RESEARCH ARTICLE

Optimizing Collaborative Task Allocation in Internet of Vehicles (IoV) through Blockchain-Enabled Incentive Mechanisms

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Abstract

The Internet of Vehicles (IoV) is a core component of smart transportation systems, making it feasible to exchange information among vehicles, infrastructure, and central systems in real time. However, the effective use of resources and the efficient distribution of tasks in these dynamic environments is a challenging task. This paper presents a blockchain-based collaborative task allocation framework method that can solve these problems by using a greedy algorithm for general task allocation and adopting a dynamic collaboration scheduling algorithm for emergent tasks. Employing the blockchain-based reward mechanism, the transparency, fairness, and security in dynamic mobile crowdsensing (MCS) tasks encourage vehicle participation. Our experimental results demonstrate that our framework achieves strong performance in terms of resource optimization and task completion time, with resource utilization reaching up to 95% and task completion time decreasing significantly as the number of participating vehicles increases, particularly for emergent tasks with real-time demand for multisite collaborative vehicles. Further results reveal that the blockchain mechanism can ensure fair rewards allocation and increase system scalability. Future work will focus on improving energy efficiency and scalability, as well as on how to apply privacy-preserving techniques to the IoV environment in the future.

Keywords: internet of vehicles (IoV), blockchain, collaborative task allocation, incentive mechanism, general task, emergent tasks, task scheduling.

1 Introduction

Internet of Vehicles (IoV) is an indispensable component of the rapidly growing Internet of Things (IoT) ecosystem, which interconnects various physical devices and vehicles to establish an intelligent connected network [1]. Vehicles in the IoV

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communicate and share data with one another, road infrastructure, and central management systems, enabling real-time communication and providing data that is used for various applications such as smart traffic management, emergency response, and autonomous driving [2, 3]. The overarching goal of the IoV is to increase the efficiency, safety, and sustainability of traffic systems and thereby the overall quality of living in urban environments. With the ability to collect and process enormous data flows, the vision of the IoV is to transform cities to become more efficient, responsive, and adaptive to new conditions. Blockchain-enabled crowdsensing frameworks have demonstrated concrete steps toward this vision by enabling multi-task collaborative data collection in intelligent transportation systems [4].

The Internet of Vehicles (IoV) is a highly sophisticated system needing the collaboration among the vehicles, infrastructure, and central authority to operate in real time. An important problem in IoV systems is how to allocate tasks and resources in a secure and transparent manner. Blockchain resolves the issue with its decentralized characteristics which provide transparency, security and immutability in task assignment. It eliminates the requirement for trusted central authorities, preventing data tampering and ensuring honest participation among users [5]. Moreover, blockchain authenticates resource sharing, stimulates the vehicle participation from a trusted reward mechanism, enhancing the security of transferring information and the trust of the collaboration.

Traditional IoV systems face several challenges: task-handling schemes are often inefficient, inflexible, and have slow response speed, especially for a centralized method. Blockchain-based consensus management using reputation and contract theory has been proposed as a more secure and efficient alternative [6]. The centralized schemes may suffer from the bottleneck problem, and the heuristic-based schemes are hard to scale and respond in real time. Systems built on blockchain provide a stronger alternative by distributing the task assignment process. This method can meet the need of quick, flexible resource utilization, fast response to emergent tasks, and system efficiency usage [7]. Leveraging a decentralized ledger and blockchain-compatible incentive mechanism, the approach can overcome the drawbacks of centralized and heuristic-based schemes and is scalable and secure with respect to task allocation in IoV.

However, the full potential of IoV can only be achieved with efficient techniques for resource allocation and task scheduling [8]. In an IoV environment, vehicles are endowed with computational, sensing, and communication capabilities that can be exploited to collect and transmit data for diverse applications. However, this also raises questions about the nature of incentivizing vehicles to share their resources, such as data processing for the sensing tasks [9]. Vehicles would also have their unique description of different interests, which might not be willing to share their resources without some really attractive incentives [9]. Similarly, resource-sharing nodes in distributed networks face analogous reluctance without adequate compensation mechanisms [10]. This hesitation is intensified when vehicles need to perform urgent and time-constrained activities that require the simultaneous arrival of vehicles to achieve the preferable service level.

To address these challenges, mobile crowdsensing (MCS) is an attractive approach in IoV systems, where vehicles are deployed as data source and equipped with sensing ability to deal with a variety of tasks. In this framework, IoT centers deploy sensing tasks on vehicles that collect and share data in order to serve smart city applications. Although with great potential, the MCS model is subject to several limitations, most notably the inefficient design of incentive mechanisms and characterizing task scheduling among multiple vehicles. Emergent tasks that arise without prediction need to be handled in a timely manner, and also be served by multiple vehicles so that sufficient resources can be allocated. Existing task allocation techniques do not satisfy the above-mentioned requirements efficiently, resulting in wastage of resources and prolonged time for task completion.

In this paper, we present a blockchain architecture to solve the problems related to collaborative task allocation and incentive mechanisms in the IoVs. Leveraging the decentralization of blockchain technology, we hope to achieve secure, transparent, and efficient collaboration of vehicles. Figure 1 illustrates the interaction between the IoT center, blockchain, and vehicles, demonstrating how tasks are assigned, tracked, and rewarded securely within this system. To model the scenario, the motivation for vehicles to offer their resources, and the way to deal with urgent tasks, we propose a bidding mechanism for vehicles to share their resources and a time-window-based approach for handling emergency tasks among multiple vehicles collaborate with each

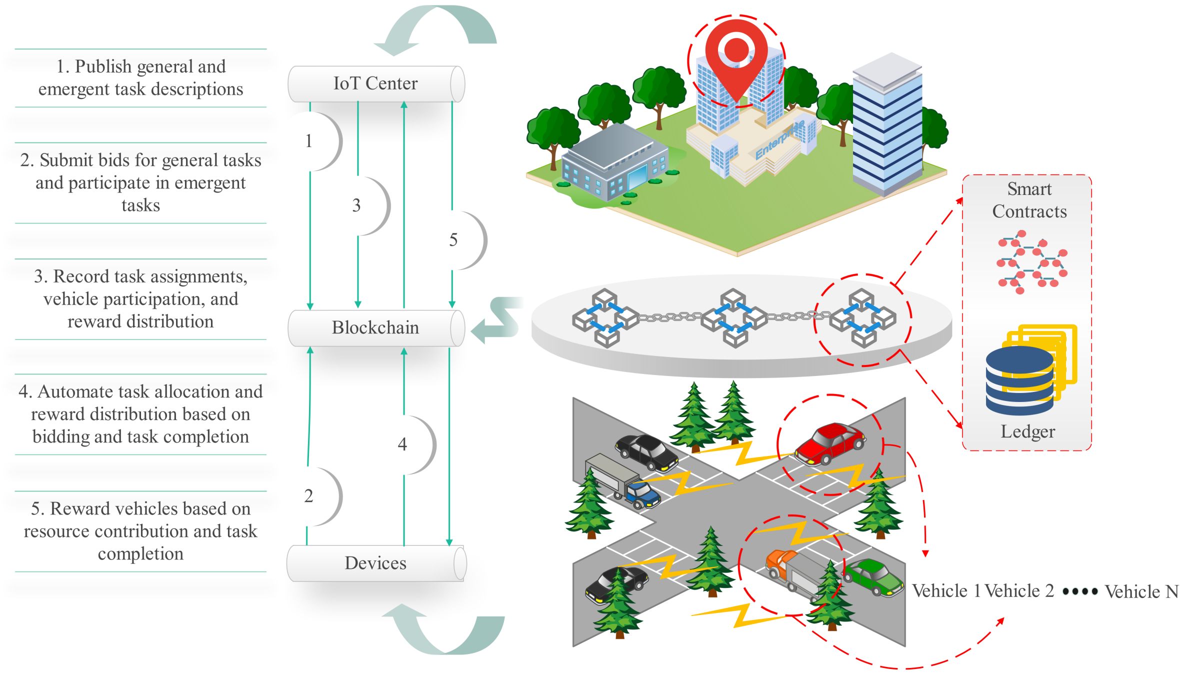

Figure 1. Task allocation and blockchain integration process in IoV.

other.

