Design and Implementation of an Automated and Decentralized Pollution Monitoring System with Blockchains, Smart Contracts, and LoRaWAN

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***Abstract*—This work proposes an IoT- and Blockchain-based, distributed system, for automated measuring, storing, and monitoring of water and air quality in environments such as lakes, mountains, urban areas, or factories. Comparable state-of-the-art solutions, require human interaction to access the data or require high power consumption or space requirements, or they are based on centralized architectures. The proposed pollution monitoring system here, on one hand, employs LoRa to address the high power consumption and long-range transmission challenges of IoT protocols. On the other hand, it is designed to be fully decentralized by using the Ethereum Blockchain to store and retrieve the data recorded by IoT sensors. Thus, data integrity is provided without the need for a Trusted Third Party (TTP) and data is collected and captured automatically without any manual operations needed. Observations on the four different types of sensors for measuring Potential Hydrogen (PH), Turbidity, Carbon monoxide (CO), and Carbon dioxide (CO2), revealed a high accuracy with the expected time-lines of measurements, non-falsified experimental values collected and can be used as reliable evidence of presence of pollution.**

I. Introduction

Exponential global population growth since 1950 [11] has raised serious environmental issues such as global warming and natural resources depletion. Drinkable water sources, clean air, wild life and human beings life are endangered by civilization and current industrial activities. Even though some international authorities or even public and independent communities spent lots of effort in protecting the Earth from human-activity-triggered environmental problems, still there is a need for human-independent solutions which, automate the process of monitoring water and air quality to use the results of monitoring as a drive against pollution generators.

State-of-the-art pollution measuring and monitoring solutions are based on applications which, require direct human interaction and they are designed based on centralized architectures which, mandate users to communicate with a central entities for storing and retrieving data as known as, Trusted Third Parties (TTP). Main problems with previous solutions can be listed as implementation cost, high space requirements, mobility, human-interaction dependence, centralization, high power consumption, lack of public access, and low communication range of sensors.

By heading towards 5G, Internet of Things (IoT)-based solutions are evolving which, lead in developing less specious solutions that can support higher ranges of communications without the need for human interaction in reading the data captured by sensors. In this work, to solve the problem of single point of failure (centralization) a blockchain-based solution is proposed which, automatically integrates the data received from IoT sensors into the Ethereum Blockchain (BC). BC provides solutions for storing back-linked blocks of data in a decentralized and distributed fashion. For the fist time, by using BC-based applications, trust to validity of stored data without the need for a centralized authority became possible. Also, the data is BC is publicly accessible.

This paper is organized as follows, Section II reviews related work. In Sections III and IV design and implementation details of the proposed pollution monitoring system are explained. Evaluation results are described in Section V and conclusion is presented in Section VI.

II. Related Work

There have been abundant theoretical research and proposed solutions in the area of pollution monitoring with different approaches. Some instances of these solutions are the methods used by *Queensland government* [2], *Semtech* [21], and *Aeroqual* [4]. Also, modern laboratories for pollution monitoring collect the data by using sensors which are placed near/in the examined area. This area might be located in far distance from the laboratories and maintenance of sensors on regular basis and accessing the sensors to read the data is not always feasible.

Along with the distance between the located sensors and data centers, main concerns in developing such a Pollution Monitoring System (PMS) can be listed as data accuracy, sensors power consumption (*i.e.,* battery life time), size of the sensor nodes, need for human interaction for accessing the data recorded by sensors, communication protocols used for connecting sensors and application servers, and following a centralized architecture. In the following parts of this Section,

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an overview of most suitable communication protocols will be explained.

For small area communications it is possible to use sensor modules with WiFi or Ethernet adopters but, these communication methods are not proper for long distance communications according to their high power consumption. There are some methods to reduce the energy consumed by sensor nodes such as using DARAL [13] - charging sensor batteries over WiFi network - but DARAL restricts the communication range of sensor nodes [8]. Another solution is the Low Power Wide Area Network (LPWAN) protocol which, helps modules to communicate over a long distance using a comparatively small amount of energy. Using LPWAN increases the battery life and reduces the overall maintenance cost of IoT devices.

