Pharmaceutical Cold Chain Management

Platform Based on a Distributed Ledger

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Abstract—**In the process of distributing pharmaceutical products multiple stages are involved until products are delivered to patient. A reliable way for validating and verifying that products had been maintained within a licensed range is required. The paper presents a solution for pharmaceutical cold chain management using distributed ledger technologies. An application framework is proposed for shipment tracking which will deliver information to all stakeholders during the distribution phase of pharmaceutical products. The solution is based on Hyperledger Sawtooth distributed ledger framework, which has been extended with a custom transactions family and a sensors gateway for automatically collecting data from temperature tracking devices. The focus of the paper is to describe the data model and how entities of the system communicate.**

Keywords—cold chain, distributed ledger, distributed sistems, internet of things

I. INTRODUCTION

Currently the mechanisms of chemical decomposition of a great variety of medicinal and food products are well known, and many methods are applied to prevent theirs degradation, the loss of properties and dangerous transformations. Oxidation and hydrolysis are the most frequent chemical reactions affecting the efficiency of medical drugs, the main factors which can influence the occurrence of undesired modifications being light, heating (avoid the temperature values higher than the superior allowed limit), humidity (storing in spaces with no more than 60% relative humidity) and atmospheric oxygen [1]. In this context, due to their crucial role, a particular emphasis is given to the ambient conditions. Consequently, strict requirements regarding preservation conditions of different categories of such goods were imposed.

For most medicines, the superior limit of temperature is 25 ^{0}C, but it can be extended in some cases up to 30^0 C. On the other part, there is the category of refrigerated medicines, which have to be stored at temperatures between 2 ^{0}C and 8 ^{0}C; the permanent maintenance of the temperature values between the previous last limits during all transportation and storage operations is known as cold chain. A separate category is represented by long term frozen products, such as some vaccines which, in some circumstances, can be transported respecting the cold chain conditions, but must be stored at about – 20 ^{0}C. Though, it must be mentioned that here are vaccines needing protection from both excessive exposure to cold and heat [2]. In order to maintain the efficacy of medicines and to avoid considerable costs and responsibilities consequent to their invalidation before the expiry date, set standards for the storage and transportation of medical drugs must be respected in detail. The practical implementation of the corresponding procedures plays a very important role during the whole time-critical and dynamic transfer process of medical drugs.

The term cold chain refers to a supply chain where the temperature of products being delivered must be maintained in a controlled range. A typical range for pharmaceutical goods is 2 ^{0}C to 8 ^{0}C degrees, but specific temperatures can vary depending on the actual product. Additional environment parameters can also be required but are more typical to fresh products than pharmaceutical products. Due to inadequate temperature management, products valued at millions could be lost or worst the life of patients could be put in danger. A typical cold chain from the manufacturer to end uses is presented in *Fig. 1*.

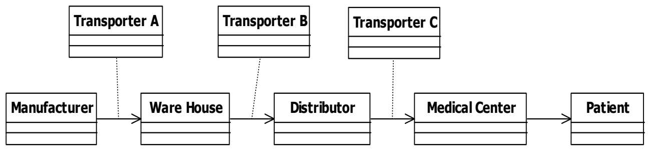

Fig. 1. A cold chain from the manufacturer to end uses.

Temperature and other attributes are required to be stored while the product is moving in the supply chain from manufacturer to patient to ensure product quality and for regulatory compliance. The process of storing and collecting these data is currently very fragmented and unregulated.

It must be mentioned that the monitoring process of the medicines, with an accurate and correct registration of all storage and transport phases from source to destination is complex and difficult taking into account multiple conditions and factors. This system must be conceived to track the inherent different temperature zones and the potential critical control points. It implies not only the fulfillment of the set of specific requirements by the chosen of appropriates warehouses, utilities and transport means and routes, but also a reliable and precise climate monitoring of different existent temperature areas, the design and implementation of a safe and efficient measurement data monitoring system.

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During the last years, many authors and companies proposed different solutions to improve transport, storage and handling of medicinal products and to implement effective management strategies for this type of processes [3]. Most specialists in supply chain logistic management consider big data analytics as an efficient possibility to improve the efficiency and to reduce the costs [4].

As a promising result of an inspired combination of existing technologies, Blockchain can be viewed as a sensible and effective option to respond to some main requirements of these type of applications. A distributed ledger or blockchain 1is a distributed database that consists of a data model that captures the current state of the ledger, a language that handles transactions and change the ledger state and a protocol that is used to build consensus among nodes participating in the network about what transactions to be accepted in the network.