The main contributions of this paper are:

- We develop an incentive model in a blockchain network to encourage vehicles to participate in IoV tasks to achieve a transparent, secure, and fair data exchange.
- To introduce a bidding method to optimize the distribution of typical sensing tasks over vehicles based on their available resources and time constraints.
- We propose time-window-based scheduling algorithms for emergent tasks scheduling in order to schedule tasks from new task requests in an efficient manner to execute the tasks with multiple vehicles to respond the unexpected scenarios.
- We develop a cooperative task distribution mechanism with blockchain support for executing the jobs of several vehicles by efficient usage of resources and having time-feasible tasks.
- We provide experimental verification of the proposed approach, illustrating its efficiency in terms of task allocation, vehicle collaboration, and incentive-based resource sharing.

The rest of the paper is organized as follows: Section II presents the related works in incentive mechanisms and cooperative strategy for IoV. The problem formulation and incentive mechanism design are presented in Section III. We introduce in sections IV and V the models of general task allocation and emergent task allocation, respectively. Section VI explains the implementation of the proposed framework, and Section VII reports the experimental results. Finally, Section VIII summarizes the paper and presents some future work.

2 Related work

With the possibility to transform the transportation systems and urban livelihood, the Internet of Vehicles (IoV) has attracted a lot of attention in the past few years, with recent works proposing truthful auction mechanisms for blockchain-based resource allocation as one representative direction [11]. Many studies have been done to identify the issues and opportunities that are related to IoV systems, including task allocation, collaboration, and incentive models for resource sharing [12]. We briefly review the related work on MCS in IoV, incentive mechanisms, collaborative task allocation, and blockchain for secure data exchange in this section.

2.1 Incentive mechanisms in IoV

Encouraging the participation of vehicles in IoV-based MCS is an important issue because vehicles are unwilling to contribute their resources without reward [14, 15]. Ensuring the security and trustworthiness of such participation further requires robust authentication mechanisms in the IoV environment [13]. Some concerned incentive based methods were proposed which are adopted to encourage vehicles participation in MCS tasks [14]. The traditional methods primarily use grant or reputation system to incent vehicles. For example, [15] suggest an incentive mechanism to encourage participation on mobile crowdsensing applications with both monetary and non-monetary rewards. Similarly [16] study location-based incentive strategies which take vehicle mobility and coverage area into account. However, these models ignore the complexities of emerging task requirements and the Idle task scheduling in IoV [17].

Recent work considers game-theoretic techniques to motivate the cooperation of vehicles, which are assumed to be rational self-interested entities. In [18] author proposes an SPM model for IoV-based mobile crowdsensing, in which the IoT center (the leader) formulates a certain incentive policy to motivate vehicles (the followers) to join MCS. Although strategic approaches for task allocation are proposed with these models, they may ignore the collaboration of emergent tasks and may not be efficient enough to achieve a good incentive that is transparent and fair.

2.2 Collaborative task allocation in IoV

Collaborative task assignment is of importance in IoV systems as well, particularly for emergent tasks which need to be cooperatively implemented by multiple vehicles [19]. The IoV task assignment problem shall coordinate the sharing resources efficiently and reduce the delay, improving overall system performance [19, 22]. The integration of blockchain and machine learning has been surveyed as a promising direction to further enhance these capabilities in IoV systems [20]. There are several works that have studied task scheduling and resource allocation in IoV, especially in VANETs [21].

In [22] author introduces a task allocation mechanism for IoV systems, employing a distributed algorithm to assign the task to the vehicles according to the available resources and distance between the vehicle and the task location. Although that strategy effectively distributes the work, it does not capture the idea of cooperation between vehicular actors in case of scarce resources [23]. Similarly, [24] proposes a digital twin-assisted task offloading and caching scheme in blockchain-based vehicular edge computing networks, which improves security and efficiency but does not explicitly address incentive mechanisms to motivate voluntary vehicle participation, which may limit its applicability in open IoV environments where vehicles act as rational self-interested entities.

In emergent task scenarios, [25] employs deep reinforcement learning combined with blockchain to enable secure crowdsensing in 5G Internet of Vehicles, allowing vehicles to dynamically respond to sensing tasks by leveraging available resources during task processing. However, it does not explicitly optimize collaborative scheduling based on vehicles' idle time windows, and the security and trust problems in open and decentralized IoV contexts remain insufficiently addressed [26].

2.3 Blockchain for secure data exchange in IoV

Blockchain has been considered as a promising technology to cope with the security, transparency, and integrity issues for the IoV systems [27]. Based on the decentralized feature, blockchain can offer a trustless setting for exchanging data, in which the transactions are maintained in an immutable ledger and confirmed by the multiple participants.

Several research studies have addressed the use of blockchain in securing data exchange and motivating cooperation in the IoV setting. [28] proposed a dynamic multi-incentive framework for edge vehicular crowdsensing in IoV networks, which motivates vehicle participation through differentiated reward strategies tailored to task urgency and vehicle contribution. Also, [29] present a blockchain-enabled framework for vehicular data sensing that enhances information freshness, ensuring that collected data remains timely and relevant for IoV applications while leveraging blockchain for secure and transparent data management. Although these studies show the possibility of blockchain in enhancing security and transparency in IoV, they often fail to deal with the problem of real time task assignment when a task is not feasible for a single vehicle and multiple ones are required to be grouped together to execute an ad-hoc task. Furthermore, existing contract theory-based incentive approaches for cooperative task offloading in vehicular networks [30] do not explicitly address the dynamic multi-vehicle collaboration needed for emergent task scenarios.

Another research direction focuses on embedding smart contracts in blockchain-based IoV systems [31]. Smart contracts can automatically assign tasks, process bids, and distribute rewards among participants, thereby eliminating the need for intermediaries and reducing transaction overhead. Zheng et al. [32] investigate the role of smart contracts in IoV to devise secure and automated incentive schemes that regulate vehicle willingness to join crowdsensing tasks. However, these solutions are generally inflexible when it comes to dynamic task environments where multiple vehicles need to cooperate simultaneously.

However, the current renewed interest in blockchain for IoV systems is now to increase trust and security in the task allocation, although scalability is still an issue [33]. Although some works, such as [34], present blockchain-based models for vehicle-to-vehicle communication, they do not completely solve the problems of scalability when dealing with real-time tasks. Our framework, however, incorporates a dynamic collaboration scheduling algorithm that is designed to achieve vehicle collaboration for multiple vehicles efficiently, with both scaling aspects and latency minimization aspects. Unlike [35], which relies on multi-agent deep reinforcement learning for task prioritization and incentive optimization but incurs substantial training overhead and lacks transparency in reward distribution, our framework works distributedly over blockchain, with fair, transparent, fault-tolerant characteristics so it is scalable for large IoV deployments.

Hybrid solutions combine blockchain with machine learning (ML) and edge computing have also been explored for task allocation [36]. Although these models, as in [37] and [38], enhance decision-making and lower the latency, they have the problem of scalability, and the same level of transparency and security is often not available. Our blockchain-based design is proposed to overcome these challenges, and to offer a decentralized, transparent, and fair task allocation mechanism that scales well for large IoV systems. We combine dynamic schedule algorithms with the secure feature of blockchain, and guarantee a better scheduling performance for achieving a more robust and efficient way of high continuum compared with traditional hybrid mode.

