EXPLORING DAG-BASED ARCHITECTURE AS AN ALTERNATIVE TO BLOCKCHAIN FOR CRITICAL IOT USE CASES

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ABSTRACT

This paper analyzes the Directed Acyclic Graph (DAG)-based architecture as an alternative to Blockchain technology for critical Internet of Things (IoT) use cases. The speed of transactions and the scalability of Blockchain technology are limitations for critical IoT applications such as vaccine cold chain monitoring. A pilot project has been developed to analyze the speed of the DAG architecture. It simulates monitoring the vaccine cold chain, recording temperatures and alarms. Using the same architecture, two cases with different IoT connectivity technologies in the pilot project are defined: LoRaWAN and Sigfox. The results of these two cases show the comparison between both technologies that show that the DAG architecture can provide the necessary time delays for critical IoT use cases. The main limitation found after the execution of the two cases of the pilot project is related to the need for worldwide coverage of the communications technologies used. For this reason, the study of communications through IoT satellites with global coverage is proposed as future work.

KEYWORDS

Distributed Ledger Technology, Blockchain, Directed Acyclic Graph, Internet of Things, IOTA

1. INTRODUCTION

Distributed Ledger Technology (DLT) is a decentralized distributed ledger technology that enables transactions and assets to be recorded, authenticated, and processed on a distributed ledger [1]. Unlike traditional distributed database architectures [2], DLTs are decentralized, trusted in untrusted environments, and cryptographically encrypted. The most well-known property of DLTs is their immutability, which means that all the information stored in them cannot be modified, deleted, or altered. DLTs also offer several different architectures, such as Blockchain and Directed Acyclic Graph (DAG) based architectures [3]. In this sense, although Blockchain is presented as a handy tool for implementing various examples in all areas of Industry 4.0 and the Industrial Internet of Things (IoT) in general, it does not always guarantee the best solution to cover the needs and requirements of the use cases.

One of the main requirements for critical IoT use cases is the speed of transactions, both for recording data and alarms in real-time, as well as for micropayments in cryptocurrencies between machines [4]. Likewise, registering sensor data in a DLT must be done immediately so users can

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have this information as soon as possible. However, two of the Blockchain's limitations are the speed of transactions and the low scalability [5]. For this reason, this article analyzes the architecture based on DAG [6] as an alternative in IoT that guarantees the speed of transactions in cases where this is critical for correct operation.

A pilot has been developed to analyze the speed of DAG-based DLT architectures. It simulates monitoring the vaccine cold chain and recording temperatures and alarms in a DAG. Given this critical nature, the information and alarms must be recorded practically in real-time. The users (in this case, hospitals, pharmaceuticals, or vaccination centers) can access temperature and alarm data when they occur, thus acting as soon as possible to avoid breaking the cold chain and discarding the monitored vaccine batch.

2. Critical Case: Cold Chain Of Vaccines

Historically, the control and monitoring of the cold chain have been carried out manually without significant changes. For this, labels with chemical reagents or thermometers have been used that recorded the break in the cold chain, but their reading or verification was always carried out manually [7]. Therefore, in most cases, it was impossible to verify whether the cold chain had been broken until the vaccines arrived at the health center, without having the possibility of checking the temperature recorded throughout the entire chain. Likewise, the current vaccine cold chain verification system, which is not connected or sends temperature or cold chain break data in real-time, and does not record these data in DLTs, en-tails a high percentage of batches of vaccines in refrigerators that are lost due to break in the cold chain during transport [8].

Control of the cold chain of vaccines requires knowing and having visibility of the temperature in real time [9], as well as alarms that indicate an excess of temperature or a break in the cold chain of vaccines at the instant they occur. In order to corroborate the correct operation of the DAG and examine the registration times in the proposed DLT, the experimental test of two environments that present different IoT platforms and Low-Power Wide-Area Network (LPWAN) communications has been carried out, such as LoRaWAN and Sigfox.

An experimental test was used as the research method. The test aims to analyze the speed of DAG-based DLT architectures in monitoring the vaccine cold chain. The experimental test simulates the recording of temperatures and alarms in a DAG, with two different IoT connectivity technologies: LoRaWAN and Sigfox. The test results compare both technologies to demonstrate if the DAG architecture can provide the necessary time delays for critical IoT use cases.