By using distributed ledger technologies is possible to improve the processes part of the cold chain, to store monitoring data near real-time, to identify problems as they appear and to take corrective actions immediately. Since data cannot be changed after being saved in the blockchain, it can be used for compliance and audit actions. Also, blockchain technologies offer a new way to provide a trustee environment for IoT (Internet of Things) devices (used for collecting environment data) without the need to set-up and configure complex and expensive IT (information technology) infrastructure. Some processes can be automated in order to speed up the processing time in the intermediate steps.

In this paper an application framework is proposed for cold chain management, which will deliver information to all stockholders during the distribution phase of pharmaceutical products. The solution is based on Hyperledger Sawtooth distributed ledger framework, which has been extended with a custom transactions family and a sensors gateway for automatically collecting data from temperature tracking devices.

In the first part of the paper we explore classic cold chain management solutions and we identify aspects which makes pharmaceutical cold chain use case a good candidate for implementing a solution based on distributed ledger. We then compare various distributed ledger frameworks and present advantages and disadvantages of each of them. In the second part of the paper the proposed solution is presented, including architecture and main functional blocks.

II. State of the Art

In [5] is proposed a new type of distributed public database (ledger) that maintains a list of transaction in a secure way, preventing alteration of past data. Each transaction is signed by an issuer and submitted to the ledger network. Transactions are collected into blocks that are validated by third party (miners) and stored in the ledger. Once a block is validated it is broadcasted to all network participants, each of the participants maintaining a copy of the ledger. One common application for distributed ledger as envisioned in [5] was creation and management of custom currencies and financial instruments – Bitcoin is one such example which is the first digital currency issued and managed using blockchain technology. Another application is "smart contract" – a system which automatically moves assets between owners according to predefined rules making possible the creation of so called decentralized autonomous organizations (DAOs) [6]. The concept of smart contract was first introduced in [7]. At high level, it can be described as a program executing a set of operation on the blockchain when a number of conditions are met. A smart contract is identified by a data model and a set of instructions to be executed when certain conditions are met.

Beginning with 2016, distributed ledger technology has started to become popular and new applications of this technology for the enterprises to be envisioned. One important development in this area was the creation of Hyperledger project by Linux Foundation with the objective of developing enterprise distributed ledgers capable of supporting global business transactions by major technological, financial and supply chain companies. Under the Hyperldger umbrella there are currently under development the following frameworks: Fabric developed by IBM, Sawtooth developed by Intel and Corda developed by R3.

In [8] and [9] blockchain technology is analyzed and use case scenarios are identified in many financial and non-financial sectors. One of the identified sectors is the pharmaceutical sector where blockchain can introduce transparency and trust to the supply chain. As concluded, the technology offers data security and cost-effective transmission of transactions in peer-to-peer networks with no central system.

In [10] a decentralized traceability system based on IoT and blockchain is proposed for the food industry. The system relies on IoT devices (RFID, WSN, and GPS) devices to collect and transmit data to a BigchainDB ledger database. All actors participating in the process are required to be registered and receive unique private keys to sign the transactions. In [11] proposes a hybrid architecture for supply chain management based on a set of private distributed ledgers for storing sensitive customer information and a public ledger where a hash of each private event is stored along with the monitoring events.

In [12] is briefly presented LifeCrypter, a blockchain solution to increase supply chain security for the pharmaceutical industry. Each item is attached an identity tag which allow for virtual ownership of the product to be transferred while it moves in the supply chain. Transactions are verified and validated by means of smart contracts.

III. Sawtooth Distributed Ledger Network

In this section are described the main characteristics of the Sawtooth Distributed Ledger (SDL) in order to justify the decision to choose it for implementing the cold chain solution. SDL is a permissioned distributed ledger solution where participant nodes must have a clear identity and be authorized in order to be able to join the network. A number of read\write policies can be defined in order to refine rights of the participants. In contrast with a permissionless network (like Ethereum or Bitcoin) where any node can join a network, in the case of permissioned network, only approved participants can join and participate in the process of validating the transactions (smart contracts) which have the effect of changing the global state of the network.