Semtech is using LoRaWAN (LoRa) [5] as the communication protocol between sensor nodes to the LoRa gateway. Other companies are investigating on other upcoming protocols such as LTE-M and Sig-Fox. In Table I, a comparison between communication protocols is presented. According to the need for long range communications, high energy consuming protocols or low range protocols (*e.g.*, WiFi, Ethernet, Zigbee) are eliminated from the comparison shown in this Table.

TABLE I
COMPARISON OF THE COMMUNICATION PROTOCOLS [9], [10], [14], [20], [23]

	WiFi-ah	**LoRaWAN /LoRa**	**SigFox**	**LTE-m**
Requires Gateway	No	Yes	Yes	No, Cellular Network
Data Rate	<347 Mbps	50 kbps	300 bps	1 Mbps
Range	>32 m	15 km	30-50 km	2-5 km
Accessibility	Licensed, Cellular Network Providers	Unlicensed	Unlicensed	Licensed, Cellular Network Providers
Security	WPA/WPA2	AES 128 bit, Encrypting Data at 3 Levels	VPN + SSL Encryption	AES 128 bit

In some of the recent IoT based PMS proposals, BC technologies are used such as the solutions in [1] and [3]. Unfortunately there is no information available regarding the technical details of these solutions.

Selecting the most proper BC plays a critical role in each use case. Transaction validation costs, Block-time, security, scalability, application use case, and supporting Smart Contracts (CS) are some of the factors in selecting a BC. Block-time can vary from almost 0 sec to more than 8 minutes, and transaction validation costs can vary from 0 to more than 10$ depending on the transaction. Scalability of a BC is also a critical aspect as it directly effects the transaction validation rate.

Some BC networks (*e.g.*, Bitcoin) are implemented for specific use cases such as Crypto-currencies (CC) while, others can be employed in various use cases (*e.g.*, Ethereum).

Supporting SC is important as SC are capable of driving data storage in a BC such as in Ethereum BC for various use cases out of the scope of CC.Since data collection from sensors is done frequently, high transaction fees and Block-time make the BC incongruous for this use case. Based on the Table I and comparisons done blockchains, the decision was taken to use LoRa technology as the communication protocol and the Ethereum BC. Sig-Fox as shown in the Table I is a subscription based protocol and other low cost and low Block-time BCs are currently not stable enough to be used in a functional PMS.

III. DESIGN

To provide a solution for addressing the requirements and challenges in developing a PMS explained in Sections I and II, this paper proposes an innovative architecture through concoction of a low power consuming communication protocol which, supports high range communication and a public BC. The proposed PMS follows a layered architecture as shown in the Figure 1. Data is traveled from the IoT sensors to the Web server through the BC or directly through the LoRa network (TTN), to keep the data secure and untampered. WiFi also can be used to connect the sensors to the Internet to access BC from the Sensors layer as well as by the Web Server layer. Once the data is retrieved from the BC it is stored on the Local DB for fast data processing in offline mode.

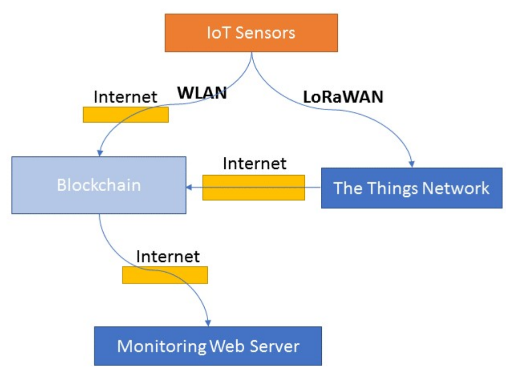

Fig. 1. PMS Architecture Design

The sensor modules play equally important role in energy consumption as transmitting data does. As the size of the module increases so is the battery usage. If the sensors are placed with long distances, changing battery frequently and monitoring the battery status is not a viable option. With LoRa high range of communication becomes possible. However, it supports only very low data rates as shown in table I which, results in elongation of battery life of the sensors.

