Distributed ledger technologies for electric vehicles charging and payment operations

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***Abstract*—The adoption of electric vehicles (EVs) is constantly increasing, and the consequent demand for charging infrastructure is growing. To enhance customer satisfaction and encourage the use of electric vehicles, it is crucial to provide a safe and efficient charging process capable of guaranteeing service efficiency and quality. Therefore, to optimize this process, it is advisable to gather detailed information on various parameters influencing charging, including data from vehicles, charging infrastructure, and urban traffic simulation models. However, despite the abundant availability of such data, their utilization to optimize the charging process can present complex security challenges, which could give space to possible date breaches that could undermine the security of the operations of recharging infrastructure systems. This paper introduces an innovative tool to simulate the charge and payment operations of an urban EV charging infrastructure where the traditional central management system is substituted by a blockchain-base decentralized solution. Electric infrastructures will be integrated with this innovative technology to ensure data privacy, transaction security, and payment reliability. The proposed solution is based on two different blockchains: (i) the Ethereum-based Quorum blockchain to enable the charge operation and securely store the charging information, providing transparent and immutable tracking of key information for the improvement of vehicle charging infrastructures; (ii) the Lightning Network protocol to ensure privacy and transparency in charging operation payments.**

I. Introduction

The adoption of electric vehicles (EVs) is steadily increasing [1], and consequently, the demand for charging infrastructure is growing [2]. To enhance customer satisfaction and encourage the use of electric vehicles, it is crucial to provide a safe and efficient charging process that ensures timely service and quality. With the growing use of electric vehicles, the risk of network overload can lead to degradation of the network itself. Crucial factors related to fast charging infrastructure are the (i) optimal routing of vehicles to charging stations and (ii) the total charging power that can be provided to each electric vehicle connecting to the infrastructure.

Moreover, in recent years, with the increase in digitization, there has been a significant rise in data generation related to both electric cars and electric vehicles. Therefore, to optimize this process, it is essential to gather detailed information on various parameters influencing charging, including data from vehicles and charging infrastructure. However, despite the abundant availability of such data, their use for optimizing the charging process can present complex challenges.

Often, charging infrastructure is connected to gateway stations via LAN networks, facilitating connection with the Central Management System (CMS) [3]. The CMS is software responsible for charging infrastructure and handles payment transactions, user management, performance monitoring, and more. There are many protocols for communication between infrastructure and CMS, such as the Open Charge Point Protocol (OCPP). OCPP has some vulnerabilities that can compromise the charging system [4]. Some of the most common cyber attacks include Man-in-the-Middle (MitM), ARP poisoning, Packet reply, and Denial of Service (DoSDDoS).

II. Blockchain Quorum and Lightning Protocol

With the increasing adoption of electric vehicles and the corresponding rise in charging infrastructure, the need to provide a secure, efficient, and reliable charging process has arisen. Blockchain offers the possibility to optimize the charging process of electric vehicles by providing a secure, shared, and immutable ledger to track and manage charging transactions. In particular, the Quorum blockchain, based on Ethereum, represents an ideal solution for enterprise applications, offering an authorized and private environment that provides greater security and scalability compared to public blockchains. One of the main features of Quorums is the ability to ensure transaction privacy by introducing private smart contracts, enabling sensitive information to be kept confidential within the blockchain. Regarding the consensus algorithm, Quorum offers flexibility in choosing between different algorithms based on network requirements. In this work the QBFT (Quorum Byzantine Fault Tolerance) consensus algorithm has been adopted. QBFT is used to reach an agreement on the validity of transactions and on modifying the state of the blockchain. It is based on a more centralized model, where validator nodes are selected and responsible for accepting transactions. The Lightning Network is a peer-to-peer network of payment channels implemented as smart contracts on the Bitcoin blockchain, as well as a communication protocol that defines how participants set up and execute smart contracts [5]. The Lightning Network was created to address Bitcoin's scalability, slowness, and high costs. The main innovation lies in the fact that transactions occur off the main blockchain, avoiding associated limitations and costs. To use the Lightning Network, you need to open a bidirectional payment channel between two partners (nodes of the network) who wish to exchange value.

III. Architecture Components

In Fig. 1 the architecture of the system is presented.

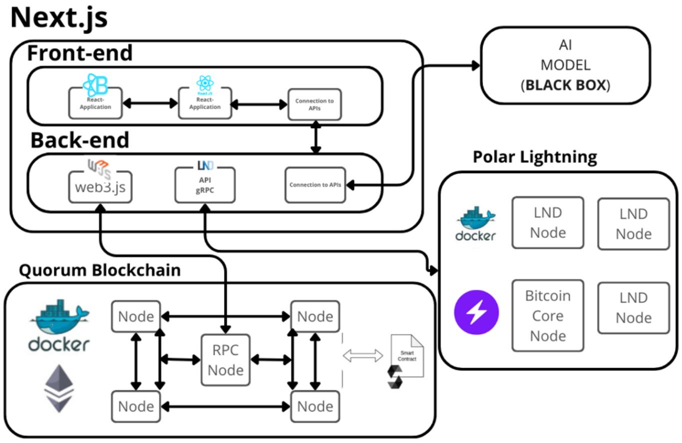
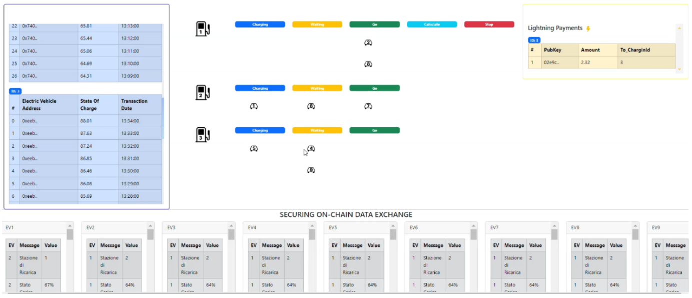


