Tremble: TRansparent Emission Monitoring with BLockchain Endorsement

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***Abstract*—Since the monitoring of environmental emissions is mostly in the hands of regulatory authorities, collected data may not be easily observed by the interested public. Centrally stored data may also tempt the authorities or others to manipulate the historical record for political or liability reasons. To enable timely, transparent and integrity-protected collection and presentation of emission data, we propose and implement *Tremble*, an emission monitoring system based on blockchain and IoT sensors. *Tremble* employs a hybrid storage approach to lower the cost of storage compared to using a pure blockchain without losing data integrity. It provides web interfaces and visualizations for end users to query emission values they are concerned about. Qualitative and quantitative studies involving a total of 62 subjects demonstrate the usability of the system.**

I. Introduction

Air pollutants emitted by industrial processes, e.g., electricity and heat generation, manufacture of chemicals, or agriculture have a major impact on global climate and can directly affect the health of humans living close to the source [1]. Air pollution can cause or exacerbate respiratory, cardiovascular, neurological, immune system and reproductive diseases[1].

To ameliorate such health impacts, many countries have enacted regulations to curb emissions from industry, such as the European Geneva Convention on Long-Range Transboundary Air Pollution or, in the U.S., the Clean Air Act. Unfortunately, enforcement may be lacking and residents often cannot easily tell whether a local point source of air pollution is complying with regulations. In some cases, local or regional governments have an interest in hiding, obfuscating or deleting data that shows excessive pollution. Thus, to increase accountability and discourage corrupt practices, ensuring authenticity and completeness of pollution data are vital.

Government-sponsored projects for measuring air quality, such as AirNow[2], have become common, but they are not available everywhere, are costly to set up and maintain and may not be trusted. There are also independent projects, such as Purple Air[3], that do not rely on regulatory authorities, but depend on users to purchase and deploy sensors from a specific vendor. None of these projects prevent data corruption.

Alexander Nußbaum and Johannes Schütte equally contributed to this research as co-first authors. Luoyao Hao and Henning Schulzrinne are the corresponding authors.

[1] https://www.niehs.nih.gov/health/topics/agents/air-pollution/

[2] https://www.airnow.gov/

[3] https://www2.purpleair.com/

We introduce *Tremble*, an air quality monitoring system relying on blockchain technologies and IoT sensors. The system can integrate sensors installed by both regulatory authorities and residents, i.e., crowd-sourced data. *Tremble* aims to provide air quality information to the public cost-effectively, while preventing tampering. The system combines both traditional databases and blockchains to strike a balance between cost and tamper-resistance. The bulk of measured data is captured only in the database, but measurements exceeding a threshold, random samples of the data or hashes are stored in the blockchain. With a focus on system usability, *Tremble* visualizes air quality metrics through a web application designed for non-technical users.

This paper makes the following contributions:

- We look at recent climate reports and the reasons for the need for research in this area, as well as compare our project to similar approaches.
- We analyze the transparency issues of air quality data and propose a novel emission monitoring system.
- We implement the prototype with IoT sensors and build a web application based on the Ethereum blockchain.
- We evaluate the system regarding the cost of contributing data and its usability to possible users.

The rest of this paper is organized as follows. Section II introduces the related work on environment and emission monitoring. Section III describes the three-layer model of the proposed system. Section IV presents the system implementation. Section V analyzes the system through usability studies. Section VI discusses potential concerns and further opportunities of similar systems.

II. Related Work

In recent years, air pollution and greenhouse gas emissions, such as CO_2 and SO_2, have increased considerably [2]. Increased emissions accelerate climate change, which can have catastrophic effects such as natural disasters [3]. In particular, emissions from industry and power generation such as power plants are the focus of this work due to the fact that they are among the largest emitters [4], [5].