Despite these, there still exist many gaps in areas such as incentive mechanisms, collaborative task allocation, and secure data exchange on blockchain in IoV. Current studies abstract the task coordination into separate general task assignments and end-to-end developed task dispatch using traffic management, neglecting the collaboration between the vehicle fleets in dynamic environments. In addition, most incentive models fail to leverage blockchain in the transparent, secure and fair transmission of data. Building upon the foundational bidding and time-window collaboration concepts introduced by Yin et al. [2], this paper aims to fill in these gaps by introducing a novel blockchain-based incentive mechanism for generalized data collection and emergency-specific task processing, extending the framework to support multi-vehicle dynamic collaboration with a formal optimization formulation and blockchain-enforced reward distribution.

3 Problem formulation

In this section, we present the problem of collaborative task allocation in the Internet of Vehicles (IoV) system and its challenges. The problem is further formulated as task assignment, single vehicle cooperation, and an incentive mechanism with real-time consideration in security data transmission. This paper addresses the allocation of tasks in an efficient manner, especially in a heterogeneous environment, where the vehicles may have different resource capacities, and with time-sensitive tasks that emerge and require the collaboration of multiple vehicles. Figure 2 illustrates the step-by-step process of task allocation and collaborative task execution in the Internet of Vehicles (IoV) system using blockchain-enabled incentives. It includes task announcement, general task allocation, emergent task scheduling, blockchain incentives, collaborative task execution, and performance evaluation.

3.1 Task Allocation in IoV

In the IoV system, the main goal is to assign sensing tasks to the vehicles on the one hand using the least resources, time cost, and on the other hand to attract the vehicle to participate. Tasks in the IoV can be essentially divided into general tasks and emergent tasks.

1. **General Tasks**: These are tasks that need to be sensed and data collected continuously, for a long duration. All tasks can be dispatched to the vehicles in the IoV network according to the resources of the vehicles, including sensing ability, battery power, and processing power. The difficulty of general task allocation is to schedule the tasks for all vehicles more efficiently and balance the load among different vehicles with respect to the resource limitations of each vehicle.

2. **Emergent Tasks**: These are the important tasks that have to be done on the fly. For example, a car accident or a quick change in road conditions

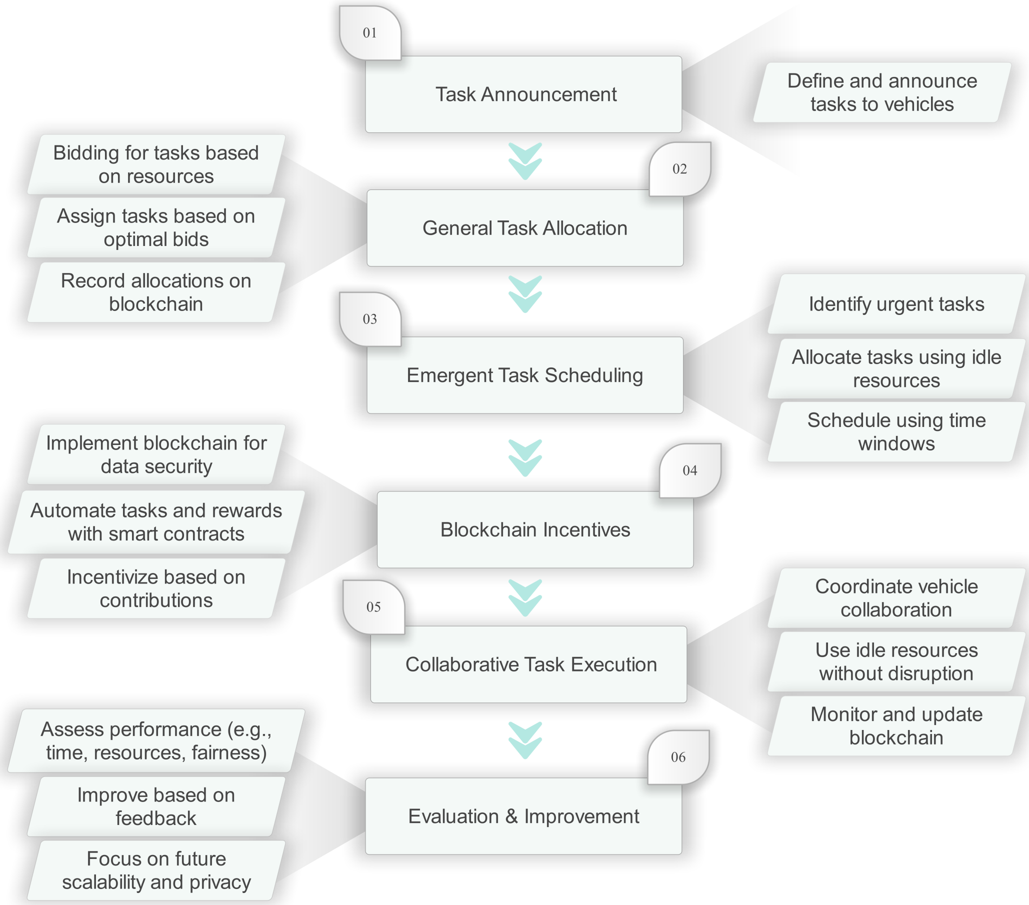

Figure 2. Flowdiagram of proposed blockchain-based task allocation and reward distribution in IoV.

may require an immediate reaction. In such cases, a solitary vehicle may not possess sufficient capability to accomplish the task, and it may have to cooperate with other vehicles. The issue in the case of emergent tasks is not only timeliness, but also a lack of time to get the task done, so that prompt and efficient collaboration among the vehicles is required.

The task allocation problem is to assign tasks to vehicles in a manner that their capabilities can accommodate the task requirements of all vehicles, and the overall system is capable of serving routine and emergent tasks together with both efficiency and effectiveness.

3.2 Collaboration and Resource Sharing

In the IoV system, there are many vehicles that cooperate together to accomplish the tasks. Vehicles need to cooperate when performing urgent tasks, which must be fulfilled as soon as possible. However, the resources of vehicles may be different at a particular time according to their different workloads and battery levels. The key is to distribute the tasks to the vehicles with spare resources in an efficient way and to maintain spare resources that can be borrowed from another vehicle when a new task arises.

We propose a collaboration method in which vehicles are idle at some time windows, and these idle resources are exploited to perform a task. This way makes full use of the resource and enables the vehicle to handle the urgent task without affecting general tasks during the operation time. The objective is to minimize the overall task completion time, and at the same time, consider vehicles participating in cooperation to share their resources with others.

3.3 Incentive Mechanisms for Participation

Encouraging vehicles to participate in both general and emergency sensing tasks is an important part of the IoV ecosystem. Lacking adequate incentives, vehicles would not be willing to share their resources, which would result in less satisfactory data collection and task execution delay. Consequently, how to design a good incentive mechanism and motivating the vehicles to contribute their resources is another important issue for task completion.

Blockchain-based incentive design ensures the fairness of task allocation and reward dispersion. With smart contracts, vehicles are assigned tasks according to their resources and participation, and rewarded according to their contribution. Blockchain has a transparent ledger, preventing tampering of workloads and rewards. Contrary to reputation-based and monetary reward systems, which could be manipulated or falsified, blockchain ensures a secure, immutable, and transparent ecosystem where rewards are equally distributed and verifiable by all involved participants. This trust-building is consistent with a decentralized approach that will also lead to a fair sharing of resources. In the proposed framework, a greedy algorithm is applied to assign tasks to vehicles in response to resources available and task demand. It evaluates the utility of each vehicle based on its capacity for sensing, computing, and timing. Tasks are assigned one after another to the maximum utility vehicle to optimize the resource and time cost. This procedure iterates until all tasks are assigned, resulting in efficient completion of tasks with better resource usage.

