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RESEARCH ARTICLE

On the Utilization of Blockchain and Smart Contracts in Charging Coordination of Roadway-Powered Electric Vehicles

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ABSTRACT With the increasing investments in on-the-move electric vehicle (EV) charging solutions and wireless charging lanes (WCLs), coordination of the energy requirements of mobile EVs becomes essential to ensure load balancing while maximizing demand coverage. This necessitates the development of online and mobility-aware algorithms for assigning EV-to-charging lanes. In this work, a decentralized, blockchain-based EV assignment and energy allocation system is presented. The objective of system is to coordinate the charging requirements of mobile EVs among the available WCLs within a network of EV chargers in an Internet of Electric Vehicles (IoEVs). This blockchain-based system offers higher security, transparency and immutability over traditional rule-based coordination schemes. It also offers an integrated end-to-end framework that handles user registration, authentication, lane activation and energy reporting. This is in addition to its main functionality of establishing a real-time and load-balanced EV-to-WCL assignment process that addresses the EV energy requirements within constraints of traveling distance and remaining EV energy. The proposed system is tested on the Ethereum blockchain and its security and transparency are both validated accordingly.

INDEX TERMS Blockchains, decentralized coordination, electric vehicles, energy management, smart contracts.

NOMENCLATURE

CEM	Centralized energy management.
CEVs	Connected electric vehicles.
DWC	Dynamic wireless charging.
EA	Ethereum address.
EV	Electric vehicle.
IOEVs	Internet of electric vehicles.
OSC	Operations smart contract.
RSC	Registration smart contract.
SC	Smart contract.
WCL	Wireless charging lane.

I. INTRODUCTION

With the growing penetration of electric vehicles (EVs) into the global transportation markets, increasing research and development activities are taking place to provide a reliable and intelligent electric transportation system with connected electric vehicles (CEV) and EV charging solutions in an internet of electric vehicles (IoEV) [1]. These ongoing research activities include, studies on EV charging system development [2], [3], charging infrastructure planning [4], [5], [6], demand modeling [7], [8] and charging coordination and energy management [9], [10], [11].

An IoEV leverages on the advantages of vehicular connectivity to coordinate the grid-to-vehicle (G2V) and vehicle-to-grid (V2G) energy exchange, and to manage the demand-supply profiles of the EV charging energy,

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while utilizing other benefits of connected vehicles including driver's assistance, environment awareness, in-vehicle entertainment, etc. This accordingly can increase the mass adoption of EVs and hence reduce the carbon footprint of transportation systems on the environment [12]. Nonetheless, the growing demand for EV charging energy with the increasing EV adoption rates requires faster and efficient publicly-accessible EV charging solutions that can provide a comparable level of convenience and accessibility as those for refuelling conventional internal combustion engine (ICE) vehicles [13]. In fact, the prolonged charging downtime of traditional plug-in AC chargers is becoming increasingly inconvenient and costly to the growing EV user community [14], [15]. This accordingly motivated the development of fast DC charging systems (FCS) and dynamic wireless charging (DWC) systems. Nonetheless, while FCSs offer a short charging downtime of 20-40 minutes to provide an 80% increase in the state-of-charge (SoC) [16], DWC systems address concerns on the charging downtime and EV driving range limitations by offering an on-the-move charging service to mobile EVs. This allows EVs to compensate for their consumed energy by receiving power from wireless charging lanes (WCLs) placed on driving roadways, without having to stop for battery recharging [2]. This is expected to contribute to an increase of at least 15% in EV adoption rates according to the associated drivers' convenience [17].

However, despite their advantages of reduced charging downtime and improved driving range, DWC systems face a number of challenges that may hinder their large scale implementation. These include their socio-economic feasibility, their energy requirements and their impact on the electric power grid. Extensive studies are conducted on the optimal planning of WCLs to minimize the associated construction and operational costs while addressing the growing users' demand. These include that works by [18], [19], [20], and [4]. In addition, the growing interest in on-the-move charging has translated into a number of WCL deployment projects that are currently implemented in different cities as proofs of the concept, using both elongated tracks of charging roadways as well as segmented charging pads. These are detailed in the 2021 and 2022 market reports provided by [21] and [22], respectively. A socio-economic study on the implementation of a network of WCLs within an urban city is also conducted in earlier work by the authors in [6] proving their feasibility for large scale deployments. In fact, the integration of electric transportation systems and the implementation of WCLs are among the key pillars in the urban planning of new, smart cities and communities, which embeds the infrastructure development costs within the overall costs of building the smart communities.

Nonetheless, the introduction of on-the-move charging solutions imposes additional energy and peak power requirements on the electricity grid, leading to instability in the electricity generation and distribution networks. This is due to the need to supply EVs in demand with large bursts of energy during the short EV traveling time along the WCLs on the electrified roadway. Significant load imbalance is also expected as the penetration of WCLs increases, due to the spatial distribution of the charging lanes across different power buses and the stochastic nature of EV traffic flows across the different lane locations [2]. In fact, studies reveal that uncoordinated EV charging causes significant voltage and frequency variations with as low as $10-15\%$ EV penetration into the transportation network [23], [24]. Accordingly, balancing the EV charging demand among available WCLs is essential to avoid overloading the electric power buses to which the lanes are connected. This needs to take place while abiding by the traveling range limitations of the EVs in demand, to maximize the overall charging demand met by the network of WCLs. As a result, different EV charging coordination approaches are proposed in the literature as outlined in Section I-A.

A. RELATED WORKS

1) EV CHARGING COORDINATION SOLUTIONS

Existing studies on EV demand management and coordination investigate spatial and temporal scheduling in both centralized and decentralized coordination modes [25]. In temporal scheduling scenarios, the EV load is considered as one of the time-shiftable loads in a demand side management (DSM) problem, and can be scheduled in advance by a central coordinator that optimizes the scheduling algorithms to avoid grid overload during peak hours [26], [27]. In contrast, decentralized coordination can take place by modeling the day-ahead scheduling tasks as aggregative game-based models as described in [28] and [29], or by disseminating optimal pricing signals to the EV users to encourage price-driven changes in their charging patterns [30]. However, time-based scheduling models also need to incorporate the spatial distribution of EVs by acknowledging the coordinates of EV locations with respect to those of the charging stations. Hence, the demand of mobile EVs also needs to be spatially coordinated, by executing EV assignment algorithms and communicating the corresponding assignment decisions to EV drivers while acknowledging their respective routes.

An online, mobility-aware spatial EV-to-station assignment model is proposed in [31] with the objective of balancing the charging load profile across multiple microgrids with clusters of EV charging stations. In their work, the optimal assignment algorithm is executed in a central aggregator, which is also utilized in [32] to run a reservation-based charging station assignment model. In the model in [32], each EV sends a charging slot reservation request to the central aggregator that performs the optimal assignment to minimize the total duration of the EV trip to the assigned station by studying the associated traveling, waiting and charging times. The authors in [33] also propose an online algorithm that determines the optimal set of charging stations at which each EV can stop for charging, to gain its desired energy along the route from its origin to destination at minimum traveling time and charging expenses. Another online and centralized multi-objective assignment problem is formulated in [34] to assign EVs with depleted batteries to battery swapping stations such that the cost incurred by the EV users is minimized while minimizing congestion at the swapping stations.