To monitor environmental data and prevent falsification, several existing projects propose to include the blockchain as a tamper-proof and decentralized data store [6]–[10]. Some

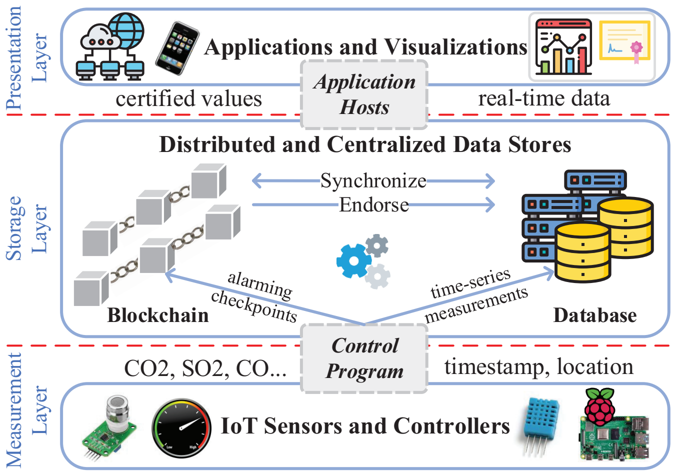

Fig. 1. Three-layer architecture of the proposed system.

existing work on combining IoT and blockchain for environmental monitoring focuses on configuring and connecting IoT devices to store environmental values in a blockchain, but does not address the blockchain application. Many concepts remain abstract above the IoT level and do not provide a blockchain application [9], [10]. Besides, the inefficiency of blockchain is rarely discussed in existing solutions.

A proposal for the utility of a blockchain in monitoring emissions suggests a system where many different IoT sensors measure data and send it to a blockchain [6]. This data is then processed by smart contracts. Here, the focus is clearly on the analysis of the data and the technical processing. Even though a sample blockchain application was developed, it was not evaluated regarding its costs or scalability. Also, the need for the system and its usability was not evaluated. A similar approach is presented in [11]. Here, smart contracts are used for processing the collected data and a web application for displaying the collected data. In this paper, the focus is on the trust and the ways to detect false data and prevent manipulation. Various mechanisms were successfully used to prevent false and unauthorized measuring stations from writing values to the blockchain, as well as to prevent values from being subsequently changed once they have been measured. Usability aspects are not applied here. To reduce energy consumption, low-energy sensors supported by LoRa network are adopted, in comparison with other possible choices [8].

In addition, a user-oriented system for emission monitoring in which IoT sensors are combined with a blockchain using the principles of usability, has not yet been implemented.

III. System Model

Tremble is based on a three-layer architecture shown in Figure 1. In this section, we give a high-level overview of the system design and architecture.

A. Measurement Layer

The measurement layer consists of IoT sensors used for collecting and processing environmental data at periodic intervals. The devices are placed outdoors near possible point sources

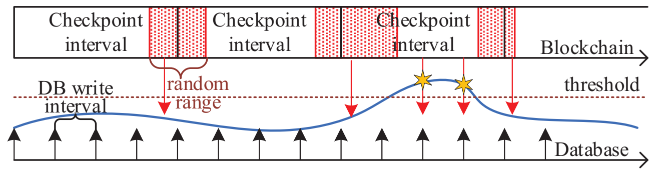

Fig. 2. Processing periods for the hybrid storages.

of air pollutants, such as power plants or industrial sites. The IoT devices periodically poll the current values of the sensors and send them to the storage layer. For greater reliability, deployments should rely on sensors from multiple vendors, owned and operated by a variety of public and private entities. We assume that sensors can run a small custom program. Issues such as managing heterogeneous devices, obtaining accurate locations, protecting devices against tampering, and sampling intervals need to be addressed, but beyond the scope of this paper.

B. Storage Layer

In the storage layer, *Tremble* uses a combination of blockchain and traditional database. This approach is based on the trade-off between the two concepts. Many IoT systems with traditional database offers fast access times and lower cost per record stored, but is managed centrally or, even if distributed, by one organization [12]–[14]. A blockchain incurs higher access overhead through replication and transaction costs, but promises complete transparency, reliability, and immutability [15], [16]. By storing data to a public blockchain, it eliminates any possibility for single instances to manipulate or delete data records. With the authenticity of the stored information being guaranteed, it provides an additional source of trust, as clients can rely on the measured values written to the blockchain. Thus, in order to achieve both the efficiency of common databases and the immutability of blockchain, we need both data stores and a strategy to balance them.

