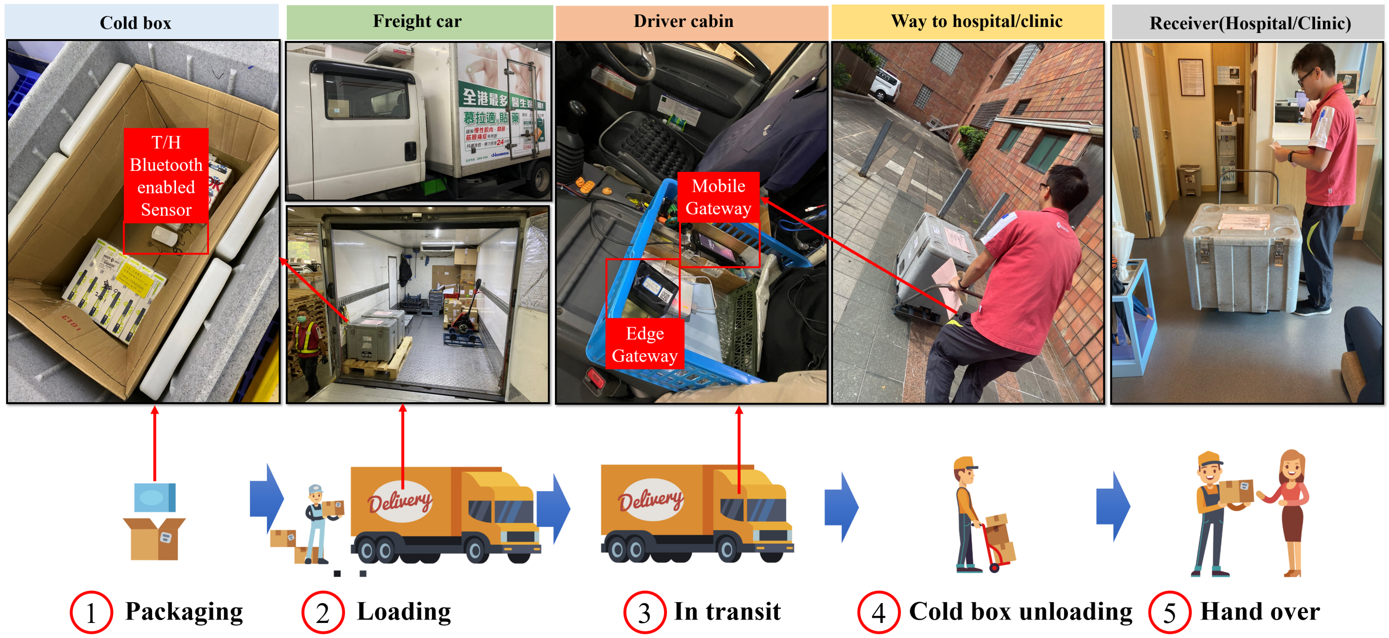

Fig. 4. Deployment of EBIQS.

one temperature/humidity monitoring IoE tag with QR code on the surface illustrating the MAC address. The operators use the smartphone application to bind the details of multiple orders with the IoE tag and the box identification number. The IoE tag consecutively broadcasts messages including the unique ID, temperature readings, and humidity readings. The smart contract is initialized by quality management department based on the temperature/humidity requirements of different vaccines which are clearly illustrated on the loading list.

Step 2: Loading The operators organize and stack cold boxes into the freight car. The edge gateways are mounted in the driver cabin of each vehicle in a distributed way. Once the loading work is done, the operator presses the "finish loading" button to start the transport. The status of smart contracts for different vaccines changes to the status of agreement. The application for the driver displays the details of the loading information and smart contracts. The smart contract including terms and conditions of cold chain breaks is reviewed and submitted by the driver. After confirmation by the driver, the delivery is ready to start. The smart contract is then deployed at the edge gateways. The sensing activities of temperature and humidity are launched.

Step 3: In transit

Driver's smartphone is used as the MEG from this moment. Usually, multiple orders need to be fulfilled for multiple customers in one trip. The broadcasting messages emitted from the many IoE tags in different cold boxes are received by the edge gateway within the transmission range of Bluetooth. The data blocks are encrypted and generated. The smart contracts are executed with "if-then-else if" clauses. Once the cold chain break occurs, the smart contracts will respond to changes such as informing relevant parties accordingly.