Nonetheless, the majority of existing studies on the coordination of EV charging demand consider only plug-in charging stations given the currently low investments in the commercial deployment of DWC infrastructure. However, acknowledging their technical and socio-economic feasibility and to mitigate the associated challenges on the electric power grid, it is essential to develop coordination strategies that are tailored to DWC systems. This enables effective on-the-road demand management given the energy supply capabilities of the electricity grid, and improves the drivers' quality of experience (QoE). Accordingly, the authors in [11] proposed a semi-decentralized, EV-aggregator based, charging coordination algorithm, in which EVs are allocated to the charging lanes by executing a spatial EV allocation algorithm on a computationally-capable, edge aggregator device. This device receives energy-related information from a centralized energy management (CEM) unit then manages the charging requests from EVs within its service region based on energy availability information from the CEM. The utilization of an EV aggregator, however, adds an extra communication layer between the EVs and the CEM, which introduces communication and execution delays in the charging request and energy allocation processes. These delays, together with the mobility of EVs, may hinder timely reception of the EV-to-lane assignment decisions, making it difficult to optimally execute the developed EV allocation plans.

Acknowledging the expected communication delays of employing an EV aggregator for decision making, the authors proposed a simplified IoEV network architecture in [35], in which optimal charging allocation decisions are determined by a centralized charging management and coordination center, which directly communicates with the EVs and the utility providers, and has sufficient computational capabilities to execute the EV-to-lane assignment decisions. This centralized architecture reduces communication delays and ensures global optimal EV assignments based on real-time charging requests and energy availability information received from the EVs and the utility provider, respectively. Centralized coordination is also addressed in the literature to achieve global, grid-related objectives such as load balancing, peak shaving and valley filling in [36], [37], and [38]. However, centralized coordination suffers from two main drawbacks in terms of scalability and security. This is because, the central coordinator is expected to suffer from an exponential increase in the computational time and resources required to execute the allocation algorithms with the growing volumes of EV charging requests [25]. In addition, information security risks become inevitable, as each EV needs to communicate its details and required demand with the centralized decision maker which demonstrates a single point-of-failure to the system.

2) BLOCKCHAINS FOR EV ENERGY MANAGEMENT

To address these scalability and security issues of centralized decision making while avoiding complex computations, this work proposes the utilization of distributed ledger technologies, i.e. blockchains and smart contracts (SCs) to enable a decentralized coordination of the EV charging demand. This offers secure and immutable energy transactions between EVs and WCLs by allowing the execution of a load-balancing EV-to-WCL assignment algorithm on an SC, while managing the registration and authentication of EVs and the activation of the WCLs using distributed ledgers. Blockchains were first introduced by Nakamoto as the underlying technology behind Bitcoin [39]. It is a distributed database with a number of blocks representing the transactions taking place on the chain. These transactions can conceptually be verified by every node on the chain, offering trustless consensus without the need for a central trust agent [40]. Different verification techniques are utilized to validate blocks added to the chain, including proof-of-work (PoW) and proof-of-stake (PoS), which vary in terms of the validating members and the validation algorithm(s) [41], [42]. Nonetheless, the underlying concept is that once a block is verified and added to the chain, it is immutable and cannot be tampered, thereby offering protection against different impersonation and data privacy threats.

The use of blockchains and distributed ledgers in EV charging coordination is currently gaining an increasing popularity in state-of-the-art literature, although it is mostly adopted for EV coordination among public charging stations. The authors in [43] utilized distributed ledgers to ensure compliance of the EV drivers to the optimal EV-to-station assignment schedules obtained using decentralized algorithms. In their work, the assignment algorithm in itself is implemented off-chain, where each EV solves a cost minimization optimization problem based on information received from the charging stations. Token bonds, in the form of a cryptocurrency, are then utilized to enforce users to comply with the optimal assignment outcomes. Blockchains are also utilized for EV registration and charging transaction validation in the IoEV described in [44] while the charging scheduling process takes place through a branch and bound algorithm executed on a charging station operator, i.e. an aggregator. The authors in [44] also adopt an off-chain payment model to reduce latency although this may impair the overall system integrity of the charging and payment processes. In [45], charging scheduling and allocation algorithms are also executed using off-chain contracts while the financial transactions are performed on the blockchain along with registration and authentication stages to provide higher security.

In contrast to integrated off-chain and on-chain solutions, a few works fully implement the charging coordination algorithms on-chain using smart contracts as virtual aggregators or third-party controllers. The authors in [46] utilized blockchains for the registration, scheduling, authentication, and charging phases and utilized a lightning network for payment management to address the scalability issues associated with Bitcoin-based payments. Nonetheless, the mobility of EVs was not considered nor their spatial allocation among different charging locations. Blockchains are also adopted for peer-to-peer energy trading between EVs connected to the same charging station in [47], and for scheduling of the energy allocated by the power distribution networks to the available charging stations in [48]. A trading framework between charging stations and EVs is also developed in [49] by using the smart contract to run an auction to determine the optimal energy exchange price. Nonetheless, while these works benefit from the security and immutability of blockchains, little works studied an end-to-end on-chain deployment of a real-time coordination of the energy requirements of on-the-move EVs. This requires an efficient and low-latency implementation of a lightweight decentralized coordination algorithm on the blockchain through smart contracts, which is the main contribution of this work.

B. THIS WORK

As highlighted earlier, this work utilizes the advantages of security, immutability and transparency of blockchains to implement a fully decentralized blockchain-based EV-to-lane assignment algorithm with the preceding registration and authentication processes and the following energy reporting procedures on smart contracts (SCs) deployed on the Ethereum blockchain. This leverages on the immutability and authenticity of blockchains to securely assign, coordinate and monitor the EV charging process from DWC lanes. In particular, the key contributions of this work can be summarized as follows:

- Design and develop SCs on the Ethereum blockchain to fully implement the end-to-end EV demand coordination system consisting of EV registration and authentication, EV-to-lane assignment for load balancing, charging activation and energy reporting. This offers a comprehensive utilization of the blockchain and distributed ledger technologies for EV demand coordination, instead of limiting their role to ensuring compliance and/or securing the relevant transactions. It also opens the door for further utilization of the smart contracts for optimal coordination algorithms and charging activation transactions.
- Debug, simulate and test the developed SCs to validate their operation for real-time EV-to-WCL assignments among the other SC functions.
- Present a detailed cost analysis for the transactions involved in the EV-to-lane assignment process to demonstrate the transaction fees associated with practical implementation and justify the need for large scale deployments to benefit from economies of scale.
- Present a security and vulnerability analysis to confirm the high security and immutability of the proposed blockchain-based system.

The rest of this paper is organized as follows. Section II presents an outline of the system model used in the work. Section III then describes the details of the proposed blockchain-based EV charging coordination system. The steps conducted for the implementation and testing of the developed smart contracts are detailed in Section IV. The performance of the developed system is then evaluated in terms of cost, security and vulnerability analysis in Section V along with a comparison with the existing literature. The paper is finally concluded in Section VI.

II. SYSTEM MODEL

A simplified network of EV charging infrastructure is modeled in this work, consisting of M connected EVs and N DWC lanes, where $j \in N$ is the index of the charging lane and $i \in M$ is the index of the EVs. All EVs and WCLs are members of a blockchain which is operated and managed by a DWC operating company and each WCL is operated by a lane controller. The roles of these entities are described as follows:

- The DWC company is responsible for deploying smart contracts (SCs) with the respective energy management algorithms on the blockchain. In addition, the DWC company is responsible for WCL entity definitions, ID assignments and WCL characterisation on the blockchain.
- The EVs interact with the system at its different stages, namely registration, request submission, energy allocation, reporting and billing.
- The WCL controllers receive instructions through the blockchain to authorize the charging service(s) upon arrival of the registered and assigned EVs. The WCL controllers activate the lane(s) accordingly and are responsible for reporting the amount of energy supplied to the EVs upon charging completion, to be used for billing the respective EV users.

