The Road Ahead: DAO-Secured V2X Infrastructures for Safe and Smart Vehicular Management

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***Abstract*—Vehicle-to-Everything (V2X) technology relies on wireless communication and coordination, aiming to improve road safety and traffic efficiency by orchestrating the interaction among the vehicles, infrastructures, and various entities. However, existing organizational and operational forms of V2X infrastructures encounter significant challenges, such as the capability to guarantee communication security, privacy, and efficiency especially when a centralized management system is used. The emerging Decentralized Autonomous Organizations and Operations (DAOs) present a solution to these challenges. DAOs embed managerial and operational protocols within a blockchain via smart contracts, facilitating smooth and efficient management of organizations without the necessity for centralized oversight. This letter introduces DAOs into the coordination of V2X infrastructures. Through a tripartite functional architecture including organization, coordination, and execution, we can achieve intelligent collaborative management among road infrastructures and vehicles. The DAO-secured V2X infrastructures are anticipated to augment the safety and efficiency of vehicular management in complex road scenarios, holding applicable potential for developing the intelligent roadways of tomorrow.**

***Index Terms*—Decentralized autonomous organization and operation (DAO), vehicle-to-everything (V2X), infrastructures, vehicular management, artificial intelligence.**

I. Introduction

VEHICLE-TO-EVERYTHING (V2X) technology, which focuses on wireless communication and coordination among vehicles (V2V), infrastructures (V2I), pedestrians (V2P), and other entities, holds the promise to enhance road safety and traffic efficiency [1]. Serving as important components, V2X infrastructure entities such as roadside units, traffic signs and lights, are treated as fixed and mobile sensors in vehicular environments, which can provide a wealth of information for V2X applications to enable smart transportation solutions. While advances in the coordination and organization of V2X infrastructures are promising for vehicular management, there are still a number of pressing issues that need to be addressed, including security vulnerabilities, privacy, data ownership, and inefficient central management.

Decentralized Autonomous Organizations and Operations (DAOs) embed managerial and operational protocols within a blockchain via smart contracts, facilitating seamless and effective organizational management without centralized control. Using these key technologies, DAOs are poised to become a secure and efficient organizational paradigm in uncertain, diverse, and complex environments. Although initial DAO explorations have surfaced in finance, science, and social networks [2], [3], [4], investigations within the V2X and V2I sectors are limited. Some discussions suggest blockchain-based decentralized V2X, veering toward security authentication and decentralized traffic governance [5]. Built on blockchain, DAOs inject organizational and operational frameworks into V2X infrastructures, and aided by artificial intelligence (AI) algorithms, aim to cultivate a more systematic vehicular management paradigm.

This letter introduces a DAO-secured V2X infrastructure coordination framework. It increases reliability and trust in data interchange among vehicles and infrastructures through blockchain applications. Moreover, it enables coordinated decision-making even in complex traffic scenarios, eliminating the need for hierarchical or centralized management systems. This fresh architecture sheds light on the route toward future safe and smart vehicular management [6].

II. Challenges and Issues With Existing V2X Infrastructures

A. Security Issues

V2X infrastructures enable V2V and V2I communications. Entities, notably autonomous vehicles, engaging in these communications are prime cyber attack targets, threatening their driving or communication capabilities [7], [8]. These vulnerabilities can lead to vehicle and/or passenger damage, user data breaches, or even network disruptions by maliciously rerouting or halting vehicles in critical areas, or using vehicles for Denial-of-Service attacks. These threats add a new dimension for attackers to exploit, disrupting mobility and eroding public

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trust in autonomous transport systems, thus diminishing their societal benefits [9], [10]. However, vehicles in DAO-enriched V2X infrastructures will enjoy enhanced communication security through blockchain applications [11], thereby reducing exploitable communication weaknesses.

B. Democratization of Resource Allocation

In traditional V2X systems, a central traffic control unit allocates infrastructure resources and routes based on set criteria [12], [13]. However, this top-down resource allocation and management approach may lead to inequitable allocation, resource monopolization, and wasteful utilization due to the central node's lack of awareness of the needs and operational statuses of downstream individuals [14]. This also undermines trust and collaboration within the vehicular network, challenging the enforcement of subsequent central node policies. On the contrary, the DAO ecosystem democratizes resource allocation processes within the V2X infrastructure, promoting open and transparent communications among network nodes.

C. Scaling and Autonomy Challenges

Traditional organization structures employ a top-down hierarchy reliant on a central controller for travel demand information collection and network-wide instruction distribution [15]. These systems, primarily focusing on region-wide optimization, involve passive user participation in decision-making processes. This approach can potentially lead to scalability issues and suboptimal resource utilization, primarily due to the complexities of centralized computation. In contrast, the DAO-based infrastructure paradigm shifts toward a more distributed approach. It allows the computation to be shared among vehicles, independent of the central infrastructure. This not only preserves driving autonomy but also facilitates dynamic vehicle routing, thereby enhancing overall system efficiency and responsiveness to real-time traffic conditions [16].