To combine the advantages of both traditional database and blockchain in the *Tremble* storage layer without introducing prohibitively high costs or losing accuracy, sensor data are sent to the database at fixed, short intervals and to the blockchain at checkpoints at larger intervals. As depicted in Figure 2, each checkpoint occurs at random, rather than periodic, intervals as that provides an additional protection against manipulation of the logged data. If the measurement value is higher than the acceptable limit, it is uploaded to the blockchain immediately. This setup offers a reasonable balance of offering higher protection against manipulation of measurements that are likely of greater interest to the public, while still reducing the cost of storage. This trade-off likely generalizes to other sensor measurements, as it is common that out-of-bounds measurements are more valuable, and also more likely to be falsified, than measurements that are compliant.

C. Presentation Layer

A number of applications can be built to display the data stored in the database and blockchain. Two major goals pursued in this layer are: (1) to present measured data in

Fig. 3. Hardware in our prototype.

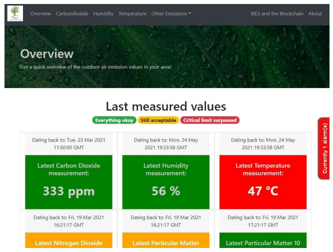

Fig. 4. Overview page in web app.

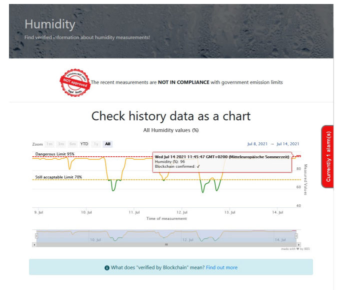

Fig. 5. Presentation of history data in a graph

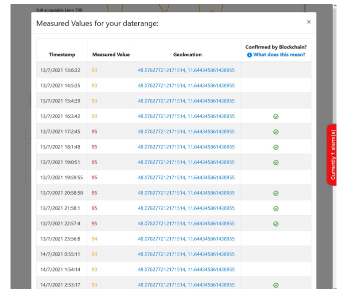

Fig. 6. History data for a specific time range presented as table

an understandable and visual way; (2) to put a special focus on reflecting the strength of blockchain. In our project, we implement a web application and convey the benefits of integrating blockchain to the public through elaborate web pages, graphical visualizations, and informative concept introduction.

Compared with relevant proposals that preventing data tempering is the gist [6]–[8], *Tremble* also focuses on cost-effectiveness in the storage layer and application usability in the presentation layer.

IV. System Implementation

In this section, we present our prototype implementation.

A. Measurement Layer

Since the purpose of our implementation is to show a proof of concept, rather than specific measurements of a wide range of emission metrics, we do not pay particular attention to the sensor types in our prototype. To reflect the notion of measuring physical constants without the expense of an air quality sensor, we set up a DHT11 sensor connected to a Raspberry Pi to measure humidity and temperature, two widely understood environmental indicators. Figure 3 shows our hardware including the outdoor sensor.

A Python script controls the sensors and queries them for updated measurements. The IoT devices are set up to take a measurement at twenty-minute intervals. The measurement, along with the geolocation and timestamp, is then encapsulated in JSON format and sent to the database in the storage layer. To reduce cost, only every third to sixth measurement, randomly chosen, is also sent to the blockchain. A development Ethereum blockchain is used in our prototype, and an IoT device is instantiated like a node on the main net to be able to send transactions. The script also generates an alert for *Tremble* users and writes the sample value to blockchain if measurements fall outside the designated normal range.