In order to execute the aforementioned roles, the DWC company starts by defining the locations of the WCLs, their energy capacities and possible routes to be served. The proposed blockchain-based EV charging coordination system is then executed using two SCs:

- A registration smart contract (RSC), which handles new EV registrations and generates unique cryptographic IDs for each of them. It also ensures that only EVs with valid addresses can obtain an ID and that no duplication of registration takes place.
- An operations smart contract (OSC), which performs the EV-to-lane assignment process by executing a load-balancing assignment algorithm (inspired by the work in [11]) acknowledging distance and energy avail-

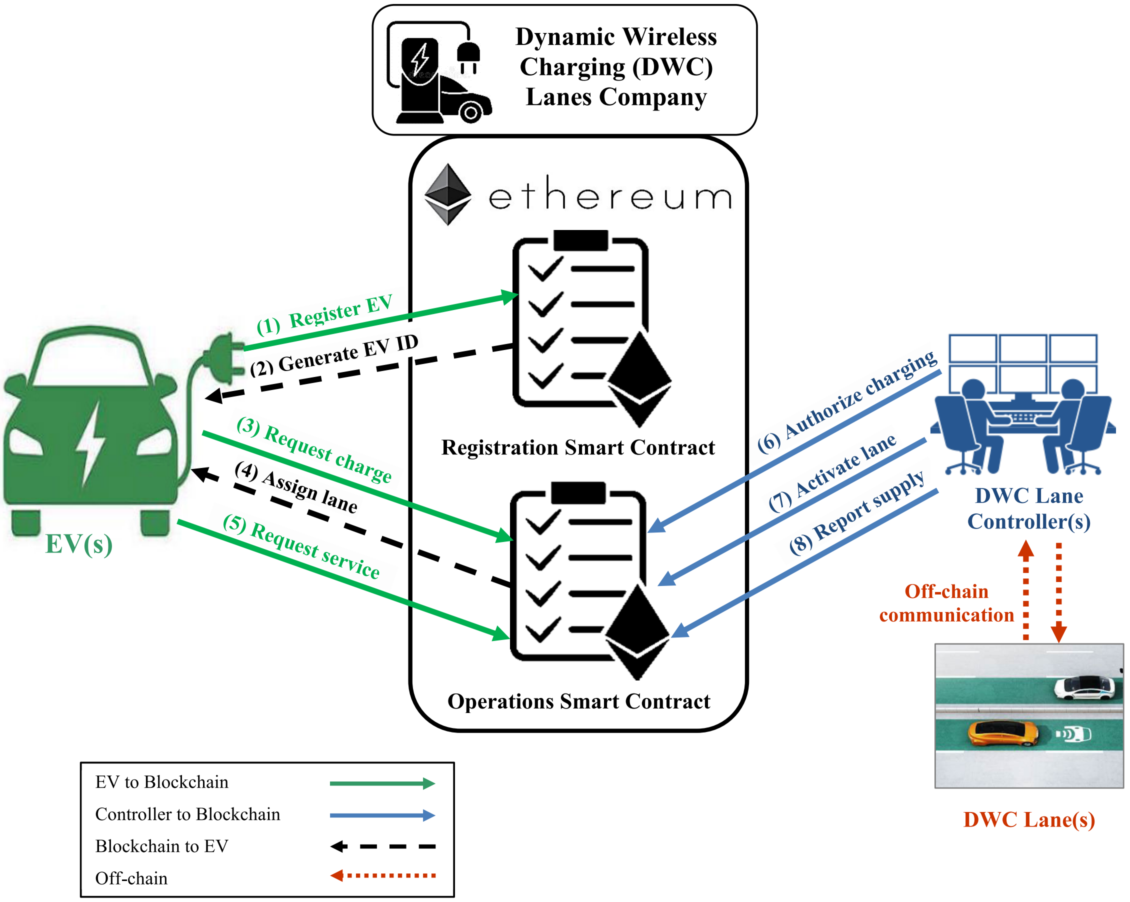


FIGURE 1. Outline of the proposed blockchain-based EV charging coordination system.

ability constraints. It also handles EV authentication, EV charging requests, lane activation and energy supply reports for billing.

The proposed system is designed utilizing the Ethereum blockchain [50] which is a distributed network that holds traceable and immutable records of the users' data and their access restrictions, as well as logs of smart contract activities and events. The SCs are developed using the Ethereum language, Solidity, to support:

- Automated, secured and tamper-proof EV registration and ID generation process.
- Authenticated, immutable, automated, traceable and transparent EV charging requests.
- Automated and optimal lane assignments according to distance and energy availability constraints.
- Verified and transparent EV service requests.
- Verified, authenticated and transparent EV charging authorization and lane activation operations.
- Tamper-proof and transparent lane energy supply reports.

The different stakeholders interact with the SCs using front-end software and/or applications that are specifically created for this purpose. In addition, each participating member receives a special Ethereum Address (EA) to communicate with the SCs which having access to all data stored on the chain, including logs and transactions. The interaction between the different stakeholders is outlined in Figure 1.

III. PROPOSED BLOCKCHAIN-BASED COORDINATION

As highlighted earlier, the proposed blockchain-based EV charging coordination system tackles issues of centralized coordination by offering a highly-secured and tamper-proof decentralized coordination framework using blockchains. The system starts operating once the SCs are deployed by the DWC company. At this stage, each WCL is already assigned a unique EA by the DWC company. The different phases of the charging coordination process are performed by the respective smart contracts as follows.

A. REGISTRATION PHASE

At the deployment stage, the system captures the DWC company name and EA and initiates the interaction between the EVs and the WCL controllers. First, each EV has to register in the system to benefit from its services. In order to register, each EV enters its plate number p_i, into the

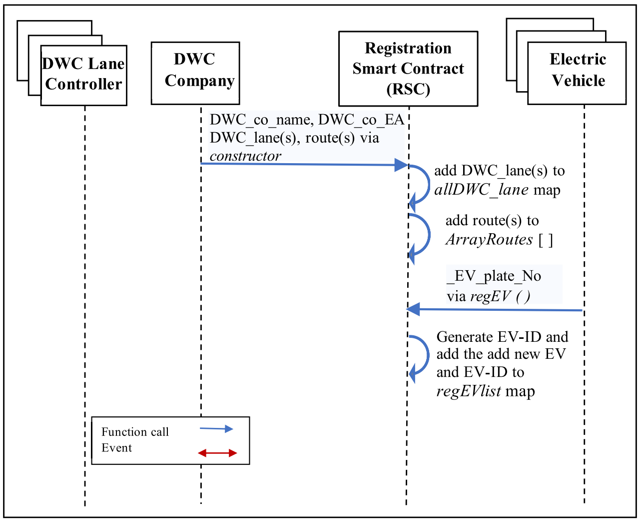


FIGURE 2. **Message sequence involved in the EV registration process.**

RSC. The RSC automatically checks the availability of the corresponding EA a_i, and compares it to existing EV EAs in set A to check for any duplication. The RSC then generates a unique ID for the EV, I_i, using the keccak256 cryptographic hash function with the vehicle plate number, EA and time of registration as input parameters. In Solidity, the different record entities, i.e. lists/arrays of data, are stored in a *map*. Figure 2 demonstrates the message sequence for deployment and registration of new EVs using the *regEV* function and the corresponding *maps*, while Algorithm 1 demonstrates the logic of the EV registration process.