III. DAO-Secured V2X Infrastructures

A. The Architecture

The architecture of DAO-secured V2X infrastructures is illustrated in Fig. 1. It encompasses five layers, namely Foundation, Organization, Coordination, Execution, and Application, aimed at realizing safe and smart vehicular management.

The foundational layer encapsulates the key technologies of DAOs and V2X infrastructures. The DAO is blockchain-encoded, propelled by smart contracts, Web 3.0, and AI. In this setup, blockchain utilizes an encrypted block chain for data validation and storage, a distributed node consensus algorithm for data generation and updating, and smart contracts for data programming and manipulation, embodying a decentralized infrastructure organization and a distributed computing paradigm [2]. The DAO-based V2X infrastructures interface with vehicular systems, encompassing sensor, computing, control, communication, and power infrastructures like cameras, multi-access edge computing units, traffic lights, cellular base stations, and microgrids, respectively. Within the DAO framework, these infrastructures and connected vehicles act as DAO nodes, forming autonomous organizations. They follow a tripartite architecture including organization, coordination, and execution to actualize vehicular management applications and services.

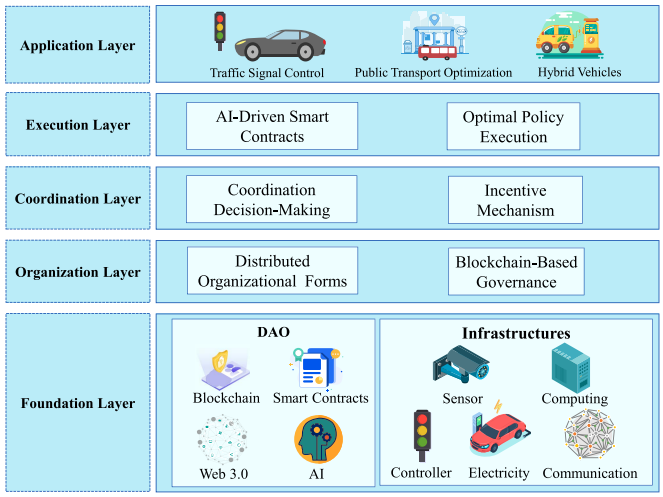

Fig. 1. Architecture of DAO-secured V2X infrastructures.

The organization layer forms a V2X infrastructure-driven vehicular management structure. It is a collaborative system with holistic objectives and a role/responsibility allocation mechanism, adaptable to evolving strategies. It devises organizational forms and governance mechanisms. Various structures are conceived based on functions and vision, assigning distinct rights to each node. A blockchain-based proposal system is employed for governance, elevating individual needs to blockchain, with DAO members engaging in on-chain voting to convert individual needs into organizational objectives [17].

The coordination layer, built upon the organization layer's foundations, engages in task segmentation and decision-management for V2X infrastructures, actualizing coordination mechanisms under specific member divisions. In this context, the collective decision-making of task-oriented DAO members is paramount. They utilize a blockchain voting mechanism and incentives such as tokens and credits to foster participation. This system allows the management and control of organizational decision-making through group consensus in a trustless environment, clearly defining individual roles and tasks for executing decisions.

The execution layer, based on task divisions from the coordination layer, handles micro-level decision execution to address practical V2X vehicular management issues, like emergency vehicular management based on V2I communication. Smart contracts driven by intelligent algorithms are primary for implementing decision solutions. They encapsulate consensus rules and are deployed on the blockchain, ensuring secure, transparent processes in value/resource allocation, and decision-making. Intelligent algorithms like self-supervised learning

and reinforcement learning enable optimal execution outcomes across diverse scenarios, fulfilling vehicular management objectives.

Lastly, the application layer delivers services for safe and intelligent vehicular management. Through this architecture, a harmonized, efficient, and intelligent system for V2X interactions is facilitated, embodying a futuristic vehicular and infrastructural synergy vision.

B. The Applications for Vehicular Management

The exploitation of DAO-driven approaches in a dedicated infrastructure provides the ideal ground for a range of new potentials for smart traffic and vehicular management. This subsection elucidates three facets: collaborative sensing and proactive management, public transportation optimization, and hybrid vehicle management.

