Secure architecture for IoT and blockchain-based waste traceability

Javier Alonso-Núñez, Diego R. Llanos

Dpto. Informática, Universidad de Valladolid, Valladolid, Spain

ABSTRACT

This paper presents a secure and scalable architecture that integrates Internet of Things (IoT), blockchain, and Data Lake technologies to improve traceability in waste management systems. The proposed system combines the MQTT protocol for efficient communication between resource-constrained IoT devices and a blockchain-based mechanism to ensure the immutability, verifiability, and authenticity of the collected data. A practical use case is demonstrated involving waste container monitoring, where IoT sensors transmit environmental and geolocation data. These data are stored in a Data Lake and cryptographically signed using Merkle trees before being anchored in a blockchain through smart contracts. The experimental results validate the feasibility of the approach and highlight its benefits in terms of transparency, auditability, and operational efficiency.

Keywords: IoT, blockchain, MQTT, Traceability, Data Security, Smart Contracts

1. INTRODUCTION AND MOTIVATION

The increasing generation of urban and industrial waste, along with growing environmental and regulatory concerns, underscores the critical need for transparent and secure waste management systems. Conventional solutions often suffer from limited data reliability, insufficient traceability mechanisms, and vulnerability to tampering or human error. These shortcomings hinder effective monitoring, complicate regulatory compliance, and limit the ability to conduct reliable audits.[1] In recent years, the convergence of Internet of Things (IoT) and blockchain technologies has emerged as a promising approach to address these challenges. IoT devices equipped with sensors can capture real-time data on environmental conditions, such as temperature, humidity, or fill levels, as well as geolocation. These data streams, however, require secure and verifiable transmission and storage systems to be of real operational value. While traditional timestamping approaches such as TSA rely on centralized trusted entities, blockchain offers a decentralized alternative that ensures immutability, consensus without a central authority, and transparent auditability. When integrated with IoT, blockchain enables the creation of tamper-evident records that are resilient to single points of failure. The synergy of these technologies facilitates end-to-end traceability of waste from the point of origin to its final destination, supporting the goals of the circular economy and fostering sustainable practices.[2,3]

This work proposes a hybrid architecture that combines MQTT-based communication for efficient data transmission from IoT nodes, a Data Lake for scalable storage and analytics, and blockchain for secure data anchoring. The design aims to overcome typical limitations such as communication overhead, integrity verification, and storage scalability, and to demonstrate its applicability through a concrete use case in waste container monitoring.

2. SYSTEM DESIGN AND ARCHITECTURE

The proposed architecture is structured around modular and interoperable components that collectively support data acquisition, secure transmission, storage, and verification. At the edge, purpose-built IoT devices are deployed to monitor key parameters associated with waste collection. These devices consist of NodeMCU boards based on ESP8266 microcontrollers, integrated with GPS modules (GY-NEO6MV2), GSM modems (SIM800L), and environmental sensors (DHT11), enabling autonomous and real-time data acquisition.

Further author information: (Send correspondence to Diego R. Llanos)
Javier Alonso-Núñez, ORCID 0009-0004-3085-5007, E-mail: jalonso@uva.es
Diego R. Llanos, ORCID 0000-0001-6240-9109, E-mail: diego.llanos@uva.es

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The choice of the MQTT protocol for communication is motivated by its lightweight design, minimal bandwidth consumption, and support for Quality of Service (QoS) levels. These features make MQTT particularly suitable for low-power, intermittently connected devices operating in constrained environments such as waste collection points. The Eclipse Mosquitto broker is used to manage message routing, while a dedicated API Gateway component manages authentication and load balancing. Incoming messages, formatted as JSON payloads, are collected and processed by a scalable Python-based worker that validates the data and forwards it to downstream systems. Two storage layers are employed: a Data Lake based on Delta Lake and AWS S3 for storing raw and structured data, and a blockchain layer for storing cryptographic digests of the data. To reduce blockchain storage costs without compromising data integrity, Merkle trees are employed. Individual data records are hashed and aggregated into a tree structure, the root of which is anchored via smart contracts in Ethereum or Hyperledger Fabric. This design enables selective and efficient data verification through Merkle proofs, eliminating the need to store all data directly on-chain.

3. IMPLEMENTATION AND EVALUATION

To validate the feasibility of the proposed system, a complete end-to-end prototype has been developed and deployed in a controlled experimental environment. The prototype includes fully functional IoT nodes configured with custom firmware developed in the Arduino environment. The firmware is responsible for data acquisition, local pre-processing, and reliable communication with the central infrastructure via either WiFi or GSM networks, depending on availability. Three experimental configurations were defined to assess the impact of data acquisition and transmission frequency on system performance. These configurations range from high-frequency sampling (every 10 seconds) with minute-by-minute transmission to low-frequency sampling (every 10 minutes) with hourly transmission. This setup enables analysis of energy consumption, data volume, and network load under varying operational conditions. Measurements taken during the evaluation focused on three key metrics: (i) the volume of data transmitted and stored, (ii) the processing latency introduced by the Merkle tree construction and blockchain interaction, and (iii) the storage overhead in both the blockchain and the Data Lake. The use of Merkle trees significantly reduced blockchain usage—up to 90% savings in some scenarios—while introducing only a marginal increase in processing time and Data Lake footprint due to inclusion proof storage.

These results confirm the practicality of the architecture and its ability to scale while maintaining data verifiability. The trade-offs observed between storage optimization and processing complexity provide a valuable basis for tuning system parameters depending on application constraints.

To promote reproducibility and facilitate the reuse of this solution, the source code associated with this contribution is publicly available in the following GitHub repositories: IoT Device Firmware: `https://github.com/danipequelangos/iot-trace-system`; Service Backend and Frontend: `https://github.com/javalon/iot-trace-chain`. Both repositories include deployment instructions, required dependencies, and usage examples.

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