Algorithm 1 EV Registration Process

```
Define registered_EV map
Function: regEV
for each incoming EV $i \in M$ do
    Input: EV plate number, $p_i$
    Generate: EV Ethereum address, $a_i$
    if $a_i \notin A$ then
        Generate EV_ID, $I_i$
        $I_i = \mathbf{keccak256}\{p_i, a_i, time\}$;
        Assign $I_i \leftarrow \{p_i, a_i\}$ in registered_EV
    end if
end for
```

B. OPTIMAL EV-TO-WCL ASSIGNMENT

Once registered, any EV that needs to charge is eligible to submit a request to the OSC. In this charging request, the EV submits details of the origin and destination points of its intended trip along with its expected traveling distance, remaining battery energy and requested recharging energy. The OSC loops through all possible routes connecting the designated origin and destination through each WCL and selects a subset of feasible lanes given a minimum distance criteria. In this work, the criteria is to include the subset of WCLs that can be reached by the EVs while maintaining a total trip length that is 2× the length of the direct route between the origin and destination points. That is,

$$r_{o\hat{j}d_i} \leq 2\, r_{od_i}, \tag{1}$$

where $r_{o\hat{j}d_i}$ is the total trip length from the origin to the destination going through the assigned charging lane and r_{od_i} is the direct trip length from the origin to the destination. Within the subset of feasible lanes, the OSC then selects the candidate lanes that can provide charging service to this particular EV request based on the remaining EV mileage. That is,

$$r_{o\hat{j}d_i} \leq m_i, \tag{2}$$

where m_i is the remaining mileage that can be driven by the requesting EV giving its current battery SoC.

Once the distance and mileage constraints in (1) and (2) are enforced, the OSC then performs the final loop through the candidate WCLs to achieve the desired load balancing objective. This takes place by assigning the requesting EV to the WCL that has the supplied the minimum energy within the current allocation time slot, in comparison with the average supplied energy by all WCLs. This is defined using the equation,

$$\textbf{Minimize} \quad E_j - E_{avg} \qquad \forall j \in N, \tag{3}$$

where E_j is the energy supplied per DWC lane j and $E_{avg} = \frac{1}{N}\sum_{j=1}^{N} E_j$ is the average energy supplied by all the lanes. This optimal EV-to-WCL assignment is executed using the function *req_EV_charge* described in Algorithm 2.

C. LANE ACTIVATION, CHARGING, AND REPORTING

Once the EV reaches its assigned WCL, the OSC is recalled by the EV to fulfill the charging service using the *req_EV_service* function. The EV user enters the EV ID, assigned lane number and required energy. The OSC verifies this information, emits an event announcing the service request, and adds the EV request as an input to the service requests map. The lane controllers, equipped with event listeners, capture the announcement and the controller of the assigned lane accordingly authorizes the charging service. The lane controller then enters the EV ID, lane number and required energy in the *authorize_EV_charge* function. The OSC verifies the information and matches it with the request submitted by the EV. It also verifies the EA of the WCL and activates it accordingly. The WCL activation process happens off-chain while the action follow-up takes place on-chain. The lane controller inserts the activated lane number, EV ID and required energy to the OSC to be added to the activated lanes map and saved in the blockchain's distributed records. This is demonstrated in Algorithm 3.

Finally, once the charging is completed and the EV leaves the lane, the lane controller uploads the information to the OSC which saves them to the supplied energy

Algorithm 2 EV-to-WCL Assignment Process

```
Function: req_EV_charge
Require msg.sender ∈ registered_EV
for each incoming request from EV $i \in M$ do
    Define Routes map
    Define selected_routes map
    Define candid_L_EV map
    Define assign_L_EV map
    Input $\{I_i, o_i, d_i, r_{od_i}, m_i, e_i\}$: EV_ID, O_Region, D_Region, Distance, remain_battery_dist, req_energy.
    Define Routes = $\{ojd_i\}$ $\forall j \in N$
    for $r \in$ Routes do
        Calculate route length $r_{ojd_i}$.
        if $r_{ojd_i} \leq 2 * r_{od_i}$ then
            route_count += 1
            Add route $r$ to selected_routes.
        end if
    end for
    if route_count == 0 then
        Emit "EV $I_i$ will not be served."
    else
        for $k \in$ selected_routes do
            if $r_{od_i} \leq m_i$ then
                cand_count += 1
                Add candidate route $k$ to candid_L_EV
            end if
        end for
        for $c \in$ candid_L_EV do
            Assign EV $i$ to WCL $\hat{j}$ to satisfy (3).
            AssignCount += 1
            Assign $I_i \leftarrow \{\hat{j}, e_i\}$ to assign_L_EV.
        end for
    end if
end for
```

records and emits an event declaring a successful charging operation using the *report_supplied_energy* function. Figure 3 then demonstrates the message sequencing of the charging request, optimal lane assignment and service request operations with the corresponding *map* records, along with an outline of the lane authorization, lane activation and energy supply reporting processes.

IV. IMPLEMENTATION AND TESTING

In order to test the operation of the proposed blockchain and SC-based coordination system, a case study of an optimally deployed network of WCLs in the cities of Dubai and Sharjah - UAE is considered, based on the study conducted in [6]. Origins and destinations are defined using 200 equal-sized, square-shaped regions, covering a total of 3859.19 km of drivable roadways and a total area of 801.12 km^2. These are shown in Figure 4. Due to the lack of empirical data on EV mobility within the road network under consideration, the machine learning-based demand prediction model in [8] is adopted to simulated incoming EV charging requests.

Algorithm 3 Charging Authorization and WCL Activation Functions

```
Function: req_EV_service
for each EV $i \in M$ do
    Input $\{I_i, \hat{j}_i, e_i\}$: EV_ID, lane_no, req_energy.
    Require msg.sender ∈ registered_EV
    if input $\{\hat{j}_i, e_i\}$ == $\{\hat{j}_i, e_i\}$ in assign_L_EV then
        Emit EV_request_service message
    end if
end for
    ▷ Assigned EV arrived and verified at corresponding WCL.

Function: authorize_EV_charge
for each EV $i \in M$ do
    Input $\{I_i, \hat{j}_i, e_i\}$: EV_ID, lane_no, req_energy.
    Require msg.sender ∈ lane_EA in EV_req_service
    if input $\{\hat{j}_i, e_i\}$ == $\{\hat{j}_i, req_G\}$ in EV_req_service then
        Run activate_lane function.
    end if
end for

Internal Function: activate_lane
for each EV $i \in M$ do
    Input $\{I_i, \hat{j}_i, e_i\}$: EV_ID, lane_no, req_energy.
    Emit activateLane
end for
```

The Remix IDE [51], which also provides debugging features, is utilized for developing and testing the SCs. The SCs are first deployed by the DWC company which is assumed to have the EA: 0 × 5B38Da6a701c568545dCfcB03FcB875f56beddC4. The available WCLs, their numbers, EAs, their energy supply capacity and the routes they serve are inserted via the constructor. Figure 5 demonstrates the successful deployment of the system.

The EV registration process is tested by selecting a test EA and inserting the EV plate number via the *regEV* function. The SC captures the following information:

- Plate number of the EV, *EV_plate_No*,
- ID of the EV driver, i.e. the message sender, *msg.sender*,
- Request timestamp, *block.timestamp*.