Ethereum BC supports SC and it also provides light and full clients. One of the major advances of designed architecture is to employ Ethereum Light Client (ELC) [6]. ELC is a specific type of Ethereum node which, only stores and synchronizes the current (recent) transactions and requires less space than

Ethereum full nodes. With ELC, direct transmission of data from the Sensors to the application via BC becomes possible. To the best of our knowledge, ELC is utilized in a PMS for the first time in this work.

IV. Implementation

For collecting the data from the IoT modules, four sensors are connected to an *Arduino Uno* board

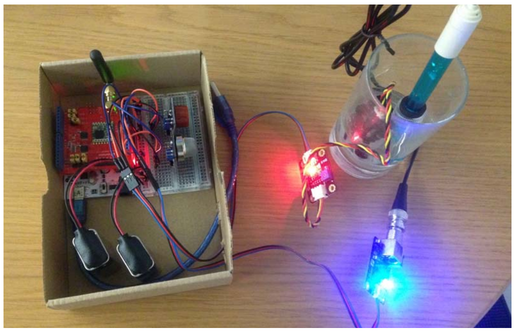

Fig. 2. Prototypical Implementation of a LoRa Sensor Node Including Four Sensors Attached to it

This module transmits the data which is then uploaded into the BC using LoRa gateways. As shown in the Figure 3, the implemented PMS is provides three approaches for selecting communication systems and BC client as following:

1) IoT sensors connected to LoRa boards (LoRa sensor nodes) connected to BC with an ELC installed on the LoRa sensor nodes.
2) LoRa sensor nodes connected to BC with an ELC installed on the LoRa gateway.
3) IoT sensors connected to Full nodes via WLAN or LoRa.

In the first approach, an *Arduino Uno* is accompanying a *Raspberry PI 3* (RPI) with inbuilt WiFi module for connecting to the internet. The RPI is used as a platform for ELC and Arduino Serial port communication. A JavaScript file running on the RPI and with help of NodeJS collects the recently received data by The Things Network (TTN) [18]. TTN decrypts the encrypted data sent from the LoRa sensor nodes. Once the data is transacted by the ELC, it is available on the BC and the pollution data will be accessible over the BC network and in the PMS monitoring web page. Data flow (1) shows the first approach in the Figure 3.

In the second approach, the ELC is installed on LoRa gateways. Every time the transaction is received and decoded by TTN, it is made available for the BC network using the NodeJS & Web3 API installed on the gateway. This way, the data is fully protected and the accuracy is maintained through out the data flow (2) shown in the Figure 3. The collected data from the sensors are transmitted to the gateway then once the gateway receives the data from TTN, it sends a transaction to store data into the BC. The SC already deployed on the BC network helps to check for the violations. The stored data is then used and presented by the web application to users for further analysis.

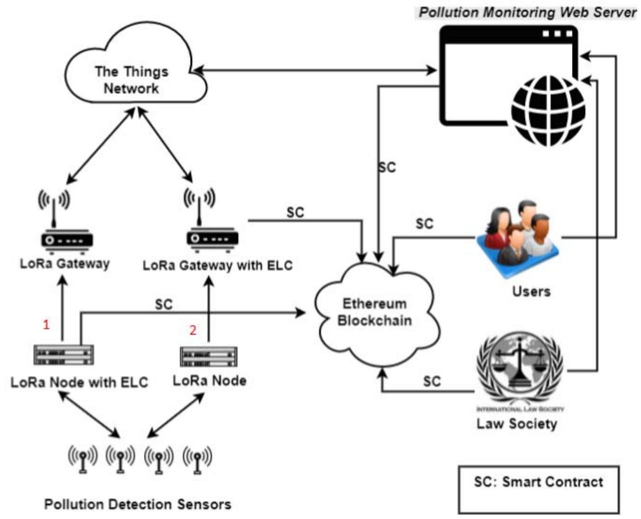

Fig. 3. Data Flow Using LoRa and ELC

In the third approach, sensor nodes collect the data and transmit it directly to the Web server which has a full node of Ethereum embedded. In this approach using LoRaWAN is optional and other communication technologies such as WLAN /WiFi is usable as well. The incentives behind using LoRaWAN even in this approach is the support for long range communications and low power consumption characters of this protocol. WiFi is best suited for a private BC network since in this approach, data transmission is restricted to the WiFi range.