It should be noted that the incentive mechanism should provide an accommodation for both general and emergent tasks. For tasks in general, the mechanism should provide an incentive to fairly compensate contributing vehicles, which have enough resources available. For these emergent tasks, the mechanism has to encourage early participation of vehicles considering the urgency of the task and vehicle resource availability.

3.4 Blockchain Integration for Secure Data Exchange

Data security and integrity are an utmost requirement in an IoV system, where vehicles are sharing sensitive information such as traffic and road conditions and accidents, and traffic patterns. Blockchain technology offers a highly secure and decentralized infrastructure that guarantees the trustworthiness of the exchanged information between cars and the IoT cloud. Every transaction (e.g., task assignment, resource allocation) is recorded into an immutable ledger that records all the transactions, thereby becoming transparent and unchangeable.

The smart contracts embedded into the blockchain design automate the process of the assignment of tasks and the rewarding process, and all these activities are carried out as programmed. This bridge between entities reduces the reliance on intermediaries, transaction fees, and prepares an audit trail of all transactions on the IoV system. The blockchain-inspired architecture improves security, and it creates trust among participants, thus attracting more participants to join the crowdsensing task.

3.5 Problem formulation

Formally, the task allocation problem in IoV can be defined as follows:

- Let $T = \{T_1, T_2, \ldots, T_M\}$ represent the set of tasks to be allocated, where M is the total number of tasks.
- Let $V = \{V_1, V_2, \ldots, V_N\}$ represent the set of vehicles, where N is the total number of vehicles in the IoV network.
- Each task T_i has a set of requirements (r_i, d_i, t_i), where r_i represents the resource requirements, d_i represents the data quality, and t_i represents the time constraint for the task.
- Each vehicle V_j has a set of resources (r_j, t_j), where r_j is the available resource capacity and t_j is the available time window.
- The objective is to assign tasks to vehicles such that the total completion time is minimized, resource utilization is maximized, and the incentive mechanism ensures that vehicles are fairly rewarded for their contributions.

We propose to address this issue by formulating a collaborative task assignment model, which considers all of the general and emergent task requirements, the resource capacities of the vehicles, and the time-sensitive nature of some tasks. It is also required that the solution to be devised shall embed an incentive mechanism over blockchain for a transparent and secure data exchange as well as to promote the vehicles to undertake these tasks.

3.6 Algorithm Details

3.6.1 Greedy Algorithm for Task Allocation

The Greedy Algorithm, as outlined in Algorithm 1, to assign tasks for vehicles for minimizing task completion time and resource utilization. The general approach is to assess the ability of each vehicle to a certain task, and assign the task to vehicle which maximizes the system's utility.

Algorithm 1: Greedy Algorithm for Task Allocation

Data: Task list, IoV system (vehicles, resources, time windows)
Result: Task allocation to the best eligible vehicle

```
for each task in the task list do
    Initialize an empty list of eligible vehicles for this task;
    for each vehicle in the IoV system do
        if vehicle has sufficient resources (e.g., battery, sensing ability) then
            if vehicle's time window overlaps with the task's time constraints then
                Add vehicle to the eligible vehicle list;
            end
        end
    end
    Calculate the utility for each eligible vehicle;
    for each vehicle in the eligible vehicle list do
        The utility function considers resource availability, vehicle capacity, and proximity to the task location;
        Utility = f(resource capacity, task urgency, distance to task, etc.);
    end
    Select the vehicle with the highest utility;
    Assign the task to this vehicle;
    Update the vehicle's resource availability;
    for each task requirement do
        Reduce the vehicle's remaining resources (e.g., battery usage, processing power);
    end
    Update the task status as "assigned";
    Log the task assignment to the blockchain for transparency and verification;
end
```

- **Step 1-2**: Enumerate all vehicles capable of fulfilling given tasks (e.g., sensing, battery, proximity).
- **Step 3**: Determine the utility score for each vehicle to quantify vehicles' ability to execute the task.
- **Step 4-5**: The task is assigned to the vehicle with the maximum utility.
- **Steps 6-7**: Refresh the task and vehicle resources after having successfully allocated the task.
- **Step 8**: Record the task assignment to the blockchain for transparency.

3.6.2 *Dynamic Collaboration Algorithm*

The Dynamic Collaboration Algorithm presented in Algorithm 2, is adopted for emergency tasks requiring real-time cooperation among several vehicles. These tasks emerge in an unplanned manner and vehicles might collaborate to accomplish them in an efficient way.

Algorithm 2: Dynamic Collaboration Scheduling Algorithm for Emergent Task Allocation

Data: Emergent task list, IoV system (vehicles, resources, time windows)
Result: Task allocation to the best eligible vehicles and logging the results

```
for each emergent task in the task list do
    Identify all available vehicles with idle time slots during the task's required time window;
    for each eligible vehicle do
        Check if the vehicle has sufficient resources to contribute to the emergent task (e.g., available battery, computing power);
        Check if the vehicle is within a time window that allows for task participation;
    end
    Create collaboration groups by matching vehicles with compatible resources and time availability;
    for each collaboration group do
        Distribute the task load across the vehicles in the group;
        Ensure that each vehicle's contribution is proportional to its available resources and task suitability;
    end
    Assign the emergent task to the collaboration group;
    Update each vehicle's resource usage (e.g., battery consumption, computational load);
    After task completion, update the vehicle's remaining resources;
    Update the task status as "completed" and log the task and vehicle interactions into the blockchain for transparency;
    Track the performance metrics of each vehicle's collaboration in the blockchain for future analysis;
end
```

- **Step 1-2**: Search for Vehicles with Resource and Time slot Openings. These vehicles must be coordinated in real-time in order to accomplish the growing task.

- **Step 3**: Dynamically create groups of collaboration, in which a number of vehicles are allowed to cooperate with each other, by sharing their available resources, to solve the task more efficiently.
- **Step 4**: Dispatch the emerging task to the coordinated fleet, indicating the role of the vehicles.
- **Step 5**: After completing the task, the resource status of the vehicles is updated and the task and the interactions of the vehicle are recorded on the blockchain.
- **Step 7**: Monitor the performance of each of the vehicles that participate in the job so that you can optimize and analyse it later.

4 General task allocation

In this section, we formulate the task offloading problem in the general sensing task assignment to vehicles in IoV. General tasks are periodic or continuous sensing tasks that must collect data over a long period of time. Such tasks may involve the monitoring of road conditions, environmental sensing, or analysis of traffic flow. The purpose is to share these tasks among vehicles efficiently, taking into account their resources and prioritization of tasks, and provide motivation to participate. It is bidding that underlies the efficient task sharing in our structure. Vehicles competitively bid for available tasks for which they have the required resources (e.g., sensing power, battery, computation capabilities). The bidding process proceeds as follows: the IoT center first advertises available tasks to the blockchain; each vehicle then determines its available utility surplus and submits a bid reflecting its willingness to process the task; the IoT center schedules the bids using a utility function that considers task urgency, resource availability, and time delays; finally, the task is allocated to the highest-bidding vehicle to maximize resource sharing.

4.1 Problem formulation for general task allocation

The general task allocation problem in IoV is a bidding-based optimization problem. In this scenario, each vehicle bids for available tasks depending on the resources at its disposal, such as, capability, battery-life, and computation power. Decentralized bidding is used to allocate tasks to vehicles that can most efficiently achieve them in a fair and efficient manner.

Let the set of general tasks be $T_G = \{T_1, T_2, \ldots, T_M\}$, where M is the total number of general tasks. Each task $T_i \in T_G$ has the following properties:

- **Time requirement**: Each general task T_i has a time window $t_i = \{t_1, t_2, \ldots, t_n\}$ in which the task must be completed, representing the required sensing duration and frequency.
- **Resource requirement**: Each task requires certain resources, such as computation and sensing capacity, denoted by $r_i = \{r_1, r_2, \ldots, r_n\}$, where r_i is the resource capacity required for the task.
- **Data quality**: The data quality requirement for each task T_i, denoted by d_i, ensures that the collected data meets the specified accuracy for the task.