These are used as input parameters to the keccak256 hash function to successfully create the EV ID indicating the registration of a new EV. The EV then submits a charging request to the system via *req_EV_charge* function by inserting the following parameters:

- ID of the EV, *EV_ID* (generated by the RSC): 98783
- Region ID of the origin, *O_Region*: 105
- Region ID of the destination, *D_Region*: 107

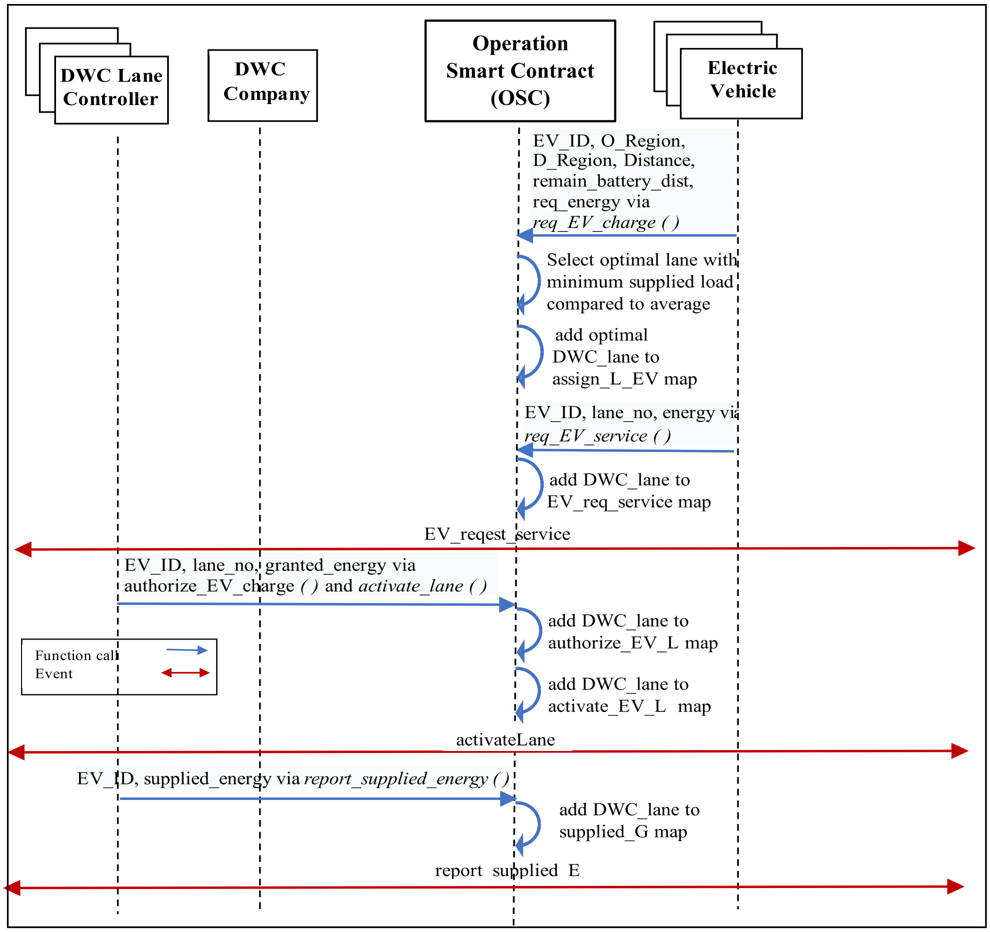


FIGURE 3. Message sequence involved in the EV charging request, lane assignment and activation processes.

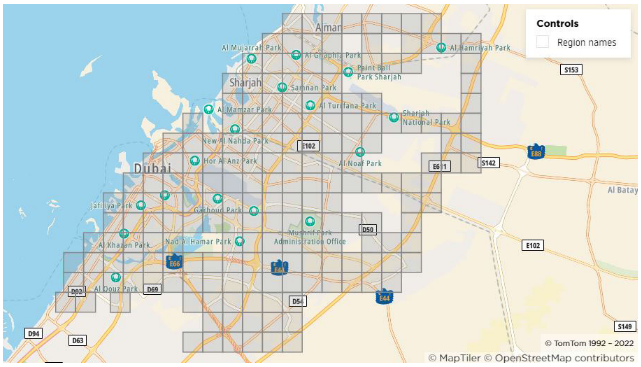


FIGURE 4. Regions used as origins and/or destinations in the charging coordination system under consideration.

- Direct distance between origin and destination, *D_Distance*: 15,000 meters
- Remaining EV mileage, *remain_battery_dist*: 14,900 meters
- EV energy demand, *req_energy*: 200 Wh

The OSC successfully executes the function as shown in Figure 6 and loops over existing routes. The OSC finds 4 routes connecting regions 105 and 107 as demonstrated in Table 1. Accordingly, the OSC generates a list of 3 selected WCLs that fulfill the condition in (1). For simplicity, the WCLs are identified with the ID of the region at which the lane starting point is located. In this case, the lanes falling in regions 78, 90 and 67 are selected. This is shown in Figure 7.

TABLE 1. Routes connecting origin region 105 to destination region 107.

Origin	Lane Region	Destination	Distance (m)
105	78	107	7212
105	90	107	14805
105	67	107	23518
105	73	107	41704

Then, the OSC generates a list of 2 candidate lanes which the EV can reach with its remaining mileage, according to constraint (2). This is shown in Figure 8. The OSC then calculates the supplied energy by all lanes and finds the difference between the average energy supplied by all lanes and the individual supply by each lane. The OSC then assigns the lane with the minimum difference to serve the EV charging request in order to achieve the desired load balance

```
[vm]  from: 0x5B3...eddC4 to: EVcharging.(constructor) value: 0 wei
data: 0x608...70033 logs: 0 hash: 0x5c9...a2934
status                 true Transaction mined and execution succeed
transaction hash       0x5c9d0829f81a903ebb6002583ce82e5de9891f7a631dc9b1a2e854d8a01a2934
from                   0x5B38Da6a701c568545dCfcB03FcB875f56beddC4
to                     EVcharging.(constructor)
gas                    7524217 gas
transaction cost       6544165 gas
execution cost         6156393 gas
input                  0x608...70033
```

FIGURE 5. Successful deployment of the system on the Ethereum blockchain.

```
[vm]  from: 0x0A0...C70DC to: EVcharging.regEV(string) 0xd91...39138
value: 0 wei data: 0xb81...00000 logs: 0 hash: 0x54c...264a6
status                 true Transaction mined and execution succeed
transaction hash       0x54cf8b3df1a9782b82ae040136988fb783f64ddc7ac824acebde864872c264a6
from                   0x0A098Eda01Ce92ff4A4CCb7A4fFFb5A43EBC70DC
to                     EVcharging.regEV(string) 0xd9145CCE52D386f254917e481eB44e9943F39138
gas                    161151 gas
transaction cost       140131 gas
execution cost         118611 gas
input                  0xb81...00000
decoded input          {
                               "string _EV_plate_No": "A111"
```

FIGURE 6. Successful execution of a new EV registration function on the smart contract.

among the WCLs under consideration. Figure 9 shows the SC assignment of the optimal lane to the EV with ID 98783.

In order to verify the load balancing functionality of the smart contract, another EV is registered and the RSC generates a new EV ID of 87499. The EV is then assumed to submit a charging request to the system via *req_EV_charge* function by inserting the following parameters:

- *EV_ID* (generated by the system): 87499
- *O_Region*: 105
- *D_Region*: 107
- *D_Distance* (direct distance): 15,000 meters
- *remain_battery_dist*: 14,900 meters
- *req_energy*: 300 Wh

The OSC calculates the average energy currently supplied by the two candidate lanes to be $E_{avg} = 50$ Wh and finds the difference between the supplied energy for each lane and the average energy supplied, according to (3). This is found to be 150 Wh for lane 78 and 50 Wh for lane 90. Therefore, the SC correctly assigns lane 90 as shown in Figure 10.