Step 4: Cold box unloading

When the vehicle approaches a customer location, the drivers are obligated to carry the cold boxes with the vaccines inside and open them under the sight of customers. Once the vehicle has parked, the drivers are required to unload the specific cold box(es) and deliver them to the customer. The rest cold boxes remain in the freight vehicle so that the edge gateway is still able to sense them. However, the messages from IoE tags in cold boxes carried by the drivers on the way to the customer is still broadcasting but cannot be received by the edge gateway since they move outside the Bluetooth communication range. These cold boxes still need to be monitored as not all the orders in the cold boxes reach the same destination. They are supposed to be returned to the freight vehicle for the following delivery. Quality control must be guaranteed in an all-weather way. The synchronization engine in the edge blockchain automatically starts to coordinate the mobile gateway carried by the driver to collect the broadcasting messages from the cold boxes outside the vehicle.

Step 5. Hand over

Before receiving the vaccines, the customers have the authority to review the transport and quality control records through their mobile application or by scanning the QR code on the surface of the cold box. The QR code is paired with the IoE tag and the orders. Once receiving confirmation is conducted, the smart contract is completed. The driver will carry the cold boxes back to the vehicle for the following deliveries.

C. How Blockchain and Smart Contracts Work

The detailed blockchain enabled workflow of the supply chain logistics is illustrated in Fig. 5. The solid arrow indicates the physical flow of things. The dotted arrow illustrates the information flow in the solution. All the blockchain and smart contracts are in line with the operation procedures. Edge gateways are equipped with GPS modules to record the absolute geographical location information while the connected objects therefore have relative location information. The proximity contributes to the nonrepudiation analytics. During the packaging phase, after the binding operations by the warehouse operators, the smart contract is initialized as the temperature and humidity requirements of vaccines are generated from the orders. The successful work of "finish loading" operations need to be validated under the requirement that the MEG should establish connections with the FEG on a specific vehicle. Then the data block is created and added in the distributed edge blockchain through the private key installed in the FEG. The drivers then review the loading list and validate it under the connection with the edge gateway. Agreement of the smart contracts is reached if the driver accept the temperature/humidity ranges. The log together with the relative location information is created as a data block in the edge gateway through the driver's private key. The smart contracts are deployed simultaneously in the edge gateways. Real-time temperature and humidity information is emitted from the IoE tag and collected by the edge gateway. These data also need to be validated from a spatial-temporal perspective before the generation of data blocks. The unloading procedure activates the mobile gateway to generate data blocks via the GPS and Bluetooth function. Cold chain breaks will be alerted automatically since the smart contracts are executing. Customers who receive the vaccines have the public key to view the records of the vaccines through the cloud blockchain for the reason that operation and business systems are the centralized solutions and the cloud provides integrated storage of sensor data from multiple edge gateways.

The smart contracts regulate the actions once the temperature/humidity of the vaccine is out of range.

The research team conducted the ADSC test of filtering and compressing the real-time temperature data recorded by the temperature sensor from 9:11 to 20:34 in a perishable SCL delivery. There are total of 1,223 pieces of data starting from the placement of the sensor to the cold box to the end of the delivery.

As can be seen from Fig. 6 , Kalman filter and SDT is collaboratively working to process the IoE data. The Kalman filter first smooth the real-time temperature readings and also avoid the false alarm caused by the cold box opening and closing event during delivery tasks. The the SDT record the trend of temperature changes but also compress redundant data. Several tests have been conducted for evaluating the overall performance. The data size of the temperature recording at one delivery task has been reduced by more than 97.5% for limited storage space at the edge side. With the support of Kalman filter, the false alarm is basically eliminated. Other sensing solutions can not acquire temperature data points of the cold box during unloading and handover process as no devices can read the temperature signals emitted from the sensors. Other sensing systems can record the whole process of temperature indexes and export from the device at each end of the delivery task. Comparatively, the proposed EBIQS can transmit sensor data (current readings) to the cloud in real time to enable prompt action to avoid quality issues. Throughput has also been increased significantly due to the reduction in the volume of data and the ability of edge computing.