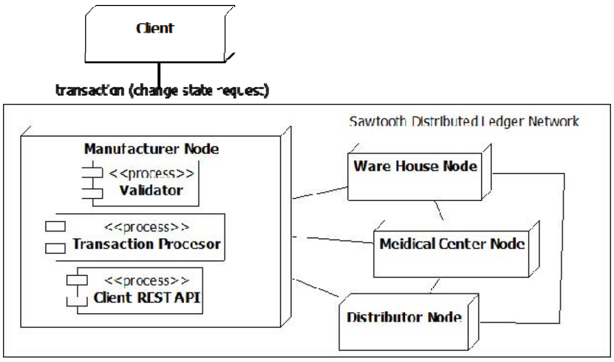

Fig. 2. Cold chain validators network.

SDL uses Proof of Elapsed Time (PoET) [13] consensus algorithm in order to make an agreement between participating nodes and change the global state. Since PoET is a kind of a lottery based algorithm, scalability of the network is theoretically unlimited and does not require expensive computation algorithms to be executed by participating nodes. Using this algorithm, the transaction validator with the shortest waiting time is selected to execute smart contracts and publish change in the global state of the ledger (e.g. record new sensors data readings).

In SDL, the concept of smart contract has been implemented through transactions and transaction processors.
A transaction defines what changes should be applied to the network. In an enterprise private blockchain is important to control what operations can be applied and in what context. To resolve this problem, SDL implements the concept of transaction families which allows designers to specify exactly what operations are permitted and in what conditions. In the cold chain network for example a sensor device will not be able to change the ownership of a product, but only to report sensor readings.

One of the unique characteristics of SDL comparing with the other ledger frameworks is the concept of transaction batches, which make possible for a client to submit multiple transactions with a single command, to process them as a whole and then to confirm or reject the entire batch. A batch represents an atomic change in the system. In the context of the proposed cold chain solution this is particular useful since sensors can generate a large number of readings and submitting those readings one at a time can create high loads on the network. By collecting multiple reading points in a single batch and submitting the batches at periodic time intervals or when enough data is collected, the load can be greatly simplified.

The requirement for an enterprise entity to join a cold chain network in order to access the management interface or to provide a way for sensor device to report the read data will be to instantiate and join in the network with a Sawtooth node.

IV. HIGH LEVEL ARCHITECTURE OVERVIEW

In this section it will be presented the architecture of the proposed cold chain management platform. The platform provides the necessary infrastructure to track the pharmaceutical assets while they are transported from the manufacturer to the end user. Each physical asset (or product) will have a sensor attached to it from the moment is manufactured and will have a corresponding record associated with it in the blockchain network.

A. Architecture layers

As shown in Fig. 3, the designed system consists of an infrastructure layer represented by the SDL network, middleware layer represented by software components which facilitate communication with SDL (SDL clients) and application layer where Cold Chain Management Application and Sensor Application are located.

Parts of the application layer are Cold Chain Management application and Sensor application. Sensor application is the component responsible for reading environment data. The sensor application is embedded in the physical sensor attached to the tracked product. The hardware and software implementation detail of the sensor device attached to products are not in scope of this paper and is assumed it can use some wireless technology (Bluetooth, Wi-Fi, ZigBee, NFC).

Cold Chain Management application is a web based application which allows users to register new tracked products, to monitor products while they are shipped and to register transport transactions for tracked products (ownership change).

Middleware layer is the interface between SDL network and external applications. Additionally, the middleware can provide supplementary security for the network and the data it transports.

At the Sensors Gateway level data received from sensors are buffered and transaction batches are built. Transaction batches are then submitted to the ledger network using Sensor Transactions Client. Sensors Gateway implements required communication protocols and provide the required physical interfaces to facilitate communication with the sensor devices.

Management Gateway is the interface between Cold Chain Management Application and the SDL network. It facilitates submission of the transactions related to changing the owner (custodian) of the product while they are transported from the manufacturer to the end-user and to read the global state (sensor readings, ownership transitions, current owner). It also provides alarms and events handling mechanisms for cases when sensor reports data outside of the specified limits.