Regardless of the approaches above, a SC is developed to check the data received by sensors. Thresholds of the variables in SC are set according to the pollution standards (normal outdoor value range) from [12], [16], [17], [19], [22]. The ranges of pollution standards used in the SC can be specified depending on the regional standards during SC deployment. The developed SC is presented in [15] includes functions for each measured factor of pollution with which, only violated values in the received data are detected and sent to the BC.

The monitoring web application used for extracting data from BC and monitor them for further analysis accordingly. The web server stores all the data received by sensors, not only the violated data (the data which is out the standard range). This implementation decision was made to provide an additive trust, and also for increasing the functionality of the application by having all the data in hand to monitor every country and every city in the world based on both pollution generation and the standard thresholds. Front-end development of the Web application involves Meteor (NodeJS), Solidity, and Web3 API. The NodeJS environment used as it ease the Web3 API to connect to the Ethereum full node (*Geth*).

V. Evaluation

Evaluation of the proposed PMS needs to be done on three different aspects of the employing communication protocol, BC and overall functionality on the basis of security, reliability, scalability, and accessibility.

Among the three approaches, the one in which ELC installed on the LoRa gateway requires less transactions to be sent in between. In the Second approach, where the LoRa gateway includes ELC, cost effectiveness and reliability are provided with the security in data transmission. In this case, the data received by the gateways from sensors were lower than other approaches and transacted into the BC directly from the gateway itself. As a result, this approach ensures integrity and accuracy of the data made available in the public domain. Reliability of the third approach in which web server includes full node of BC is also high as all the data coming form sensor nodes are being logged (unlike other approaches where the amount of data transmitted is restricted though the TTN fair access policy [7]) to give broader analysis on the Web server.

Scalability of the proposed PMS can be divided into three parts as back-end (*i.e.*, BC scalability), front-end (*i.e.*, Web Server scalability) and sensors (*e.g.,* number of sensors). Scalability of the BC depends on the Ethereum network. At the moment, Ethereum with the transaction validation time of utmost 10 seconds, addresses the time-related requirements of this use case. Number of sensors in/and sensor nodes can be easily increased depending on the requirements by altering number of data fields in the present model without affecting the logic of the current setup.

Regarding power consumption of the proposed PMS, the whole sensor node setup uses with 4 sensors, power generated by $\approx$ 18 V of battery (9 V batteries in series) to start up and transmit the data over LoRa network. Total power consumption of the sensor nodes needs to be divided to power consumption in transmitting data and sensing (gathering) data. Regarding the data transmission, LoRaWAN enables the communication to be power efficient as discussed in the Section II. Which narrows down the major power consuming parts of the PMS as Sensors and Computing board (Arduino Uno), the major part of power consumption directly relates to the number of sensors and their power consumption.

VI. Conclusion

In this work, a power-efficient, long-range communication enabled, automated, and decentralized IoT and BC-based pollution monitoring system is introduced, which on the one hand, leverages the unique nature of BC by providing tamper resistant decentralized and trustable distributed systems, and on the other hand, employs LoRaWAN communication protocol to provide long range and low power enabled communication. This helps in communicating with IoT sensors in environment far from gateways.

For the first time, through this work ELC is deployed on LoRa gateways which is a great advantage in combining IoT-based applications and BC-based systems. This approach addresses the need for installing BC full nodes in the IoT sensors which is in most cases not possible considering the small spaces, computation power, and power resources given to the IoT sensor nodes. The proposed PMS covers another approach in which, ELC is installed on the LoRa sensor nodes and the Web server receives all the data from sensor nodes and it has a full node installed on it.

Approaches taken in this PMS enable users to access the data which is gathered by IoT sensors automatically and send them to the Ethereum BC. This data can be used as an evidence of pollution existence in the monitored area. This PMS is capable of being used in many countries according to the coverage of TTN network. Evaluations of various factors on this PMS indicate advantages of using the LoRaWAN and the Ethereum BC while expressing their drawbacks as well.

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