Crowdsensing Intelligence by Decentralized Autonomous Vehicles Organizations and Operations

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***Abstract*—With the rapid growth of connected and autonomous vehicles (CAVs), vehicular crowdsensing (VCS) has emerged as an effective way in a wide range of applications, especially in intelligent transportation systems. However, centralized VCS frameworks have confronted many problems, such as privacy, security, utility, and dependability. To remedy these challenges, blockchain technology can be applied in VCS systems for effectively forming decentralized autonomous vehicles organizations and operations. This article briefly introduces blockchain-based VCS solutions addressing the current problems and presents potential directions for future research.**

***Index Terms*—Connected and autonomous vehicles, Vehicular crowdsensing, Blockchain technology**

I. Introduction

THE practice of data collection through traditional static sensor networks is not only coverage-limited but also cost-consuming. With the enrichment of social sensors and the development of connected and autonomous vehicles (CAVs), vehicular crowdsensing (VCS) has attracted increasing attention for being effective in collecting specific data and providing precise services [1]. By integrating human and machine intelligence, this promising sensing paradigm makes full use of onboard devices and participating CAVs to collect multi-domain data, further transform the data to cognitive-level information and form crowdsensing intelligence.

Though the current centralized VCS framework brings convenience to collaborative management and control, it also confronts many severe challenges, including but not limited to privacy, security, utility, efficiency, and dependability issues [2]. Taking privacy and security issues as an example, since worker selection often requires personal information and task content are often related to a range of movement, such information may result in personal location and identity information leakage. Besides, malicious participants could be a potential threat to the central mode since they send fake results to gain rewards easily. Without effective solutions to these challenges, the participation confidence of CAVs and the widespread of VCS applications cannot be guaranteed.

Fortunately, the rapid development of blockchain technology in recent years has provided an opportunity to implement a decentralized VCS framework since it spawns the emergence of the so-called Decentralized Autonomous Organization (DAO), a new vehicle organization and operation form that various rules are encoded on a blockchain with the help of smart contracts [3]. Moreover, it can not only operate with third-party intervention but also achieve a transparent, secure, and traceable transaction of data/tasks. Therefore, some blockchain-based solutions are designed and applied to VCS to enhance the performance of VCS-based services [4]. Moreover, to cope with the complexity of social demensions and optimize the decision-making process in the decentralized VCS organizations and operations, the ACP approach and blockchain technology were integrated to construct the parallel VCS system [5].

Although promising, leveraging blockchains to build decentralized autonomous VCS systems is non-trivial and it remains several issues to be addressed [6]. First, public blockchain lack support for data privacy. Second, different entities may misbehave in serving VCS applications. Further, simply putting all workload on-chain would increase the processing costs. To remedy the current literature on "crowdsensing intelligence by decentralized autonomous vehicles organizations and operations", we propose a typical system model of blockchain-based VCS based on existing literature, briefly introduce blockchain-based VCS solutions addressing centralized VCS-related challenges, and present open issues and opportunities for future research.

II. System Model of Blockchain-based VCS

Blockchain is a distributed ledger with natural properties of decentralization, trust, anonymity, and tamper-resistant and is promising to be integrated with CAV systems to address the privacy, security, and utility issues of crowdsensing. Since interactions are traceable and immutable in a blockchain, blockchain-based VCS overcomes various vulnerabilities and improves crowdsensing in various ways, such as improving reliability, introducing a fair evaluation of reward and reputation, preserving sensitive information, and reducing deployment costs. In light of the current research, a typical system model of blockchain-based VCS is proposed, as shown in Fig. 1.

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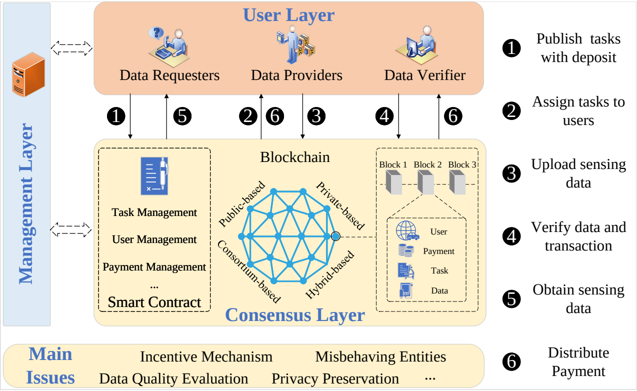

Fig. 1. An illustrative system model of blockchain-based VCS.