2.1. Proposed architecture

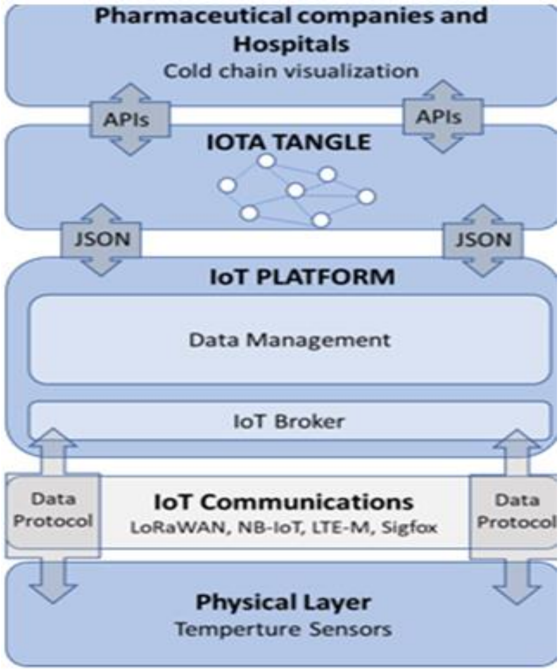


Figure. 1. Architecture of the pilot project used For Lorawan And Sigfox Cases

The architecture proposed to develop the pilot project is presented in Figure 1. It is used for the two cases with different connectivity technologies: LoRaWAN and Sigfox. Each of the defined layers fulfils a specific function in the process of collecting, processing, and displaying temperature data and alarms from the installed sensors:

- **Physical Layer:** Houses the IoT sensors that measure the temperature inside refrigerators or cooling boxes. These devices, characterized by low consumption and ARM architecture, use LPWAN connectivity to transmit the temperature to the IoT platform periodically. The pilot project will use temperature sensors measuring between -80 ºC and +70 ºC and LoRaWAN and Sigfox communications from the manufacturer SLB System. Also, QR codes are included that are placed on the fridge and on the sensor itself, and that will be redirected by reading them to the web or address of the DAG viewer that shows the recorded data.

- **Iot Communications:** This layer is responsible for transporting the data from the sensors to the IoT platform. Depending on the IoT device and the communication technology, different data transport protocols exchange information between the IoT platform and the sensors.

- **Iot Platform:** On it, the ingestion and processing of the data from the sensors installed in the vaccine refrigerators is carried out. When the platform receives the temperature data from the sensors, the information is automatically recorded in the DAG to know the temperature recording times or the alarms in said DLT.

- **Dag-Iota Tangle:** It is the DLT where the temperature sensors and alarm information are stored. It allows open access to pharmaceutical companies, hospitals, or health centers to view the real-time status of vaccines or the cold chain.

- **Visualization Applications:** Layer for the software tools that allow the visualization of the temperature data and alarms registered in the IOTA Tangle.

2.2. Case 1: Lorawan

This first case uses SLB Systems sensors and a private LoRaWAN network at 868 MHz with a LoRaWAN gateway from the manufacturer Multitech model Conduit AP. From this gateway, an IPsec VPN tunnel is established to an instance of Microsoft Azure where the Chirpsctack server is located, in charge of managing and administering the private LoRaWAN network. IoT devices and LoRaWAN gateways are enlisted from this server, and the initial ingestion of temperature da-ta sent by the LoRaWAN gateway and its processing and storage is done on the Thingsboard IoT platform. Instead of storing the data internally, they are upload-ed through a Rest API to the DAG to the corresponding address where the temperature data of each sensor is saved as a transaction in the DLT with value 0 and the "Message" field of the transaction to save the value of the temperature measured by the sensors. Once the information is stored, it can be accessed immediately by hospitals, pharmaceutical companies, or patients.

2.3. Case 2: Sigfox

In this second case of the pilot project, Sigfox connectivity technology and the IoT platform of SLB IoT Site, hosted in a public cloud in Germany, have been used. The same SLB Systems temperature sensor model has been used, but with Sigfox connectivity, which makes it possible to use an operator network and not have to implement a private network, contracting only connectivity with the Sigfox operator. The sensor periodically transmits the temperature of the vaccines or refrigerators through the Sigfox connectivity to the nearest base station of the Sigfox operator. This data is immediately available on the Sigfox backend, which integrates with the IoT platform of the SLB IoT Site to collect the temperature data. Instead of storing the data in an internal database, through an API, a transaction is performed with value 0 and with the temperature value in the message field to the DAG, to save the temperature data in the corresponding address for the sensor. Similarly to the previous case, once stored, different users (for example, hospitals, pharmaceutical companies, or patients) will have immediate access to the information stored in the DAG. This approach allows effective traceability of vaccines and guarantees their integrity during transport and storage, which is critical for the protection of public health.