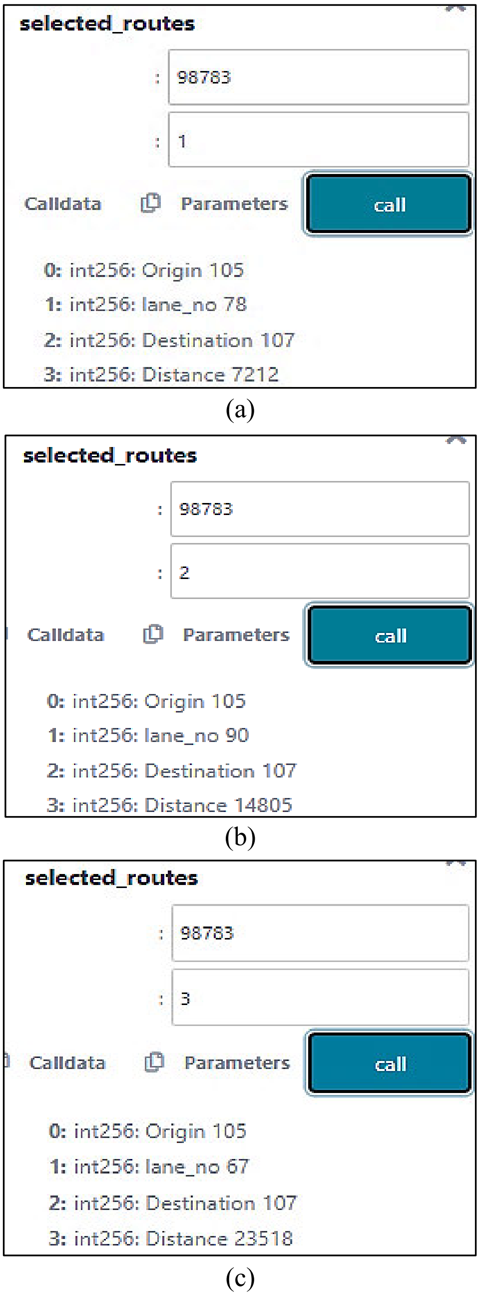
A third vehicle is also registered and is assigned the ID 906277. The *req_EV_charge* function input parameters are:

- *EV_ID* (generated by the system): 906277
- *O_Region*: 104
- *D_Region*: 109
- *D_Distance* (direct distance): 18,000 meters
- *remain_battery_dist*: 17,000 meters
- *req_energy*: 1,000 Wh

The OSC correctly assigns lane 73 as shown in Figure 11 after executing all the previously detailed steps to ensure load balancing among the WCLs. This confirms the optimal operation of the load balancing EV-to-WCL assignment algorithm. The OSC then provides a list of all assigned requests in the *listAssign* map for stakeholders to follow up on the performance of the system.

The OSC developed in this work also supports a request rejection option in case no lane could be assigned to an EV charging request due to unfulfillment of the assignment rules. The EV with ID 98783 is assumed to have requested the services once reaching the location of lane 78 using the function *req_EV_service* by inserting the following parameters:

- *EV_ID*: 98783



```
: 98783
: 1
0: int256: Origin 105
1: int256: lane_no 78
2: int256: Destination 107
3: int256: Distance 7212
```

(a)

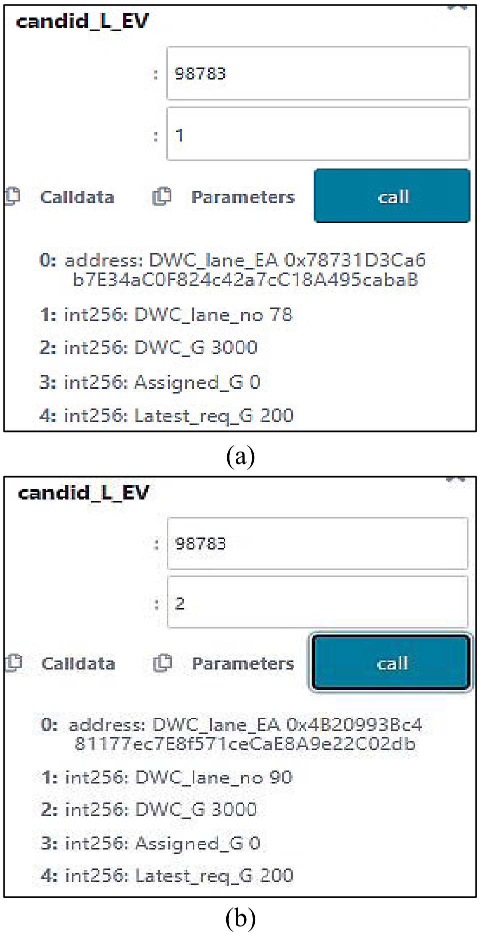
```
: 98783
: 2
0: int256: Origin 105
1: int256: lane_no 90
2: int256: Destination 107
3: int256: Distance 14805
```

(b)

```
: 98783
: 3
0: int256: Origin 105
1: int256: lane_no 67
2: int256: Destination 107
3: int256: Distance 23518
```

(c)

FIGURE 7. **The three selected lanes for the charging request by the EV with ID 98783.**



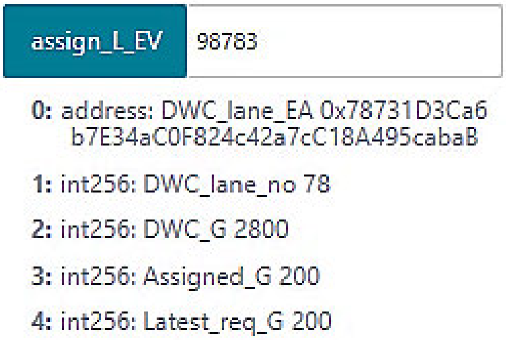
```
: 98783
: 1
0: address: DWC_lane_EA 0x78731D3Ca6
   b7E34aC0F824c42a7cC18A495cabaB
1: int256: DWC_lane_no 78
2: int256: DWC_G 3000
3: int256: Assigned_G 0
4: int256: Latest_req_G 200
```

(a)

```
: 98783
: 2
0: address: DWC_lane_EA 0x4B20993Bc4
   81177ec7E8f571ceCaE8A9e22C02db
1: int256: DWC_lane_no 90
2: int256: DWC_G 3000
3: int256: Assigned_G 0
4: int256: Latest_req_G 200
```

(b)

FIGURE 8. **The two candidates lanes for the charging request by the EV with ID 98783.**



```
98783
0: address: DWC_lane_EA 0x78731D3Ca6
   b7E34aC0F824c42a7cC18A495cabaB
1: int256: DWC_lane_no 78
2: int256: DWC_G 2800
3: int256: Assigned_G 200
4: int256: Latest_req_G 200
```

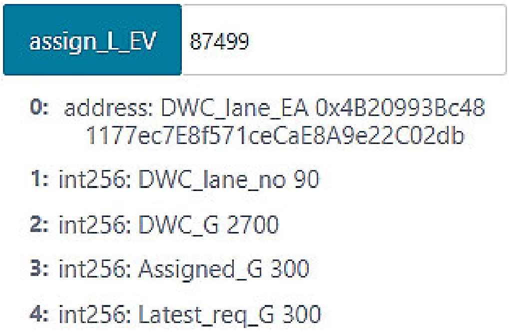
FIGURE 9. **Successful assignment of EV with ID 98783.**

- Assigned lane ID, *lane_no*: 78
- Energy demand, *req_energy*: 200 Wh

The OSC executes the function as shown in Figure 12 by ensuring that the request parameters correctly match the assignment parameters, emitting the event *req_EV_service* and adding the request parameters to *EV_req_service* map. At this stage, the lane controller authorizes the charging service using the function *authorize_EV_charge* which calls the function *activate_lane*. Figure 13 demonstrates the successful execution of the function. Once the EV finishes charging, the lane controller reports the energy delivered during the charging process using the function *report_supplied_energy* where the required parameters are inserted into the *supplied_G* map.