Infrastructure layer is represented by the SDL network composed of Sawtooth specific processes which are joined in a peer-to-peer network where the state of the system (product associated sensor readings, assets current owner ship and history of all ownership changes) is kept as a decentralized database (a copy of the state is kept in each validation node). Each participant in the network verifies transactions and is engaged in a protocol that ensures universal agreement on the

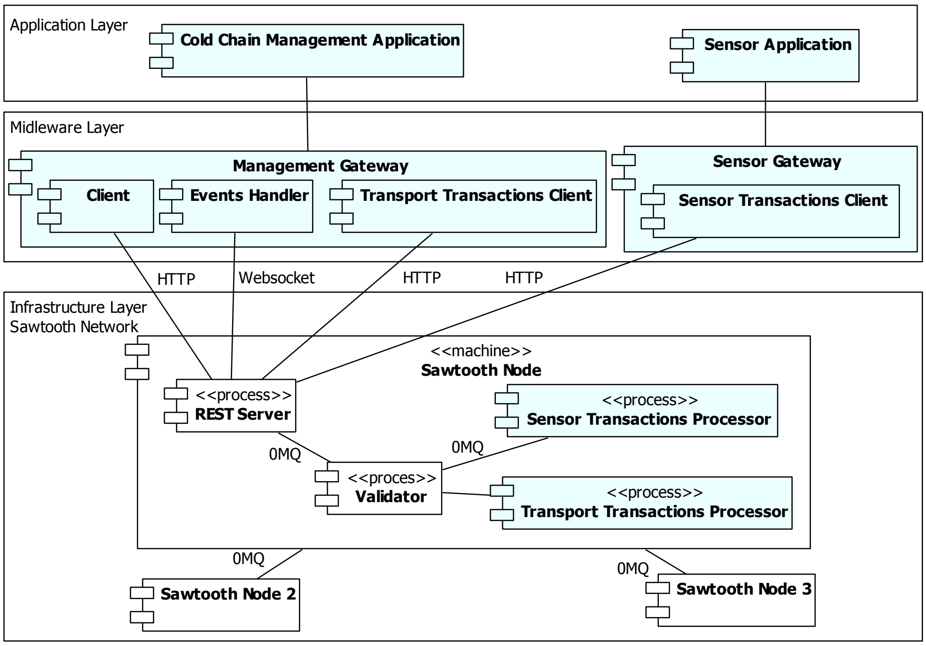

Figure 3 – High level architecture.

state of the ledger [14]. At the infrastructure level are located Management Transaction Processor and Sensors Transaction Processor. These two components implement the cold chain transaction family specifications and execute specific actions when transaction batches are submitted by clients.

B. Cold Chain Transaction Family Specification

A typical application developed on top of the Hyperledger Sawtooth requires defining transactions programs and implementing transaction processors and client programs. When a transaction family is defined in the Sawtooth network, the following components must be specified: state – it describes how data is stored and addressed in the blockchain; addressing – it defines the addressing schema; transaction payload – it describes the request payload which will be stored in blockchain; execution – it describes the execution logic implemented by transaction processors.

The data model used for storing cold chain data into Sawtooth blockchain is described by Cold Chain Transaction Family (CCTF) specification. CCTF stores the following object types:

Organization:

- organizationId – unique id of the organization
- name
- address
- type – e.g. company, warehouse, manufacturer

Product:

- productId – unique id of the product to which the tracking sensor is attached
- name
- ownerId – unique id of the owner
- sensorId – unique id of the sensor attached to product; is reporting reading data
- state – active, locked
- lastIndex – total number of written data records. This increment is used to calculate the address of the next written data record

TrackingData:

- sensorId
- productId
- index – an increment which identifies the current written record
- readingTime – the time when data has been read
- type – type of the reported value (temperature, humidity, etc.)
- value – actual value sent
- lat, lon – reported latitude and longitude when the value was read (if available)

Each record is stored at a specific index which is incremented and stored in the associated Product object. In this way, when a new reading should be stored, the storing address is computed based on the next available index (see addressing schema for more details of how the address is computed).

Addressing Scheme

```
{
  family_name: "cold_chain"
  family_version: "1.0"
  encoding: "application/json"
}
```

The CCTP uses two namespaces for storing cold chain objects. Each object type defined in the previous section (Product and TrackingData) will be stored in a separate namespace:

- cold_chain.product
- cold_chain.trackingdata

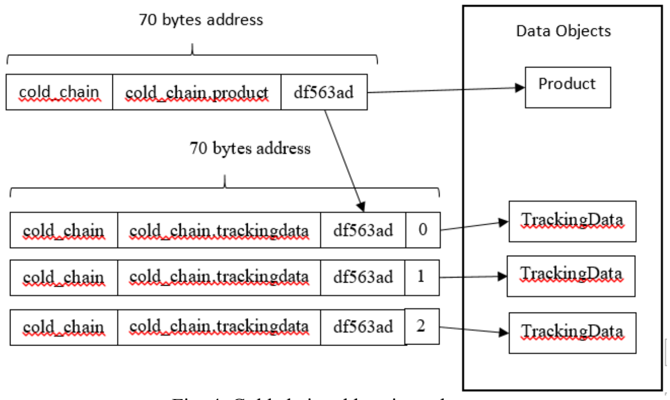

Fig. 4. Cold chain addressing schema.