Let the set of vehicles be $V = \{V_1, V_2, \ldots, V_N\}$, where N is the total number of vehicles in the network. Each vehicle $V_j \in V$ has the following properties:

- **Resource capacity**: Each vehicle has available resources $r_j = \{r_1, r_2, \ldots, r_n\}$, which may include sensing capability, computing power, and battery level.
- **Time availability**: The time window t_j during which the vehicle V_j can contribute to the task. Each vehicle has a limited time frame during which it can participate in general tasks.

The objective is to assign tasks T_j to vehicles V_j such that the time constraints are met while overall resource utilization is maximized, and the resource requirements of each task. In addition, the incentive mechanism must be measured, ensuring that vehicles are rewarded properly for their participation.

The task allocation problem can be formulated as follows:

- **Maximizing the total utility**: The goal is to maximize the overall utility of the system by choosing the ideal vehicle-task pairings based on limited resources and time constraints. This can be expressed as:

$$\text{Maximize} \sum_{j=1}^{N} \sum_{i=1}^{M} x_{ij} .\, u_{ij} \tag{1}$$

where x_{ij} is a binary decision variable that indicates whether task T_i is assigned to vehicle V_j, and u_{ij} is the utility of assigning task T_i to vehicle V_j, which is determined by the vehicle's resource availability and task suitability.

- **Subject to resource and time constraints**: The allocation has to take the resource and time constraints of the vehicles and the tasks into consideration. The constraints are as follows:

$$\sum_{j=1}^{N} x_{ij}.\, r_j \geq r_i \quad \forall \sqsupset \in T_G \tag{2}$$

$$\sum_{i=1}^{M} x_{ij}.\, t_j \leq t_{ij} \quad \forall j \in V \tag{3}$$

These constraints ensure that the selected vehicles can supply the necessary amount of resources to accomplish the tasks, according to their time windows.

4.2 Problem formulation for general task allocation

To efficiently assign general tasks, we develop a bidding process where each vehicle bids on tasks according to the resources it has available and time windows. The bidding is intended to motivate vehicles to sign up for general purposes, and also make sure that the assignments are fair and efficient.

Each vehicle V_j calculates its bid for each task T_i based on the following components:

- **Resource availability**: Vehicles having more resources, i.e., better sensing and processing capabilities, tend to bid more for tasks that have a potential extensive resource consumption.
- **Time availability**: Vehicles with flexible time windows also bid more for tasks with temporal constraints and periodic sensing.
- **Incentive**: The incentive for each vehicle V_j is proportional to the expected reward w_j, which is based on the vehicle's contribution to the task. This reward is determined by the blockchain-based incentive mechanism, where vehicles receive tokens or monetary rewards based on their resource allocation and task completion.

The bidding process proceeds as follows:

1. **Task Publication**: The tasks offered by the IoT center are published to the blockchain, including task resources, time windows, and task data quality.
2. **Bid Submission**: Each vehicle V_j submits its bid B_{ij} for each task T_i, where B_{ij} reflects the vehicle's willingness to participate in the task based on its resource availability and time window.
3. **Task Assignment**: The IoT center reviews all bids and selected those vehicles that offer the best use of resources for a given task, taking into account the vehicle's capacity and incentive. The chosen tasks are recorded into the blockchain for everyone to ensure, keeping everything transparent and accountable.

4.3 Smart contract execution for task allocation

To ensure the secure execution of the task allocation process, we leverage smart contracts on the blockchain. Smart contracts automate the entire task allocation and reward distribution process, eliminating the need for intermediaries and ensuring that all participants adhere to the predefined rules. Once the IoT center selects the vehicles for a task, the corresponding smart contract is executed, recording the task allocation in the blockchain and triggering the reward distribution.

The smart contract ensures transparency by recording all task assignments and bidding information on the blockchain, security by preventing fraudulent tampering of task assignments and data, and fairness by automating reward distribution proportionally to each vehicle's contribution.

4.4 Solution Method for General Task Allocation

To solve the generic task allocation problem, we introduce a greedy algorithm that chooses successive best vehicles for the task according to the vehicle's resources and the requirements of the task. The algorithm is described as follows:

1. For each task T_i, identify the vehicles that have sufficient resources to handle the task.
2. From the eligible vehicles, select the vehicle V_j that offers the highest utility u_{ij} (calculated based on the vehicle's bid and available resources).
3. Allocate the task to the selected vehicle and update the vehicle's resource availability.
4. Repeat the process for all tasks until all tasks are allocated.

This greedy algorithm optimally allocates tasks to the vehicles with the ability to execute them based on the current resource and time constraints, whilst maximizing the overall system utility. We selected a greedy-based task scheduler for task allocation as it is simple and competent in decision making in a real-time environment where the major concern is to minimize the task completion time and resource utilization. Greedy algorithms make local choices for each iteration and correspond to the dynamical and resource-restricted scenario of IoV systems. Although genetic algorithms and machine learning methods have good performance but their implementation demands high complexity of computation, which requires large training data. Genetic algorithms, for example, use population-based solutions, which are time-intensive, and which may be unacceptable when dealing with a large IoV network. Despite their promising performance, machine learning models need large amount of training and may not be suitable or efficient in real-time applications. The greedy algorithm, however, delivers low-latency responsiveness–more suitable in the context of real-time IoV applications, where the system is required to make prompt decisions for task allocation without suffering from computation overhead.

5 Emergent task allocation

In this section, we consider the allocation of emergent tasks of the IoV system. Emergent tasks are spontaneous and time-critical, requiring immediate attention. For example, such tasks may be associated with accidents, roadblocks, or other emergencies which require on-site (real-time) data collection and instantaneous decision making. Imminent tasks may fall beyond the resources of a vehicle, which requires coordination with other vehicles to satisfy the resource and time constraints. The goal of this section is to present a framework for efficiently allocating emergent tasks while utilizing the idle resources of multiple vehicles.

5.1 Problem Formulation for Emergent Task Allocation

Emergent tasks are different from general tasks, since they are urgent and require real-time service. Since these duties need to be handled as soon as possible, the assignment process needs to reduce as much lag as possible while ensuring that all resources needed to accomplish the task are in the system. The allocation process must take into account several factors, including:

- **Time Constraints**: It is required to deal with emerging tasks with a time limitation. Emergent tasks have a smaller time window for processing than general tasks, therefore effective resource allocation must be made as fast as possible.
- **Resource Availability**: Each vehicle in the IoV network has a limited set of resources, such as computing power, sensing capability, and battery capacity. Emergent tasks require the pooling of resources from multiple vehicles to meet the task's requirements.
- **Collaboration among Vehicles**: During specific time windows, vehicles with idle resources can collaborate to complete emergent tasks. However, these vehicles must be selected and coordinated efficiently to avoid conflicts and ensure that the task is completed within the required time frame.

The emergent task time-window based scheduling algorithm guarantees that tasks with a high level of time urgency are dealt with at the early stage by choosing idle time slots in each vehicle under the premise of whether there are more idle slots at the given task-execution time window of time-sensitive tasks. This is how by using this one, the vehicles work together without any interruption to the current job. For instance, in case of task being available for a vehicle and the available time slot is blocked in the region of the vehicle's current emergency task, the vehicle can participate without changing its schedule and therefore can return to perform its original task as soon as possible with minimal delay.