V. PERFORMANCE EVALUATION

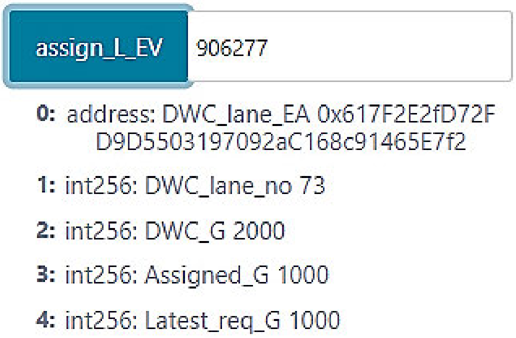
This section provides a detailed security, vulnerability and cost analysis for the proposed blockchain-based EV charging coordination system for a network of WCLs.



```
assign_L_EV    87499

0:  address: DWC_lane_EA 0x4B20993Bc48
      1177ec7E8f571ceCaE8A9e22C02db
1: int256: DWC_lane_no 90
2: int256: DWC_G 2700
3: int256: Assigned_G 300
4: int256: Latest_req_G 300
```

FIGURE 10. Successful assignment of EV with ID 87499.



```
assign_L_EV    906277

0:  address: DWC_lane_EA 0x617F2E2fD72F
      D9D5503197092aC168c91465E7f2
1: int256: DWC_lane_no 73
2: int256: DWC_G 2000
3: int256: Assigned_G 1000
4: int256: Latest_req_G 1000
```

FIGURE 11. Successful assignment of EV with ID 906277.

TABLE 2. Cost analysis of the different system functions.

Function	Tx cost (Gas)	Tx fees (Ether)	Tx fees ($)
Deployment	6,544,165	0.20941	396
req_EV_charge	140,131	0.00448	8.47
req_EV_service	149,206	0.00477	9.02
authorize_EV_charge	265,027	0.00848	16.04
report_supplied_energy	138,869	0.00444	8.4

A. COST ANALYSIS

The deployment of the SC code involves payments [52]. Miners use their resources, including electricity, time, and hardware to run the SC code simultaneously. As a result, there are specific "gas fees" associated with executing SCs rather than being free. A unit of cost called gas was created to quantify and compensate miners for their work in executing a smart contract in the Ethereum Virtual Machine (EVM) [53]. Thus, the gas cost should be taken into account when creating an SC in Solidity [52]. The cost of each transaction is displayed in the Remix IDE interface. Since the price of gas is not fixed, unlike the price of fiat money, the system transaction costs are computed using an Ether exchange rate of 1 Ether = $1, 886.19. The results are displayed in Table 2.

Table 2 reveals that the maximum cost is endorsed by the administrator at the deployment of the charging system. This is a result of using a constructor at the deployment stage that needs multiple variables to be written and saved on-chain for the first time. The average transaction fee is approximately $396 which is considered quite a reasonable cost to be paid by the DWC company for launching a complete EV load balance charging system that supports several operations. Looking at the remaining system functions, it is observed that the authorization function *authorize_EV_charge* is the most costly with a fee of $16.04. This is expected as it calls another function which is *activate_lane*. The average transaction costs for the rest of the functions fall below $10. These can be further reduced if a private Ethereum blockchain is utilized such that it is permissioned to specific stakeholders, similar to the solution proposed in [45].

In today's electric vehicle market, the equipment and installation costs of commercial WCLs can go as high as ≈ $1.4M-$3M per km [21] owing to the advanced technologies and features embedded within these premium charging systems. Accordingly, the transaction charges for the proposed blockchain-based coordination system represent only a minute proportion of the associated infrastructure costs, particularly acknowledging its importance in ensuring an efficient, scalable and load-balanced operation of the wireless charging process. Furthermore, in comparison with other non-blockchain-based coordination solutions with no transaction fees, the proposed system offers advantages of security, immutability and robustness, which justifies the added costs of blockchain integration. Furthermore, with mass adoption of EVs and the growing need for these decentralized charging coordination operations, economies of scale are expected to further neutralize the initially high transaction costs.

Nonetheless, it is important to highlight that the adoption of layer 2 Ethereum scaling solutions can also help in improving the cost effectiveness of the proposed solution [54]. These are a secondary set of protocols that extend the Ethereum blockchain to solve problems of scalability and transaction throughput. One of the well-known layer 2 solutions is zkSync which scales Ethereum using the zero-knowledge roll-up technology [55]. zkSync offers reduced transaction costs with higher processing speeds, while fully inheriting Ethereum's characteristics. Another layer 2 solution is Loopring which lowers the transaction costs to 0.1% of the Ethereum Mainnet and increases the throughput by 1000×, while maintaining the security level of layer 1. These layer 2 solutions are recommended for future works but are beyond the scope of this work.

B. SECURITY AND VULNERABILITY ANALYSIS

The proposed EV charging coordination system inherits significant characteristics from blockchain as its supporting technology. These include,

- Man in The Middle (MITM) attack: This attack happens when a malicious entity interferes with the information relevant to the process and blocks communication between two legitimate stakeholders. However, the blockchain withstands this attack as it is a fundamental requirement for all transactions to be cryptographically

```
[vm]  from: 0x0A0...C70DC to: EVcharging.req_EV_service(int256,int256,int256) 0xd91...39138 value: 0 wei
data: 0x22d...000c8 logs: 1 hash: 0x056...b0927
status                    true Transaction mined and execution succeed
transaction hash          0x0567c703298cbb70f2c82684fac6e9f9bc271f970a1441f4adf37992128b0927
from                      0x0A098Eda01Ce92ff4A4CCb7A4fFFb5A43EBC70DC
to                        EVcharging.req_EV_service(int256,int256,int256) 0xd9145CCE52D386f254917e481eB44e9943F39138
gas                       171587 gas
transaction cost          149206 gas
execution cost            127698 gas
input                     0x22d...000c8
decoded input             {
                                  "int256 EV_id": "98783",
                                  "int256 L_number": "78",
                                  "int256 energy": "200"
                          }
decoded output            {}
logs                      [
                                  {
                                          "from": "0xd9145CCE52D386f254917e481eB44e9943F39138",
                                          "topic": "0x4d5cb6b7527955d0e0c5eb8fdfad2261025d6eed604f370faa2321c6e9de9720",
                                          "event": "EV_reqest_service",
                                          "args": {
                                                  "0": "Ev request service",
                                                  "1": "98783",
                                                  "2": "78"
```

FIGURE 12. Successful execution of the *req_EV_service* function.

```
[vm]  from: 0x787...cabaB to: EVcharging.authorize_EV_charge(int256,int256,int256) 0xd91...39138
value: 0 wei data: 0x2d8...000c8 logs: 1 hash: 0x588...56e04
status                    true Transaction mined and execution succeed
transaction hash          0x588db752c0cb81503fd65211607ae744c43e66b2e1a8e520cbaa52d97e856e04
from                      0x78731D3Ca6b7E34aC0F824c42a7cC18A495cabaB
to                        EVcharging.authorize_EV_charge(int256,int256,int256)
                          0xd9145CCE52D386f254917e481eB44e9943F39138
gas                       304782 gas
transaction cost          265027 gas
execution cost            243519 gas
input                     0x2d8...000c8
decoded input             {
                                  "int256 Vehicle_id": "98783",
                                  "int256 Lane_number": "78",
                                  "int256 granted_energy": "200"
                          }
decoded output            {}
logs                      [
                                  {
                                          "from": "0xd9145CCE52D386f254917e481eB44e9943F39138",
                                          "topic":
                          "0x197d019dc91d89bc233fe0a29f12d2b7ea9d1e1c72aef2f55bff2c70524e3dd0",
                                          "event": "activateLane",
                                          "args": {
                                                  "0": "98783",
                                                  "1": "78",
                                                  "2": "200"
```

FIGURE 13. Successful execution of the *authorize_EV_charge* function.

signed using the sender's private key. Since it is impossible to create a fake private key, and because the transactions in each block are linked to the previous and the following blocks, this attack completely fails in blockchain-based systems.