B. Storage Layer

In the storage layer, we adopt MongoDB (version 4.4.6) as the traditional database, which is hosted in MongoDB Atlas [17], a fully managed cloud database service. The database is extended by a Node.js server with the Express framework, to which requests required by the presentation layer are directed. In order to be further integrated smoothly into the public Ethereum blockchain, favored by developers for its Turing completeness, we set up the blockchain environment using Ganache-CLI as a development instance. We use the Truffle framework to compile and deploy smart contracts.

To accommodate different regulations and achieve better scalability, we have written individual smart contracts for each measured emission type. So far, we have written smart contracts for SO_2, humidity, and temperature. The use of multiple smart contracts provides a modular structure, so that users can address those contracts for which they use the corresponding sensors. Listing 1 shows the simplified structure of a generic smart contact used in our system. In the smart contract, sensor values are received and checked for completeness, consisting of timestamp, measured value and geolocation. Then, the measured value is checked regarding the encoded predefined limits. An alarm event is triggered if the value exceeds the limits, which is going to be processed by the web application of the presentation layer.

```
contract Emission_Monitoring {
    event StatusMessage(
        string timestamp, geolocation,
        uint measurement, critical );
    function submit(
        string memory _timestamp, _geolocation,
        uint _measurement
        ) public {
            if (measurement >=
                critical_emission_limit) {
                emit StatusMessage(_timestamp,
                    _geolocation, _measurement,
                    critical = 2);}
            else if (measurement >=
                medium_emission_limit) {
                emit StatusMessage(_timestamp,
                    _geolocation, _measurement,
                    critical = 1);}
            else {
                emit StatusMessage(_timestamp,
                    _geolocation, _measurement,
                    critical = 0);}
        }
}
```

Listing 1. General structure of a *Tremble* smart contract in pseudo code.

C. Presentation Layer

To dynamically process the data stored in the database and blockchain, a web application[4] is developed using React.js. We focus on presenting measured data in an understandable and transparent way.

To serve non-technical users, we apply an easy-to-understand structure with an overview page, as shown in

[4]Source code: https://github.com/JCCLaude/IoT-Blockchain

Figure 4, and individual sub-pages for every specific type of measured emissions. The latest information is present by default on the overview page which also serves as landing page. On the subpages, historical data can be queried and displayed in common display types. On the one hand, the development of values can be displayed via a graph, as can be seen in Figure 5. On the other hand, it is also possible to select any time period using a date picker and to display the corresponding values in table form, which can be seen in Figure 6. By filtering the events stored in the blockchain, a specific alarm function is implemented as a sticky message linked to the exceeding values. Since a natural merit of the application comes from the use of hybrid data stores, the differences regarding the trust in displayed data are highlighted in an interactive way, marking whether or not the displayed data is validated by the blockchain.

V. Evaluation

We evaluate the prototype and web application through a comparative study and two usability studies.

A. Cost of Blockchain Storage

Since deploying each smart contract or completing each transaction into the blockchain has to be paid for in a public chain, we evaluate the costs as an indicator of efficiency. For contributors to the system, these expenses should be kept as low as possible. For this purpose, alternative implementations of the smart contracts are considered and compared in terms of their transaction costs. Two alternative system designs are realized in addition to the one used in our primary implementation, which are described in Table I. The costs of execution and deployment of smart contracts are shown in Figure 7, and the costs in USD is given in Table II.

For the first alternative, smart contracts do not judge if measured values are exceeding any more. Thus, the mission of smart contracts is to transmit the measured data and store them in the blockchain. As a result, the alerting function, which is supported by trusted computing, has to be dropped. Even so, replacing this function in the presentation layer would still be promising, and it could still refer to the values stored in the blockchain, which are available in a readable and

TABLE I
Different designs of smart contracts

Annotation	Description
Original	Store measurement and check against limits.
No checking	Store measurement but do not check against limits.
Hash only	Only store SHA-256 hash of the measurement.