There are several inherent characteristics of blockchain applications in the proposed solution.

Decentralization: We consider that various stakeholders in SCL such as logistics service providers, manufacturers, suppliers, and customers are peers in the blockchain ledger. The edge gateways act as distributed ledgers to record and generate data blocks to avoid single-point failure and performance bottleneck in a centralized manner. The data generation can be automatically validated between peers without intervention by a third party.

Immutability: The data which reflects the quality of transported goods are of great importance in the whole chain. Malicious falsification may lead to the crisis of confidence and even threats to public health. The data blocks in blockchain are consecutively linked, and each link is an inverse hash point of preceding blocks. The modifications of the data may invalidate all data blocks. Any tiny modifications may generate a new Merkle tree that can easily detect the falsification.

Nonrepudiation: Spatial-temporal stamp is added to sensor data for validation of the data blocks. Private keys are used to the endorsement of each operation. Both kinds of actions cannot be denied by any logistics parties.

Transparency: For SCL stakeholders who have a public key, the records and details of any logistics transaction can be viewed with equal rights. Quality details can be accessed and verified by every stakeholder. Derived from the smart contracts, the smart QM contracts state the predefined conditions clearly among SCL parties, so that they can jointly supervise the SCL operations.

Traceability: Together with IoE technology, each data block in the blockchain is attached with sensed IoE data encapsulated with timestamp and location information. Synchronization engine in edge gateways guarantees the integrity and visibility of the sensor data about QM of goods. The logistics transactions data including spatial temporal information sensor information and temperature/humidity information of the product storage reflects the quality of the goods during the transportation procedure. SCL stakeholders can easily verify the origins of the data.

A comparative study of the proposed EBIQS and other sensing solutions is conducted. Most of the previous research using RFID based temperature sensors with ease of near field communication, IoE sensor data cannot be acquired in a real-time manner unless within RFID readers' distance. The wireless technology enables the real-time data exchange between the end side and the edge side. As can be seen from Table I, EBIQS focuses on the in-transit delivery section where the mobile scenario requires robust information acquisition method to maintain data integrity. In this section, abrupt temperature changes occur frequently due to opening and closing events during last-mile delivery or bumps in the road. In addition, a lot of end devices generate a substantial amount of data which poses great storage pressure to not only the edge devices but also validation and data block generation. In [32], GPS is used to record the logistics route information as reference,

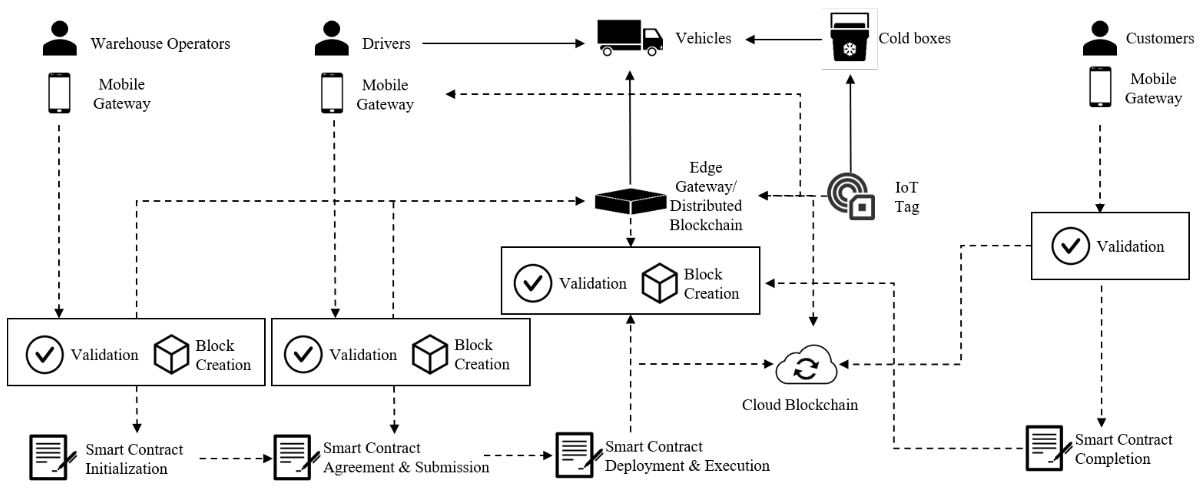

Fig. 5. The workflow of the blockchain and smart contract.