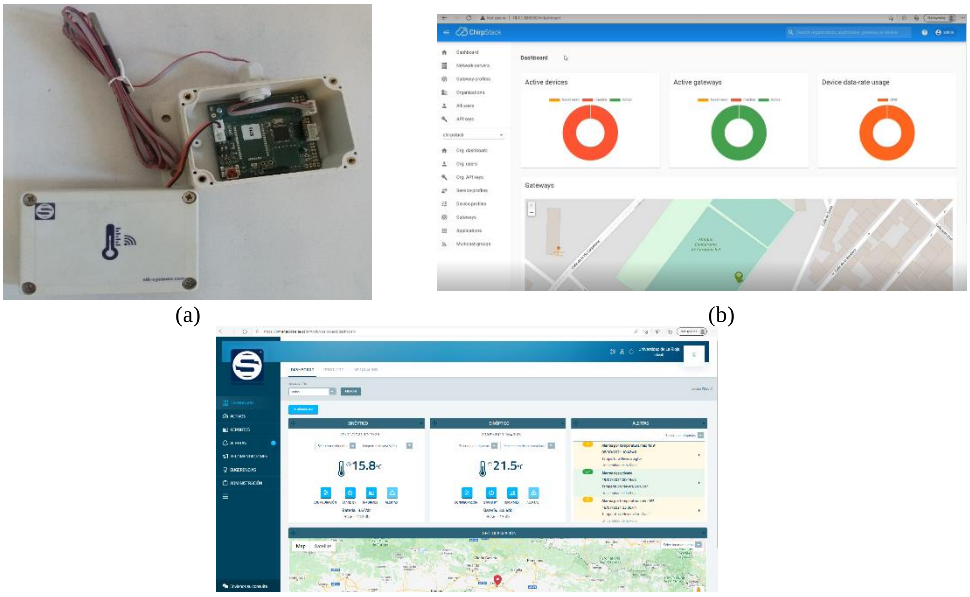
2.4. Administrative Management

Regardless of the architecture and technology used, a public or private organization or administration is responsible for coordinating the implementation of a cold chain monitoring solution for a health system at a regional, national, or international level. This coordination must include the definition of the technical requirements of the IoT temperature sensors, the connectivity protocols allowed for communication with the IoT platform, and the information exchange protocols between the IoT platform and the sensors. In addition, it is necessary to generate addresses in the DAG to store the information, register the IoT sensors in the IoT platform, and associate them with an address in the DAG. Also, the methods must be defined to access the cold chain information stored in the DAG, manage and centralize all the information received from the IoT sensors, and guarantee the operation of the solution from the moment the information is received from the sensors until it is stored in the DAG. Lastly, it is essential to coordinate with the logistics teams of the pharmaceutical companies and the healthcare teams in charge of receiving and maintaining the vaccines to ensure the efficacy and safety of the system.

The initial sensitization of refrigerators and other vaccine refrigeration systems should fall to pharmaceutical companies, replacing the temperature control systems used by IoT temperature sensors. They will be responsible for generating the QR code placed on the fridge and the sensor itself. The rest of the process would remain as currently used, with the sensor installed inside the refrigerator or refrigeration system. Vaccine transport and storage need not undergo any operational changes.

3. RESULTS

The mentioned cases of the pilot project (Figure 2) have been running for 15 days. During this time, messages from the sensors have been transmitted to the platform with 100% success in both cases. The response times, which represent the speed of the transaction and depend on the number of hops between the backend where the IoT platform of each of the pilots is hosted, have been analyzed in depth.



(a) (b) (c)

Figure 2. Experimental setup: (a) Sensorization, (b) Dashboard of Chiprstack Network Server from Thingsboard and (c) IoT Site platform from SLB Systems developed

Table 1 shows an exhaustive statistical analysis of timed delay in two communication protocols: Sigfox and LoRaWan. These data result from time measurements in seconds obtained in various observations. In the case of the Sigfox protocol, a minimum value of 1 second is observed, while the maximum reaches 5 seconds. This generates a 4 s time range where the events unfold. In terms of mode, the most frequent value is identified as 1 second, which reveals a clear trend in the data. With the measures of central tendency, it is determined that the mean for the Sigfox protocol is 1.76 s. This figure allows to understand the average value of the delay times. On the contrary, the median, representing the midpoint in an ordered data set, is at 2 s. This value gives a more precise view of the central location of the data. To evaluate the dispersion of the data, the variance, and the standard deviation are calculated.

The variance obtained for the Sigfox protocol is 1.0233 s squared. This value shows how the data moves away from the mean and gives us an idea of the present variability. Likewise, the standard deviation, which is the square root of the variance, is calculated to be 1.0116 s. This value indicates how much the data is spread out about the mean. In addition, the asymmetry of the data distribution is analyzed. In the case of the Sigfox protocol, an asymmetry value of 1.7265 is obtained. This figure reveals a skewed distribution to the right, meaning that high values can affect the mean and move it away from the central tendency. This information, collected visually, is also presented in Figure 3.

Table 1. Statistical analysis of timed delayed in the two cases of the pilot project.