Let $T_E = \{T_1, T_2, \ldots, T_K\}$ represent the set of emergent tasks, where K is the total number of emergent tasks. Each task $T_i \in T_E$ has the following properties:

- **Time window**: Each emergent task T_i has a tight time constraint $t_i = \{t_1\ , \ t_2\}$ representing the start and finish times of the task that must be adhered to.
- **Resource requirement**: Emergent tasks require a significant amount of resources, such as sensing capability, computation, and communication power. These requirements are denoted by $r_i = \{r_1, r_2, \ldots, r_n\}$.
- **Urgency**: The urgency of an emergent task is more important and higher than that of general tasks, which demand immediate allocation of available vehicles with the required and limited resources.

The set of vehicles is $V = \{V_1, V_2, \ldots, V_N\}$, where N is the total number of vehicles in the network. Each vehicle $V_j \in V$ has:

- **Resource capacity**: $r_j = \{r_1, r_2, \ldots, r_n\}$, which represents the available resources for each vehicle.
- **Time availability**: The vehicle has a set of time slots t_j during which it can contribute to emergent tasks. When vehicles have idle time windows and assigned general tasks they can be used to participate in emergent tasks.

The challenge is to assign newly arising tasks to vehicles, so that the time constraint of the task is fulfilled, with the goal to maximize the resource usage and to minimize the time-to-service of the task. More precisely, the problem can be formulated as:

- **Maximizing resource utilization**: The objective is to allocate resources from multiple vehicles to emergent tasks in a way that ensures all resource requirements are met while minimizing the time needed to complete the task.

$$\text{Maximize} \sum_{j=1}^{N} \sum_{i=1}^{K} x_{ij} .\, u_{ij} \tag{4}$$

  where x_{ij} is a binary decision variable that specifies whether task T_i is assigned to vehicle V_j, and u_{ij} is the utility of assigning task T_i to vehicle V_j, which is based on the vehicle's available resources and time window.

- **Subject to time and resource constraints**: The resource availability of vehicles must align with the available time windows of emergent tasks. The constraints are as follows:

$$\sum_{j=1}^{N} x_{ij} .\, r_j \geq r_i \quad \forall \beth \in T_E \tag{5}$$

$$\sum_{i=1}^{K} x_{ij} .\, t_j \leq t_{ij} \quad \forall j \in V \tag{6}$$

  These constraints ensure that requested emergent tasks are allocated to only those vehicles which are well-equipped and have a time to spare to achieve such task in the given time interval.

5.2 Time-Window-Based Collaborative Task Scheduling

To address the problem of emergent task allocation, we proposed a collaboration mechanism based on time-window for emergent task allocation. This approach helps the vehicles to cooperate with each other by making use of their free time slots not occupied by the general tasks. Emergent tasks are allocated into these idle times so that the resources of several vehicles can collaborate to meet the emergent tasks requirements.

The time-window-based scheduling method proceeds as follows:

1. **Identification of idle time windows**: Each vehicle identifies its time intervals of idle, i.e., the time periods during which it is not busy with any general task.
2. **Collaboration formation**: Vehicles with available resources during these idle time slots collaborate to complete the emergent task. The collaboration is formed dynamically based on the resource requirements of the emergent task and the time availability of the vehicles.
3. **Task allocation**: The generated task is allocated to the cooperating vehicles in terms of their available resource and time window compatibility. Vehicles that have sufficient idle time and computational resources to complete the task are selected to participate in the collaboration.

The approach ensures emergent tasks are dealt with as quickly as possible with available resources. Since vehicles that have idle time can easily join the task, and can reduce delays and improve the system efficiency.

5.3 Incentive Mechanism for Emergent Tasks

Ensuring the success of the collaborative task allocation process, incentivizing vehicles to participate in emergent tasks is crucial. To encourage vehicle participation, we integrate the blockchain-based incentive mechanism. Vehicles are rewarded on the basis of the time and amount of resources the vehicle contributes to the emergent task.

Incentives for emergent tasks are distributed using the same bidding mechanism as for general tasks, but with the following adjustments: Vehicles participating in emergent tasks receive higher rewards proportional to their contribution within the required time frame, reflecting the urgency of the task. The reward for each vehicle is automatically calculated and securely distributed by the smart contract once the task is executed.

This ensures that vehicles are well compensated for their participation, providing a high incentive for them to contribute resources to emergent tasks.

5.4 Solution Method for Emergent Task Allocation

To solve the emergent task allocation problem, we propose a greedy algorithm that selects vehicles based on their available resources and idle time windows. The algorithm proceeds as follows:

1. For each emergent task T_i, identify the vehicles with idle time windows and sufficient resources to participate in the task.
2. From the eligible vehicles, select the vehicle V_j that offers the highest utility u_{ij}, where u_{ij} is determined by the vehicle's available resources and time window.
3. Allocate the task to the selected vehicle and update the vehicle's resource availability.
4. Repeat the process for all emergent tasks until all tasks are allocated.

This greedy approach ensures that emergent tasks are handled efficiently, minimizing delays and maximizing resource utilization across the IoV system.

6 Implementation of the proposed framework

In this section, we present the design and implementation of the proposed framework based on a blockchain in collaboration with the IoV system for collaborative task allocation. The proposed framework is composed of several components, task allocation, vehicle collaboration, and incentive mechanism and it concentrates on secure data sharing in the blockchain. We describe the system architecture, implementation details, mathematical formulations, and the optimization problem of the task allocation and collaboration.

6.1 System Architecture

The system is created to deal with both general tasks and emergent tasks effectively through blockchain to guarantee transparency, security, and fairness. The system architecture is composed of the following main components:

1. **IoT Center**: The central controller that manages the publication of tasks, the allocation of tasks to vehicles, and the management of rewards.
2. **Vehicles (Participants)**: Vehicles that offer bids for tasks and participate in collaboration for emerging tasks. Every vehicle has computing power, sensing, and communication resources.
3. **Blockchain**: An arrangement of bid and reward based decentralized ledger that records all task assignments, bids and rewards. Blockchain ensure the secure, transparent and unchangeable task releases.
4. **Smart Contracts**: Smart contracts deployed on the blockchain to automate task allocation, bidding, and reward distribution processes.

The blockchain supports secure communication between vehicles and the IoT center, and ensures that all communication activities are tamper-proof. The blockchain layer in our architecture is dedicated to providing a transparent and secure way for fair task allocation, preventing collusion. We have developed a Proof of Work (PoW) based consensus protocol which, despite being used conventionally in blockchain-based applications, has higher computational overhead and may reduce transaction latency. However, we selected PoW because its security guarantees are very strong, guaranteeing the integrity of the task allocation process. For security purposes, to enhance scalability, we want to investigate other consensus algorithms which are more environmentally friendly and able to process a larger number of transactions without compromising on security, such as Proof of Stake (PoS) or hybrid consensus models. The consensus mechanism used has a direct effect on the scalability as well as the security of the system, therefore, more related studies are needed to identify the best approach for deploying IoV on a large scale.

6.2 Mathematical Formulation for Task Allocation

In this section, we introduce the problem of task allocation in IoV systems. The system handles two categories of tasks: regular tasks and emergency tasks. A vehicle bids for each task according to its resource reserve and time. The goal of task allocation is to maximize the utilization of resources, minimize queuing, and maintain reasonable throughput for tasks that appear suddenly.

Let $T_G = \{T_1, T_2, \ldots, T_M\}$ represent the set of general tasks, and $T_E = \{T_1, T_2, \ldots, T_K\}$ represent the set of emergent tasks, where M and K are the total number of general and emergent tasks, respectively.

For each task $T_i \in T_G \cup T_E$, we define the following attributes:

- **Resource requirement** $r_i = \{r_1, r_2, \ldots, r_n\}$, where r_i represents the total resource capacity required to complete task T_i.

- **Time constraint** $t_i = \{t_1, t_2, \ldots, t_n\}$, representing the time slots during which the task needs to be executed.
- **Data quality requirement** d_i, representing the level of accuracy or fidelity required for the collected data.