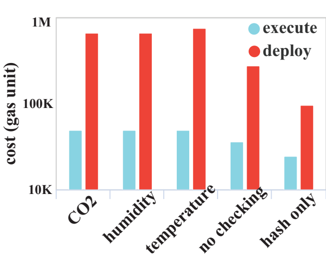

Fig. 7. Smart contract costs.

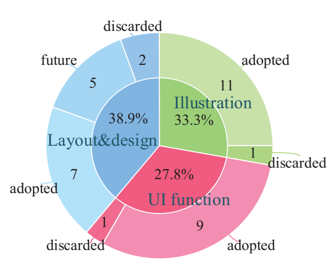

Fig. 8. Summary of interviews.

TABLE II
Transaction cost in USD (gas usage), as of 07/08/2021

Contract Type	Initial Deployment	Regular Transaction
Original	25.07 (690000)	1.78 (49700)
No checking	10.11 (278091)	1.34 (36908)
Hash only	3.57 (98345)	0.89 (24463)

TABLE III
Transaction cost in USD (gas usage), as of 11/09/2021

Contract Type	Initial Deployment	Regular Transaction
Original	11.57 (690000)	0.82 (49700)
No checking	4.58 (278091)	0.61 (36908)
Hash only	1.62 (98345)	0.40 (24463)

easily auditable way for all users. This modification yields a 25.74% reduction in execution cost and a 59.70% reduction in deployment cost.

Even greater reductions of 50.78% and 85.75%, respectively, are achievable by the second alternative. Here, only the hashed value in SHA256 of the collected data is transmitted to the blockchain by smart contracts, while the entire measurement is written to the regular database. The use of hashes in the blockchain then requires a presentation-level integrity checking to compare the hashes with the hashed data of the database. It is to be observed that a sequence of measurements can be hashed together to further reduce the cost. In practice, the size of the sequence can be dynamically altered by the control program in order to meet the budget. Although data integrity and user trust are still promised, some convenience would be lost as data are no longer in a readable form on the blockchain. Needless to say, retrieving original data might be hard if data tampering occurs in the database. Another aspect of blockchain costs is the so-called gas price, which depends on the utilization of the public blockchain network on the one hand and on the current Ethereum price on the other. During the development of *Tremble*, this price rose sharply due to a high demand of cryptocurrencies and was subject to strong fluctuations. In the meantime, the so-called London update [18] has had the opposite effect, in which the gas price has arrived at a constant and predictable level due to adjustments. The comparison of table II with table III shows that the costs can be reduced and the operation of a metering station becomes more attractive, which can be considered as a key factor for contribution of volunteers.

B. Usability of the System

To evaluate the usability of our approach and application, we conducted a qualitative study using the "Think Aloud" method [19] (similar to a study by Froehlich et al., [20]) and a quantitative questionnaire study[5].

Semi-structured interviews regarding the handling of the website are conducted to obtain detailed feedback from the subjects. This involves interviewing 10 participants, who are divided into a balanced ratio of experts and non-experts in the field. We adopt the "Think Aloud" method, in which participants express aloud their thought process at each step

[5]Studies involving human subjects were approved by the Ethics Committee at Bundeswehr University Munich under the project "IBES Nutzerstudie".

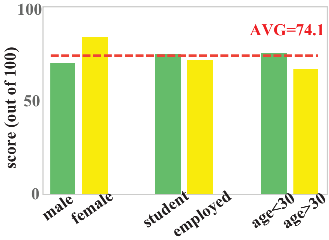

Fig. 9. Usability rated by subjects.

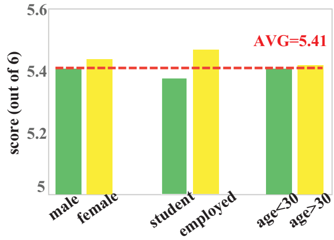

Fig. 10. Usability by operations.

of experiencing all the features and functionalities of the web application. Figure 8 shows the taxonomy and our responses of collected suggestions. Valuable insights into the usability are marked down and useful suggested functions are considered.