TABLE I
COMPARISON BETWEEN THE EBIQS AND OTHER SENSING SOLUTIONS

Related work	[20]	[21]	[26]	[32]	EBIQS
Sensor adoption	Semi-Passive RFID based temperature sensor	Active RFID based temperature sensor	Zigbee based temperature sensor	RFID-based temperature sensor	Bluetooth based temperature sensor
Wireless technology adoption	-	-	Wi-Fi	4G	Bluetooth; 4G
Geographical location information	-	-	-	GPS	GPS;Bluetooth
Monitoring section	Storage	Storage	Storage	Storage	In-transit
Data integrity under poor network connectivity	-	-	-	-	Synchronization engine
Data filtering and compression	-	-	-	-	ADSC
Monitoring quality risks/Local decision	-	-	K-means and SVM	-	Smart contracts
Data security	-	-	Cloud blockchain	Cloud blockchain	Edge-cloud blockchain

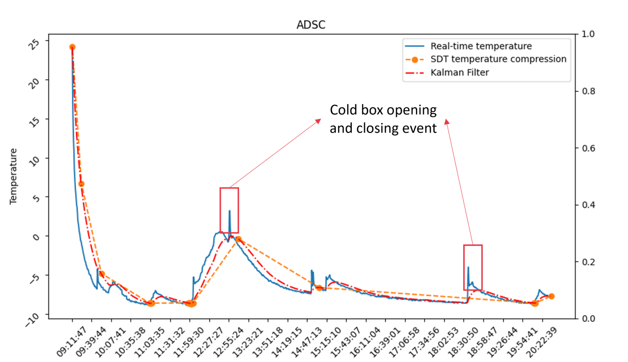

Fig. 6. ADSC of temperature data in perishable supply chain logistics delivery task.

while the EBIQS adopts the GPS and Bluetooth information as spatial temporal stamp to verify the data authenticity. Synchronization engine in EBIQS contributes to ubiquitous sensing during transition between SCL operations especially under poor network connectivity environment. [26] monitored the potential quality risks through K-means and SVM by the data collection at the end of each logistics transaction, while EBIQS uses smart contracts to monitor quality issues and generates local decisions with rapid response from edge gateways.

V. CONCLUSION AND FUTURE WORK

The perishable products will degrade and give rise to significant losses if required storage and transport conditions have been violated for some time during the logistics. So it is critical to enhancing safety and quality management for cold supply chain logistics, by adopting methods of continuously monitoring and automatically reporting the logistics conditions in real time. From different perspectives, stakeholders want to obtain real-time status about the whole logistics process. To address those issues, we proposed a platform (called EBIQS) for quality management of perishable supply chain logistics. The contributions of this paper mainly include: Firstly, considering the limited storage and computing resources of end devices, we proposed an adaptive data smoothing and compression mechanism including Kalman filter and SDT to smooth noise and compress massive IoE data for the ease of data block validation, generation and storage in the edge blockchain. Secondly, the synchronization engine that coordinates fixed and mobile edge gateways are developed to realize continuous IoE sensing and data exchange in the entire transport process especially during transitions between SCL operations, so that the integrity and real-time visibility of the sensor data is guaranteed. The situation of missing data points especially under poor network connectivity environment is basically eliminated. All-weather efficient monitoring and trusted reporting of supply chain logistics (SCL) quality is realized to support the transparency of the SCL. Thirdly, the smart contracts built in the edge blockchain support agile local decisions for the alertness of potential quality risks and regulate the data block generation. In the quality management perspective, the architecture of edge-cloud blockchain supports low delay and rapid response for stakeholders to take corrective action and reduce economic losses and health risks before circulation of risks to later part. We implement EBIQS in a real-life case study of vaccine logistics to verify the effectiveness. Future work will concentrate on the two following aspects: (1) investigate how to achieve the trade-off between transparency and privacy, as some raw data is sensitive to logistics companies. (2) design efficient flexible algorithms for data cleaning, storage, and reporting, as the blockchain system has performance and scalability bottlenecks.

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