The system model is mainly divided into three layers: the user layer (different entities involved), the consensus layer, and the management layer [7]. The user layer is mainly responsible for handling various interactions between participating entities and the crowdsensing system. The consensus layer transmits and records various transaction information based on the blockchain network to ensure worker privacy, data security, and system efficiency. The management layer, connected by dotted arrows, is not necessarily needed in a specific blockchain-based VCS application. On-chain processing incurs a monetary cost, so simply putting all workload on-chain is highly uneconomical. Thus, it is required to realize a delicate joint on-chain and off-chain design. The management layer here is used to cope with the issues (e.g., worker reputation management) on an off-chain network to enhance execution efficiency and save execution costs.

There are mainly three kinds of entity roles in the user layer: data requester, data provider (or worker, participants), and data verifier. The requester publishes the task to the blockchain to obtain information meeting his/her needs and provide corresponding rewards. The data provider is the participating vehicle that undertakes the tasks on the blockchain. They can choose to accept tasks from a public or private blockchain according to their privacy considerations. Once the task is completed and the required data is uploaded, the data provider will be rewarded according to their contributions. While the data verifier is responsible for generating new transactions, verifying the data quality, fixing the problems, and recording them on the ledger. Since data verifiers contribute to evaluation and recording, they deserve to obtain part of the transaction costs or rewards. It is noteworthy that the identity of an entity is not fixed, that is to say, a participating user on the blockchain can be either a data provider or a data verifier.

Four categories of blockchain can be used to construct the blockchain part of the system model: public, private, consortium, or hybrid [8]. The different categories vary in their properties where the respective blockchain can be selected according to the needs of the system model. A public blockchain-based model is permissionless and open for any interested user to join, gather, allocate, and process the information through a consensus mechanism as Service Level Agreement. While a private blockchain-based model is permissioned and has certain restrictions to access the information for different entities in a VCS platform. Unlike a public blockchain, transactions are recorded by selected verifiers from the same organization. And thus, it can be designed to support some critical factors, such as privacy, security, and reliability. The consortium blockchain-based model is semi-decentralized and has a pre-selection ability to indicate the type of intelligent services in the VCS platform. A hybrid blockchain-based model integrates public and permissioned types of blockchain, in which a feature-based approach is applied to support a flexible environment for sharing secured information and easy for users to join contracts.

The functional components with respective computational mechanisms are implemented as smart contracts and hosted on blockchains. In a typical blockchain-based VCS application, a variety of smart contracts are used to transmit and record information, including user management smart contracts, task management smart contracts, compensation management smart contracts, etc. Among these, user management contract is designed to maintain and update user addresses, types, and reputation; task management contract is used to select task-worker pairs; and payment management contract is used to pay reasonable rewards to workers. The operation process of the decentralized VCS system generally includes six steps: 1) requesters release the tasks along with the data quality criteria, and advance the deposit; 2) a certain smart contract assigns tasks to appropriate workers according to the matching mechanism; 3) workers perform tasks and upload sensed data to the network; 4) verifiers evaluate the data quality and checks the legitimacy of the transaction; 5) the requester receives the data and releases subsequent rewards; 6) a certain smart contract sends rewards to workers and verifiers.

III. The Current Focus of Blockchain-based VCS

DAO paves the way for the design of decentralized autonomous VCS systems. Regarding blockchain-based VCS systems, existing studies focus on coping with the issues of location privacy preservation of participants, misbehaving entities, data quality control, incentive mechanism design, reputation management, sensitive data privacy-protection, etc [9]. This section follows a short introduction to these issues.

A. Blockchain-based location privacy and identity preservation

Current studies typically integrate blockchain, location obfuscation, and smart contract design to address the privacy issue. When a VCS application is deployed on a public blockchain, a specified mechanism is required to ensure privacy preservation, such as differential and distortion location privacy technology. Besides, instead of novel location obfuscation mechanisms, the features of private blockchain can be used to provide a secure environment. The study in [7] proposed a blockchain-enabled conditional decentralized VCS by exploring the characteristics of participating entities. Specifically, a strict privacy preservation scheme where the zk-SNARK proof is integrated with a mixed task smart contract was designed to ensure that the transaction content in the blockchain would not reveal any private information of participants. With the designed scheme, both privacy disclosure can be prevented and data confidentiality can be guaranteed. To tackle location and re-identity attacks, Yang et al. [10] proposed a MCS platform comprising several private blockchain networks and a public blockchain network. The operational process of this platform can be mainly divided into four steps: (1) requesters initiate and submit tasks to the public blockchain; (2) agents (associate miners between public blockchains and private blockchains) upload a copy of tasks to a private blockchain; (3) a smart contract allocates rewards to participants who complete tasks and contribute to blockchains (e.g., both private and public); (4) agents submit the sensed data to a public blockchain. The innovative task allocation mechanism proposed in this work ensures that the location and identity information of participants are invisible to the MCS platform.