Fig. 1. Architecture Overview

To fully understand the system's operation, it is important to examine the architecture. The system is divided into various interconnected components, each of which plays a crucial role:

1) User Interface: provides users with an interface to initiate and monitor transactions, both on Quorum and Lightning Network, as well as to visualize the different phases of the simulation;
2) Backend: constitutes the core of the system and manages all the logic. It is responsible for providing the user interface with the data to display and interacts with Quorum and Lightning Network nodes;
3) Quorum Blockchain: the backend communicates with the Quorum blockchain for the registration of charging transactions and management of smart contracts related to vehicle charging;
4) Lightning Network: the backend communicates with the Lightning Network through the LND client. Through the APIs provided by the latter, we can manage channel openings, invoice creation, and payment submissions.
5) AI Model: leveraging on vehicles data, energy network condition data and traffic condition data can calculate the optimal routing of vehicles to the charging stations and the optima distribution of the total charging power. This software is conceived as software module securely running within the black-box of each vehicle.

IV. Implementation



22	0x740..	65.81	13:13:00
23	0x740..	65.44	13:12:00
24	0x740..	65.06	13:11:00
25	0x740..	64.69	13:10:00
26	0x740..	64.31	13:09:00

ID: 3

#	Electric Vehicle Address	State Of Charge	Transaction Date
0	0xeeb..	88.01	13:34:00
1	0xeeb..	87.63	13:33:00
2	0xeeb..	87.24	13:32:00
3	0xeeb..	86.85	13:31:00
4	0xeeb..	86.46	13:30:00
5	0xeeb..	86.08	13:29:00
6	0xeeb..	85.69	13:28:00

Lightning Payments

ID: 3

#	PubKey	Amount	To_ChargingId
1	02e9c..	2.32	3

SECURING ON-CHAIN DATA EXCHANGE

EV1

EV	Message	Value
2	Stazione di Ricarica	1
2	Stato	67%

EV2

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV3

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV4

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV5

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV6

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV7

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV8

EV	Message	Value
1	Stazione di Ricarica	2
1	Stato	64%

EV9

EV	Message
1	Stazione di Ricarica
1	Stato

Fig. 2. Vehicle States

In this project, we aim to model the entire lifecycle of drivers who decide, in parallel, to recharge their electric vehicles. As shown in Fig.2, vehicles can be in different phases. In the "calculating" phase, messages will be exchanged between vehicles to calculate which charging infrastructure to head to via the Quorum blockchain and stored therein. Subsequently, the vehicle may be in the phase of:

- Go: the vehicle is heading to the charging station and will take some time to arrive;
- Waiting: the vehicle is waiting as the charging station is occupied by another vehicle;
- Charging: the vehicle is charging.

During the charging phase, we want to track the vehicle's charge. To do this, after every minute of charging, a transaction is recorded on Quorum to record the change in the vehicle's charge. When a vehicle completes the charging phase, a payment is made through the Lightning Network protocol. Vehicles and charging stations are connected to a hub that acts as an intermediary between the two. In doing so, vehicles only need to create a single channel to make payments at each infrastructure connected to the hub. The process is as follows:

- Opening a channel: initially, if there is no open channel, one must be created. The channel will be opened with the hub, and payments will flow through it. Charging stations also initially create a channel with the hub;
- Issuing an invoice by the charging station: once the charging is completed, the charging station can issue an invoice, with the amount the vehicle must pay and its address. Then the invoice can be sent to the vehicle;
- Payment of the invoice by the vehicles: upon receiving the invoice, the vehicle can proceed with the payment. Before reaching its destination, the payment flows through the hub, which charges a fee for the transaction.

V. Conclusion

The transactional nature of the blockchain and the immutability of its ledger ensure secure access to the charging infrastructure information and authorize only vehicles that meet globally optimized criteria calculated by our AI model, providing transparency and traceability in energy operations. This contributes to optimizing resource allocation and reducing waste, ultimately improving the efficiency of charging infrastructures. The blockchain provides a secure method for exchanging data related to electric vehicle charging operations, minimizing the risk of manipulation or unauthorized access. Implementing the Lightning Network protocol for payments enables fast, secure, and scalable transactions, enhancing the overall efficiency of the electric charging system.

References

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