- Non-repudiation: On the blockchain, the sender's private key is used to sign each transaction. This cryptographic protocol is essential for all network users. Participants on a blockchain cannot decline to send or accept a transaction. A transaction moves forward to complete the requirements to be added to a block once it has been signed. As a result, nodes cannot choose whether to validate transactions or not.
- Availability: Because Ethereum is a distributed blockchain by design, all the network nodes will save the SC codes and the records of how they were executed. This means that even if certain nodes experience problems or lose their connection to the blockchain, the blockchain will always be functional. Hence, the proposed SCs are always available thanks to this structure, which also solves the single-point-of-failure problem. The availability of the proposed EV charging

TABLE 3. Comparison of proposed system with existing literature.

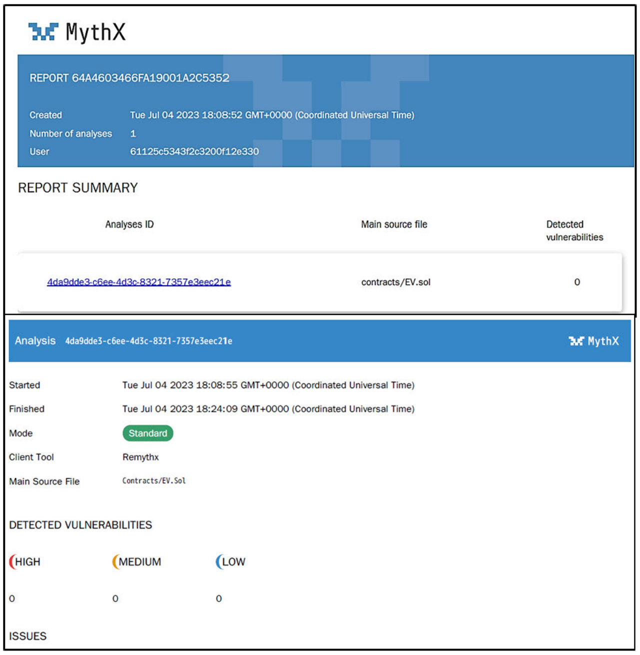
Ref.	On-chain transactions						Scheduling	Spatial coordination
	Registration	Authentication	Coordination algorithm	Charging activation	Energy reporting	Billing		
[43]	√	√	x	x	x	√	x	√
[44]	√	√	x	x	x	x	√	x
[45]	√	√	x	x	√	√	√	x
This work	√	√	√	√	√	x	x	√

coordination system is not jeopardized by some nodes' unavailability. This is because, the nodes that are still a part of the decentralized network are going to mine and validate the execution transactions. Additionally, the history of transactions will always be accessible because replicated data is always stored at each node.

- Accountability is upheld since legitimate transactions are recorded onto the logs, time-stamped, and preserved in an immutable ledger. As a result, system users are responsible for their actions.
- Integrity: In the proposed blockchain-based charging coordination system, integrity refers to the fact that data is stored and saved immutably, with no possibility of deletion or alteration by any entity. As a result, the system logs' integrity is guaranteed, and all event listeners can rely on the system's on-chain data. Cryptography is used to protect data integrity. Each legitimate transaction that contains sensitive system data is encrypted, recorded in the ledger, and registered on-chain. This makes sure that system transactions can neither be canceled nor reversed.
- Transparency: All participants are always able to view and comprehend the transactions of the system functions with their associated logs. Since it increases trust in the activities carried out, transparency is crucial for the integrity and dependability of the EV charging system.

To further evaluate the vulnerability of the developed SCs, the Remix development environment checks for compilation and run-time issues. The successful compilation and testing of the SCs prove that they are free of bugs and errors. In addition, Solidity 0.8 version compiler is used for the development which automatically detects integer underflow and integer overflow vulnerabilities. Moreover, the leading Ethereum smart contracts security analysis service, Mythx [56], is used to run a professional security analysis on the developed system codes. Mythx is capable of preventing expensive security errors as it identifies several security and vulnerability problems such as:

- Byte-code safety,
- authorization controls,
- assertions and property inspection,
- Solidity coding best practices,
- control flow.



MythX

REPORT 64A4603466FA19001A2C5352

Created Tue Jul 04 2023 18:08:52 GMT+0000 (Coordinated Universal Time)
Number of analyses 1
User 61125c5343f2c3200f12e330

REPORT SUMMARY

Analyses ID	Main source file	Detected vulnerabilities
4da9dde3-c6ee-4d3c-8321-7357e3eec21e	contracts/EV.sol	0

Analysis 4da9dde3-c6ee-4d3c-8321-7357e3eec21e MythX

Started Tue Jul 04 2023 18:08:55 GMT+0000 (Coordinated Universal Time)
Finished Tue Jul 04 2023 18:24:09 GMT+0000 (Coordinated Universal Time)
Mode Standard
Client Tool Remythx
Main Source File Contracts/EV.Sol

DETECTED VULNERABILITIES

HIGH	MEDIUM	LOW
0	0	0

ISSUES

FIGURE 14. Security analysis report generated by Mythx for the developed smart contracts.

Figure 14 shows the security analysis report generated by Mythx for the developed SCs.

C. FURTHER INSIGHTS

A comparison of the scope of the proposed system with existing works on EV charging coordination using blockchains is shown in Table 3. Furthermore, acknowledging the advantages offered by the proposed blockchain-based charging coordination system, the following limitations and areas of improvement are highlighted.

- Conventional blockchains suffer from scalability issues due to the complex consensus algorithms used in PoW and PoS validation processes. Hence, lightweight and scalable blockchains are essential for utilization in EV-related applications to enable efficient real-time energy management and response to EV charging requests.
- Further improvements to the Ethereum blockchain are expected to enable its connectivity to other data sources/applications through application programming

interfaces (APIs). This shall enhance the route selection process by allowing the operations smart contract to communication with Google Maps API or other geographical information system (GIS) tool to obtain real-time route status and traffic updates. This offers more convenient route selection that minimizes the traffic time for the EV drivers in addition to achieving the desired load balancing objectives.

- The proposed coordination algorithm can be further expanded to incorporate the EV charging price as an input and/or output of the optimal EV-to-WCL assignment plan. The charging price as an input is one of the factors governing the optimal assignment to minimize charging costs for EV users and/or maximize revenues for the WCL operators. In contrast, an output pricing signal can be provided by the algorithm to reflect the level of congestion at the different WCLs.

VI. CONCLUSION

This work presents an end-to-end implementation of a blockchain-based EV charging coordination and management system in a network of WCLs within an Internet of Electric Vehicles. This leverages on the security, immutability and transparency advantages of blockchains and utilizes smart contracts to execute the coordination algorithms on-chain to ensure process security and integrity. The proposed system is proven secure and cost-effective when implemented on an Ethereum blockchain, and is recommended for on-the-move EV charging management acknowledging its low latency and real-time operation. Nonetheless, with the currently low implementations of DWC systems, future studies may test the operation of the proposed system in real-world EV-to-charging-station assignment problems while imposing strict requirements on execution latency and communication delays to reflect the requirements of a DWC system. In addition, further research may leverage on the load balancing objective adopted in this work to investigate the operation of a blockchain-based auctioning scheme that utilizes smart contracts for maximizing the benefit of the bidders while achieving grid-related objectives.

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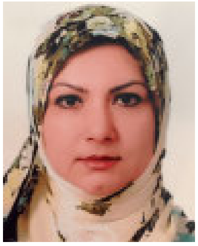

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