In addition, we conduct a questionnaire study[6] and collect feedback from a larger targeted user base. Compared with the above study, the system is now operated online by users from different backgrounds. A self-created online questionnaire, which contains a link to the website, is sent to our participants, who are asked to answer parallel tasks in the questionnaire. The usability is evaluated using the System Usability Scale (SUS) [21], and six light-weight tasks for operating the elements of the website (e.g., operate the graphical view, detect whether or not certain emissions exceeded a limit in a given time period, etc.) were set to determine the understanding of the website. 52 participants from seven different countries completed the questionnaire. Since a normal distribution can be assumed from a sample size of more than 30 subjects [22], the number of test persons in our study is considered enough to make reliable conclusion, although we do suspect that more test persons could give more exact results over the usability and operability.

We consider demographics (e.g., age, gender and occupation) during the analysis. The first thing that stands out in Figure 9 is that the female proportion of subjects (31%) rated the usability of the system significantly better with an average of 84.84 points than the male proportion (69%) with 73.06 points on a scale from 0 to 100. However, no clear difference can be observed between subjects under and over 30 years of age, in that those under 30 years of age rated usability similarly with 76.86 points as those over 30 years of age with 76.15 points. Interestingly, we observe that there is no clear difference in the correctness of completing the asked tasks, as shown in Figure 10, which implies that the usability differences might be negligible with respect to those demographics. The rated system usability scores average 76.68, well above the standard average rating (i.e., 68 according to SUS [21]), which demonstrates the decent usability of the system.

VI. Discussion

Cost Evaluation: Storing various records to public blockchains is not uncommon in creating a trusted service [23], [24]. However, we would like to point out that the feasibility becomes questionable with the tremendous increasing popularity of cryptocurrencies. Through our evaluation, we demonstrate reasonable costs in gas unit [24], but the real cost, deploying to the public Ethereum main chain, ranges and is only affected by the market. It can be prohibitively high when the market increases (e.g., we observed 3 to 8 USD per transaction on 05/24/2021). Although the overall cost is adjustable by the approaches presented earlier, we are concerned about whether they can be generalized to different applications as long-term solutions, in the context of huge market fluctuations. The London Update, which was carried out during the development of the project, is an advantage in this respect, because transaction costs not only become more predictable, but also less expensive.

Choice of Blockchain: We take no position on whether the system should be built upon a public or a permissioned blockchain. Public blockchain provides a fully decentralized solution to establish mutual trust among entities, rather than relying on a trusted third-party [25]. Permissioned blockchain likely works more efficiently, as participants are authenticated, but then we fall back to trust the operator. Analyzing this trade-off is beyond the scope of this paper. We adopt the Ethereum blockchain not only from its popularity, but also because it's potential in serving as both models [26].

Data Protection: With *Tremble*, a transparent and protected emission monitoring system was developed. While the public blockchain prevents tampering with stored data, capturing and transmitting value is a challenge. To prevent values from being altered even before they are recorded on a blockchain, a mechanism for detecting false values is required. Although this mechanism was not explicitly developed as part of *Tremble*, the existing system can be extended to include this functionality. For this purpose, measured values of a region could be compared with each other and with alternative, possibly public sources, so that individual deviating measurements could be marked as an anomaly.

VII. Conclusion

In this work, we introduce the design and implementation of *Tremble*, a novel emission monitoring system based on blockchain technologies. The system achieves transparency and cost-effectiveness with the tamper-proof nature of blockchain and a hybrid solution of data storage. We build our prototype with commodity sensors for measuring environmental data and set up a web application to display the visualizations. Our ultimate vision is to provide a publicly supervised platform with trustworthy data and drive operators of industrial sites compliant with regulatory guidelines. In the future, we will implement supplementary features, including mobile push functionalities, geographical supports, and emission fading analysis regarding the measuring distance.

VIII. Acknowledgements

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[6]https://github.com/JCCLaude/IoT-Blockchain/blob/main/Questionaire%20(ibessurvey)%2025.05.2021.pdf

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