Each vehicle $V_j \in V = \{V_1, V_2, \ldots, V_N\}$ is associated with the following properties:

- **Resource availability** $r_j = \{r_1, r_2, \ldots, r_n\}$, representing the resources available on vehicle V_j.
- **Time availability** t_j, denote the time slots during which vehicle V_j can participate in tasks.

The allocation of general and emergent tasks problem is formulated as an optimization problem towards a trade-off between overall system utility, time and resource constraints.

6.3 Task Allocation Objective Function

We outline the utility function u_{ij} to denote the benefit of assigning task T_i to vehicle V_j. The utility function depends on the vehicle's available resources, its time window, and the task's requirements. The utility u_{ij} is given by:

$$u_{ij} = \alpha_1 \cdot f(r_j, r_i) + \alpha_2 \cdot f(t_j, t_i) + \alpha_3 \cdot f(d_j, d_i) \quad (7)$$

where:

- $\alpha_1, \alpha_2, \alpha_3$ are weights that control the position of resource matching, time window alignment, and data quality in the utility function.
- $f(r_j, r_i)$, $f(t_j, t_i)$, $f(d_j, d_i)$ are functions that calculate the suitability of vehicle V_j for task T_i based on resource availability, time compatibility, and data quality requirements.

The objective is to exploit the total value of the system by selecting the best vehicle-task pairs. The objective function is:

$$\text{Maximize} \sum_{j=1}^{N} \sum_{i=1}^{M} x_{ij} . u_{ij} \quad (8)$$

where x_{ij} is a binary decision variable that indicates whether task T_i is assigned to vehicle V_j (i.e., $x_{ij} = 1$ if assigned, and $x_{ij} = 0$ otherwise).

6.4 Constraints for Task Allocation

The task allocation procedure must satisfy several constraints to ensure feasibility and fairness:

1. **Resource Constraints**: Each vehicle can only be assigned a task if it has sufficient resources to complete it. The entire resource capability used by vehicle V_j for all assigned tasks must not exceed its available resources:

$$\sum_{i=1}^{M} x_{ij} . r_i \leq r_j \quad \forall j \in V \quad (9)$$

2. **Time Constraints**: Each vehicle can only participate in tasks during its available time slots. The total time required by vehicle V_j for all assigned tasks must not exceed its available time window:

$$\sum_{i=1}^{M} x_{ij} . t_i \leq t_j \quad \forall j \in V \quad (10)$$

3. **Task Assignment Constraints**: Each task t_i must be assigned to exactly one vehicle that fulfills its resource and time constraints:

$$\sum_{J=1}^{N} x_{ij} = 1 \;\; \forall i \in T_G \cup T_E \quad (11)$$

This ensures that for either general or emergent tasks, each task is allocated to a vehicle that can handle it

6.5 Emergent Task Allocation with Time-Window-Based Collaboration

For emergent tasks, vehicles must collaborate to complete the task within the required time window. The time-window-based collaboration method allows vehicles to pool their resources by utilizing idle time slots between their assigned general tasks.

Let t_{ij} denote the time window for the collaboration of vehicle V_j on task T_i. The collaborative task assignment for emergent tasks is formulated as:

$$\text{Maximize} \sum_{j=1}^{N} \sum_{i=1}^{K} x_{ij} . u_{ij} \qquad (12)$$

with the time-window constraints ensuring that vehicles are still able to collaborate without interfering with their dedicated or assigned tasks:

$$t_{ij} \cap t_{kj} = \varnothing \qquad \forall j \in V \qquad \forall i,\ k \in T_E \qquad (13)$$

where t_{ij} and t_{kj} are the time windows for vehicles V_j collaborating on tasks T_i and T_k, respectively.

6.6 Solution Method for General and Emergent Task Allocation

For general and emergent task assignment problems, we solve the allocation of general tasks through greedy tasks allocation, while for emergent tasks scheduling, we use a dynamic cooperation scheduling method. The greedy algorithm is simply used because it greedily selects the vehicle-task pair with the largest utility u_{ij}, the collaboration scheduling algorithm is a dynamic algorithm that allocates vehicles to the emergent task based on vacant resources and idle time slots.

7 Experimental results

In this section, we provide the experimental results to analyse the performance of the proposed blockchain-based collaboration-based resource provisioning in IoV system. The experiments are to inspect the efficiency of the task allocation algorithms on aggregated tasks and emergent tasks, and the effectiveness of the incentive mechanism used to process the reward distribution on blockchain to ensure that the endpoint receivers work reasonably and fairly.

7.1 Experimental Setup

The proposed framework was implemented using Python for task and resource management, and Ethereum for blockchain integration. The smart contracts were developed using Solidity, and the task allocation algorithms were coded using a greedy algorithm with general task allocation and a dynamic collaboration scheduling algorithm for emergent tasks.

We considered a network of vehicles with changing resource capacities and time availability, to examine the framework's performance. The system was tested under different traffic conditions, with tasks ranging from regular traffic monitoring to emergent tasks like accident detection. The parameters used for the simulations are as follows:

- **Number of vehicles**: 100 to 500 vehicles in the network.
- **Number of tasks**: 50 general tasks and 20 emergent tasks, kept constant across all vehicle-count configurations to isolate the effect of network scale on task allocation performance.
- **Task resource requirements**: Tasks required different amounts of resources, ranging from low (e.g., 1 unit of sensing power) to high (e.g., 10 units of sensing power).
- **Vehicle resource capacity**: Vehicles had resource capacities ranging from 1 to 10 units.
- **Time window for tasks**: General tasks had time windows of up to 12 hours, while emergent tasks had strict time constraints (e.g., within 30 minutes).
- **Incentive reward system**: Vehicles were rewarded based on their contributions, with emergent tasks offering higher rewards.

The key performance indicators (KPIs) used to evaluate the system's performance include:

- **Task completion time**: The total time required to complete all tasks.
- **Resource utilization**: The ratio of computational and sensing resources consumed by task-assigned vehicles to the total resources available among all participating vehicles in the network.
- **Fairness of reward distribution**: The distribution of rewards among vehicles is based on their contributions to the provided task.
- **Blockchain transaction costs**: The cost of executing transactions on the blockchain, measured in gas fees.

7.2 Results for General Task Allocation

We completed experiments to test how the performance of the general task allocation model is in terms of how good the greedy algorithm can allocate tasks to vehicles from the pool of all task and vehicle resources. Table 1 presents the effect of increasing the number of vehicles on the average task completion time and resource utilization rate in the IoV system.

As the number of participating vehicles rises, both task completion time and resource utilization improve significantly. Task completion time and resource utilization results are depicted in Figure 3 for general task allocation.

Table 1. Impact of vehicle number on task completion time and resource utilization.

Number of Vehicles	Average Task Completion Time (hours)	Average Resource Utilization (%)
100	8.5	80%
200	6.2	85%
300	5.1	90%
400	4.4	92%
500	3.9	95%

- **Task Completion Time**: As the number of vehicles increases, the time required to complete the tasks decreases, as more vehicles are available to handle the workload in parallel. The greedy method was able to effectively allocate tasks among the most capable vehicles, leading to the satisfaction of time windows.

- **Resource Utilization**: Resources were used efficiently by the allocation process. As the number of vehicles increased, the resource utilization ratio improved, confirming that the greedy algorithm effectively manages resource allocation.

We also evaluated the scalability of the proposed approach under high-load conditions by progressively increasing the number of vehicles and tasks. The results show that the system maintained satisfactory task completion performance up to approximately 500 vehicles; however, performance began to deteriorate as network scale approached and exceeded this threshold, particularly for emergent tasks with strict time constraints. This degradation is attributed to the increasing dynamism of the environment, where vehicles frequently change positions and resource availability fluctuates, making real-time scheduling more challenging. These findings highlight the need for further optimization of the task scheduling algorithms to support larger and more dynamic IoV deployments. Future work will focus on enhancing the scalability of the blockchain framework and developing more robust scheduling strategies for high-density vehicle networks.