For the cold-chain.product namespace, addresses are generated as follows:

$$sha256(\text{'cold\_chain'})[0:6] + sha256(namespace)[0:60] + sha256(sensorId)[0:4] \quad (1)$$

being composed of the prefix represented by the first 6 bytes of the sha256 of the family name, followed by first 60 bytes for the sha256 of the name space and suffixed by the first 4 bytes of the sha256 of the sensorId.
For the cold_chain.trackingdata namespace addresses are generated as follows:

$$sha256(\text{'cold\_chain'})[0:6] + sha256(namespace)[0:4] + sha256(sensorId)[0:10] + sha256(index)[0:50] \quad (2)$$

When a product is first recorded, a Product object is saved in cold_chain.product namespace and lastIndex initialized to -1. Based on the lastIndex, the transaction processor will be able to compute the next address where to store the data sent by sensors. The product object is uniquely identified by the sensorId attached to the product.

When a data reading is reported by a sensor, based on the sensorId, the transaction processor will find the corresponding Product object and will read the lastIndex. Then it will compute the address where the data must be stored by composing the address using the cold_chain.product addressing scheme presented above. After a write is performed successfully, the lastIndex in Product object is incremented with 1.

C. *Transaction payload*

Transaction payload defines the content of the message sent by the client to the transaction processor. There are 2 types of operations which can be performed:

Operations performed at the product level:

- create a new product record – this is the first step required so that when a sensor reading is received to be automatically associated with an existing product (the matching is done by sensorId which is referenced in the product object;
- change product owner – this operation is performed by operator manually from the user interface or by using some automatic mechanism which identifies the ownership change;
- change product tracking state – this operation is used to lock or unlock a product for further sensor readings. When product is locked no sensor readings can be stored;
- read product details – return details corresponding to a product

Operations performed at the sensor level:

- save data reading – this operation will store in the TrackingData object associated with Product object as a reading or a list of readings received from the sensor
- read data – read data stored for a particular sensor and product

V. Implementation Details

In accordance with the proposed architecture, the main point of interaction between a user and the Sawtooth Distributed Ledger is the Cold Chain Management Application. The main programming language used to build this client is Javascript. Sawtooth packages a versatile Javascript SDK (software development kit) that gives a developer all the needed tools to develop the desired functionality.

The client is lightweight and does not contain any business logic. The client has two functionalities: to read the state of the blockchain and display it in a human readable form; to create valid transactions, batch them and then submit those batches to a blockchain validator. Each transaction contains a payload, data which is transmitted to the validator in order to modify the state of the blockchain. The payload is formatted as a JSON and has the following structure:

{

"action":"read-sensor-data",

"payload":{

"value":"10"

}

}

The action field represents a type of command that can be given to the validator in order to modify the state of the blockchain (e.g. create, transfer, initialise). The payload field represents the data needed in order for the action to be executed successfully. This simple approach gives enough flexibility to the client in order to send multiple types of data to a validator. The validator interprets and processes the payload through custom transaction processors.

The proposed transaction processors (Sensor Transaction Processor and Transport Transaction Processor) are built in Java using the provided Sawtooth SDK. It's main purpose is to implement the business logic at validator (blockchain node) level and to modify the state of the global state accordingly (save sensor readings and transport transactions).

The first operation that it does is to decode the payload data received from the client. Each payload needs to have an 'action' defined as proposed in the above JSON structure. If the condition is not satisfied, an exception will be thrown and the transaction will be invalidated as well as the batch that contains it. There are a series of methods implemented in the transaction processor in order to determine if the data received from the client is in the correct format. If the payload satisfies these conditions, then data will be used in order to modify the state of the blockchain (e.g. save a new sensor reading).

VI. CONCLUSIONS

In this paper it has been presented a platform for cold chain management based on distributed ledger technologies. A custom transaction family has been proposed in order to store and track delivered products and associated environment data.

The Solution is based on the Hyperledger Framework which has been extended with a custom transaction family in order to keep track of information. Being a permissioned network, Sawtooth allow trusteed enterprises to collaborate and to track products using a scalable, yet, not very complex or expensive infrastructure. Participation in the cold chain network requires each participant to join the network with one validator node.

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