DAO-based infrastructures, which respond to specific demands of regional or local traffic, can proactively transmit pertinent information to the infrastructure and nearby vehicles. This includes both macroscopic or mesoscopic traffic status data related to traffic congestion, hazards, or specific area characteristics (such as a high presence of pedestrians near a school at closure time) [18], [19], and detailed scene data like images and point clouds [20], [21]. With clear information, DAO community members can enhance routing through collective decision-making. Moreover, by utilizing communication and edge devices, such as roadside units and smart traffic signals, complex urban maneuvers like platooning can be coordinated with synchronized traffic lights to facilitate smooth travel, ease congestion and reduce emissions [22], [23], [24].

DAOs also promote novel public transport (PT) optimization strategies, encouraging local authorities to favor PT systems over private cars by offering better passenger information and more regular services, independent of human drivers [25]. By leveraging edge devices and expansive sensor networks, DAOs significantly enhance PT system performances. They enable efficient, demand-responsive service through smartly integrated transit hubs, which adapt to varying passenger needs. They also improve the timeliness of fixed-schedule services by enabling transit signal prioritization, mediating priority movements, and advising on speeds that align with synchronized signals for effective traffic management.

Regarding hybrid vehicles, DAOs enable intelligent switching between electric and petrol modes based on the characteristics of the traversed area, a feature especially beneficial in city centers or pollution-sensitive zones where environmental impact is a key concern. With electricity infrastructures, DAOs can support energy-aware routing and strategic deployment of energy-efficient facilities. The facilities account for battery capacity, charging infrastructure, and use regenerative braking to boost vehicle range. Vehicles with low batteries are expected to utilize DAOs to negotiate priority access to charging stations, a crucial step to ensure their safe and timely arrival at destinations.

C. The Characteristics of DAO-Secured V2X Infrastructures

1) Security: Within the infrastructure, blockchain, smart contracts, and decentralized architecture are used to enhance the security of vehicular management. DAOs, through blockchain, furnish a secure, transparent, and immutable environment to ensure that all communications and decisions are verifiable. The inherent features of blockchain, such as immutability and encryption, provide a robust safeguard for the V2X infrastructure. The decentralized architecture with smart contracts augments system security by dispersing control and management authority, thus reducing the risks of single-point failures and centralized attacks.

2) Equity: The DAO-based V2X framework increases equity in resource, value, and responsibility distribution within vehicular management. In this framework, all participants, including vehicles and infrastructures, allocate essential resources fairly and transparently, reducing data and resource monopolization risks. The value distribution is handled accurately, transparently, and fairly via blockchain and smart contracts, offering appropriate incentives to high contributors to encourage better service provision. DAOs render transparent responsibility quantification, with all decisions and operations blockchain-recorded, enabling accurate traceability and verification of responsibilities.

3) Efficiency: The DAO-based V2X infrastructure can augment vehicular management efficiency. Decentralized operations and decision-making, driven by participants, tap into collective wisdom and swift consensus to speed up decisions, thus boosting responsiveness and adaptability on unpredictable roads. Moreover, the automatic execution of smart contracts reduces the need for manual handling and management, thereby enhancing the timeliness of decision-making. This can be further integrated with advanced AI technologies exemplified by foundation models [26], and intelligent testing methods represented by scenario engineering [27], [28], [29], to ensure the optimality of decisions.

IV. Conclusion and Perspective

This letter presents the integration of DAO technologies into V2X infrastructures for safe and efficient vehicular management. This decentralized V2X infrastructure framework facilitates bottom-up proactive vehicular management and democratic decision-making. By harnessing technologies such as blockchain, smart contracts, and distributed collaborative networks, the architecture facilitates coordinated and orderly vehicular organizational management, elevating the security, equity in resource allocation, and operational efficiency of vehicular management.

We can envision a future in which DAO-secured traffic infrastructures play a pivotal role in intelligent transportation systems. In this future scenario, everyone, along with every vehicle and infrastructure component, simultaneously becomes a participant and decision-maker in the intelligent transport ecosystem. Within the DAO framework, each node or entity can freely associate to form autonomous organizations, contributing their decision proposals. These proposals, shaped through organizational negotiation, align with the collective objectives of the organization. This dynamic has the potential to profoundly enhance human travel experiences and the efficiency of traffic decision-making processes.

Imagine a vehicle actively engaged in traffic management and highly esteemed within the DAO community. Should this vehicle identify an issue with the traffic light experience on a particular stretch of road, its proposal for signal control adjustment would be communicated through the DAO to other members of the organization, including traffic participants, managers, road infrastructure, and intelligent vehicular agents. Upon garnering widespread support and consensus, this proposal could lead to a modification of the signal control scheme. Such an ideal democratized vehicular management system, driven by DAO-secured infrastructures, promises to offer an exceptional mobility experience for everyone, heralding a new era of safe, smart and participatory transportation [30].

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