Evaluated Statistics	Sigfox	Lorawan
Minimum	1	1
Maximum	5	8
Range	4	7
Mode	1	1
Mean	1.76	2.72
Median	2	2
Variance	1.0233	3.1267
Standrad deviation	1.0116	1.7682
Asymmetry	1.7265	1.2659

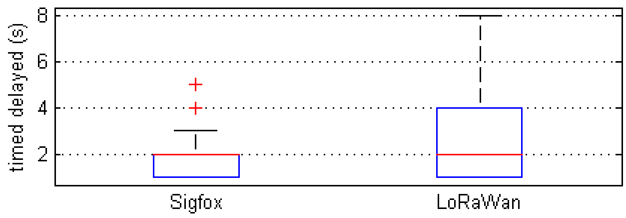


Figure 3. Probability distribution of the data recording time in the DLT using Sigfox and Lorawan

Although Blockchain is still the most widely used DLT today, it is important to highlight the existence of other architectures, such as IOTA, which has been specifically designed to address certain problems associated with the use of the IoT. Compared to Blockchain, the DAG architecture stands out for its high scalability since Blockchain blocks act as bottlenecks that can generate network congestion and delay transactions. DAG greatly mitigates this problem, allowing greater transaction processing efficiency [10]. Another advantage of DAG is its lower energy consumption in terms of computing resources, significantly reducing network maintenance costs [11]. In addition, in DAG, the payment of commissions per transaction is not required [12] since there are no miners involved in the validation of transactions, and they are processed with greater speed [13], which improves the ability of the network to record and manage large volumes of data. The results obtained in these pilots show that the DAG architecture, regardless of the communications protocol and the IoT platform used, can provide the necessary speed and scalability for critical IoT use cases.

This solution focuses on taking advantage of the capacity of satellites dedicated to IoT communications to establish broader and more reliable connectivity. Using IoT satellites seeks to guarantee global and more extensive coverage, thus allowing data exchange in areas where terrestrial connectivity is insufficient. To adapt the existing architecture to this emerging trend, a ground station would be required, which facilitates communication between IoT devices and satellites [14]. The IoT satellite architecture with IOTA Tangle is presented in Figure 4.

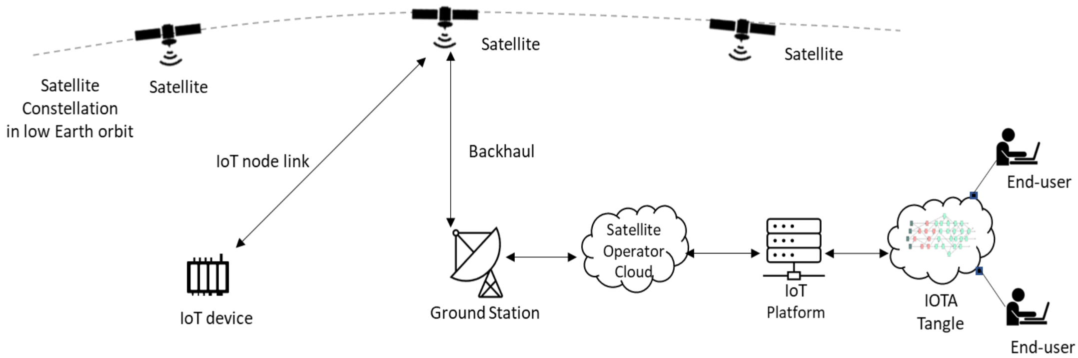


Figure 4. Iot Satellite Architecture With Iota Tangle

In vaccine supply chain monitoring with satellites, temperature data from IoT monitoring devices is transmitted through LPWAN communication channels to a satellite. The satellite serves as a relay transmitting the data to a ground station. Subsequently, the ground station forwards this information to an IoT platform for systematic processing. The processed data is then securely recorded on the IOTA Tangle, ensuring a secure and immutable storage mechanism.

4. CONCLUSIONS

The study focuses on the feasibility of monitoring the cold chain of vaccines through DLT technologies based on DAG architecture as an alternative to Blockchain to solve the lack of information in transport. The main improvements obtained in this critical case are remote and real-time monitoring of the temperature throughout the cold chain, secure and immutable storage of data, checking the status of the cold chain using QR codes, and detection of breaks in the cold chain during storage or transport. This solution will reduce the number of vaccine consignments spoiled by cold chain breaks, increase the general availability of vaccines for patients, and have centralized management and monitoring of the vaccine cold chain with reliable information stored in the DLT of the IOTA DAG. Furthermore, this solution can be used for similar use cases in healthcare and food environments. The work presents two cases of a pilot project based on the use of Sigfox and LoRaWAN and statistically evaluates the time delay that occurs due to the backend of the IoT platform used. Finally, it is worth mentioning that one limitation of the pilot project is the lack of global coverage in all cases, which hinders the continuous transmission of data over extended periods. As a suggestion for future work, the utilization of IoT satellite communication technologies is proposed to address this limitation.

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