B. Blockchain-based solutions to misbehaving entities

In a typical VCS system, the entities include requesters, participants, and a centralized platform. The different entities may misbehave, for instance, the recruited workers submit false sensing data; the requesters upload a number of tasks during a short time interval to clog the centralized server providing service for other requesters; a misbehaving platform intentionally modifies the reputation scores of participants or adjusts evaluation results of submitted data [11]. Relying on smart contracts, DAO's operational rules, participants' responsibility and authority, and the rewards and penalties terms are open and transparent. To address these security threats, the study in [12] presented a consortium blockchain-based VCS system (namely VeSenChain), which is transparent and traceable for miners accessing all interactions. The decentralized VeSenChain system tackles the security threat using a tamper-proof feature and ensures authenticity by registration on the chain. Moreover, intelligent organizations and operations among different entities (i.e., requesters, workers, and roadside units) are supported by an interactive protocol based on smart contracts. All VCS activities transactions and service requests generated by requesters are recorded in a smart contract and thus enable a secure and transparent interactive environment. Before participating in sensing tasks or acquiring services, CAVs are required to register into VeSenChain first.

C. Consensus-driven quality control

It is a significant issue to ensure data quality in crowdsensing activities since it could be impacted by many factors, such as CAVs' movements, the precision of the embedded sensors, and the quality of communication channels. Different from traditional solutions, the study in [13] proposed a blockchain consensus-driven quality control model for crowdsensing. In the system model, a verifier selection mechanism and a two-times consistency policy are devised to build system credibility and integrity. The whole operation process of the proposed system is organized within 11 steps and two consensuses. Before sending the sensed data to the requester, the verifier is responsible for evaluation through a novel approach, which integrates fuzzy logic theory and circuit-breaking technology for protecting evaluation criteria. After the workers upload sensed data, the verifier produces a Merkle tree published to the whole network and the system achieves the first consensus. Besides, the verifier also generates the grades for the data quality assessment in order to determine the rewards of workers. After that, the verifier generates another Merkle tree based on previous Merkle trees and other factors (e.g., worker's identity and reward). The second consensus is achieved after the new Merkle tree is generated and published.

D. Blockchain-based incentive model

As a distributed ledger, blockchain is applied in crowdsensing to resist security risks in the incentive process. The existing blockchain-based crowdsensing incentive models can be roughly classified into two categories: main incentive goal and rewards form [14]. The main incentive goal refers to the abovementioned issues, such as service quality-oriented, privacy security-oriented, trusted transaction-oriented, and hybrid target oriented. While incentive models based on rewards form can be divided into social service, game playing, and monetary reward. Among these models, the study in [15] proposed a decentralized architecture built on the consortium, taking both economic incentives and data quality into account. Blockchain technology eliminates the need for a trusted third party. In this work, the authors proposed a hybrid incentive approach considering data quality, reputation, and monetary awards to boost worker willingness to participate in sensing tasks and submit sensed data. The proposed reward model achieves a remarkable improvement of the task initiator's utility compared to the state-of-the-art incentive models. Another incentive model using zero-knowledge proof methods [16] can achieve information privacy protection, but contract execution costs are relatively high. In summary, the existing blockchain-based crowdsensing incentive models have their merits and limitations.

IV. Open Issues in Blockchain-based VCS

Through the introduction and discussion in previous sections, we have understood the existing studies of crowdsensing intelligence by decentralized autonomous vehicles organizations and operations. However, a number of related open issues have not been deeply investigated and remain addressed. First, it is promising to address threat modeling in VCS using blockchain techniques. Since DoS attacks, malware attacks, and eavesdropping attacks in VCS systems are not fully addressed by blockchain-based approaches and blockchain is capable of mitigating these attacks due to its natural properties. Besides, to achieve accurate evaluation and verification, most of the entities in the blockchain would participate in the process. As the number of sub-tasks and participants increases, the multi-point verification feature may cause a decrease in the execution efficiency and further magnify the execution costs. Therefore, it is promising to study the design of on-chain and off-chain scheme to save costs as well as a reasonable verification mechanism to improve efficiency. Moreover, with the increase of entities' privacy preservation requirements and the increasingly complex and changeable sensing scenarios, the single-chain structure can no longer meet the sensing requirements. Therefore, it is necessary to study practical multi-chain structures to cope with the multi-domain complex environment. For instance, the incentive model can be integrated with a cross-chain consensus mechanism to realize multi-domain crowdsensing. Last but not the least, we also need to break through the technical limitations and security issues of DAO itself to further improve the decentralized self-organization of VCS, so as to achieve extensive applications.

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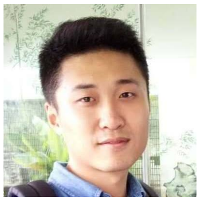

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