7.3 Results for Emergent Task Allocation

The allocation of emergent tasks was tested using the time-window-based collaboration method. The dynamic cooperation scheduling algorithm enabled idle resources of the vehicles to be promptly found and allocated to emerging tasks. Table 2 shows the relationship between the number of collaborating vehicles and the performance of emergent task handling. As more vehicles collaborate, the average task completion time decreases and collaboration efficiency improves, highlighting the effectiveness of the proposed time-window-based scheduling. Results for emergent task allocation are depicted in Figure 4.

Table 2. Effect of vehicle collaboration on emergent task completion time and efficiency.

Number of Collaborating Vehicles	Average Emergent Task Completion Time (minutes)	Average Collaboration Efficiency (%)
2	25	60%
3	20	75%
4	17	85%
5	15	90%

- **Task Completion Time**: The time for task completion was greatly decreased for emergent tasks when vehicles cooperated. The average deadline satisfying time in emergency tasks is shortened with the growing number of vehicles for cooperative task processing.

- **Collaboration Efficiency**: The collaboration efficiency was the number of vehicles working on emergent tasks. The system generated collaboration groups effectively based on the vehicles with compatible time windows and available resources.

7.4 Incentive Mechanism Evaluation

In order to evaluate the efficiency of the blockchain incentive mechanism, we evaluated the fairness of the reward handing out to vehicles. The motivating mechanism was evaluated by means of general tasks as well as emergent tasks, where vehicles were rewarded according to contribution in task completion. Figure 5 shows the fairness of reward distribution. The summarized entropy-based fairness evaluation is presented in Table 3, highlighting a more balanced reward distribution, especially in emergent task scenarios.

- **Fairness of Reward Distribution**: To measure the reward diversity, the reward distribution

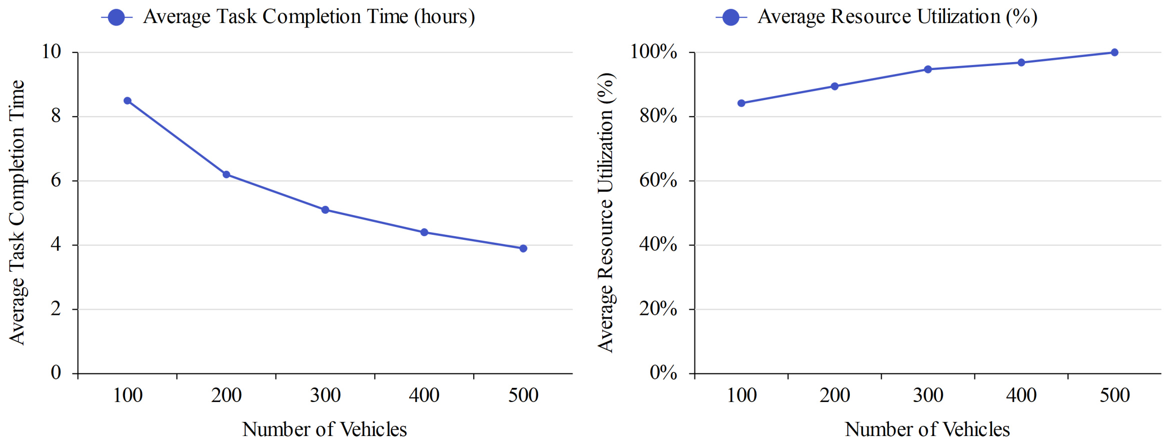

Figure 3. Result for general task allocation.

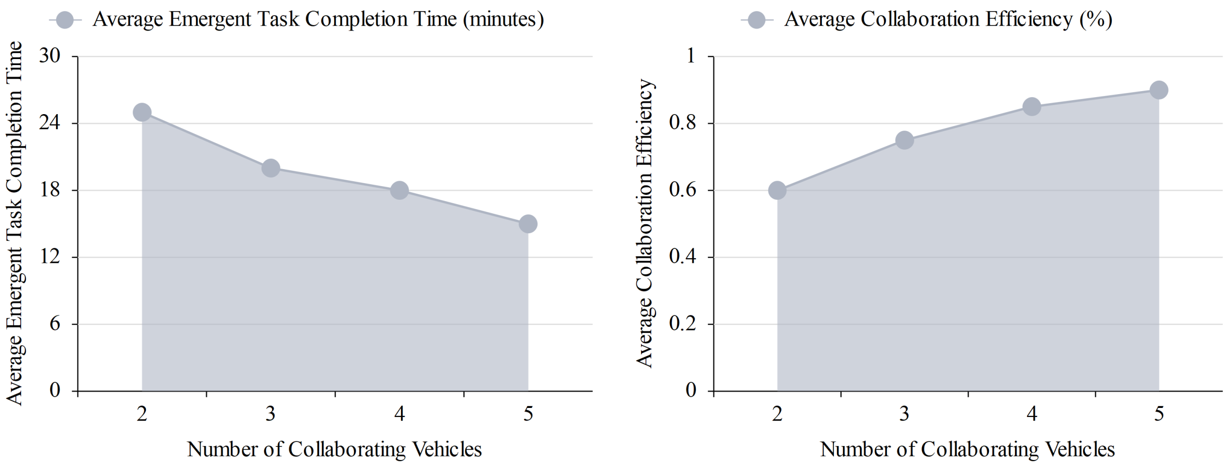

Figure 4. Result for emergent task allocation.

was also computed using the Shannon entropy measure to quantify the unbiasedness of reward distribution. Higher entropy implies rewards are distributed more evenly. The experimental results demonstrate that the incentive mechanism can offer reasonable rewards. The higher entropy value observed for emergent tasks (0.82 vs. 0.75 for general tasks) indicates that the blockchain incentive mechanism distributes rewards more evenly among participating vehicles in time-critical scenarios, reflecting a more equitable recognition of multi-vehicle collaborative contributions.

- **Transaction Costs**: The cost of executing transactions on the blockchain was also considered. The blockchain experienced higher transaction costs for emergent tasks due to the increased number of transactions. However, these costs were acceptable given the transparency and security benefits provided by the blockchain.

7.5 Scalability and Performance

We evaluated the scalability of the proposed system by simulating scenarios with an increasing number of vehicles and tasks. The results demonstrated that the system scaled efficiently, with task completion time decreasing as the number of vehicles increased, while resource utilization remained consistently high. As depicted in Figure 6, the systems performance in terms of scalability showed positive trends across various vehicle and task sizes. Additionally, the blockchain framework maintained transaction

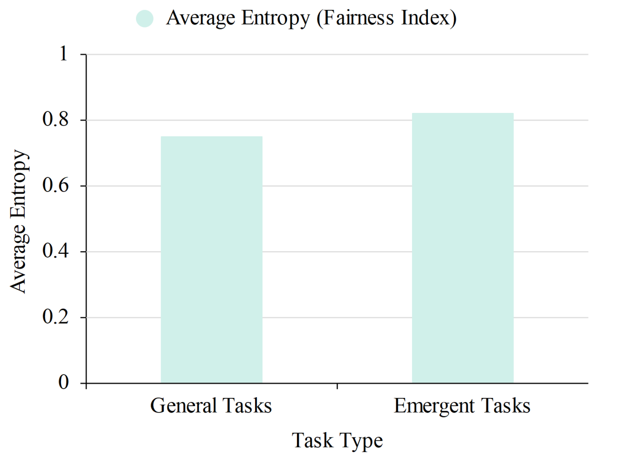

Figure 5. Fairness of reward distribution (Entropy Index).

efficiency, ensuring the system's capability to handle large-scale deployments effectively.

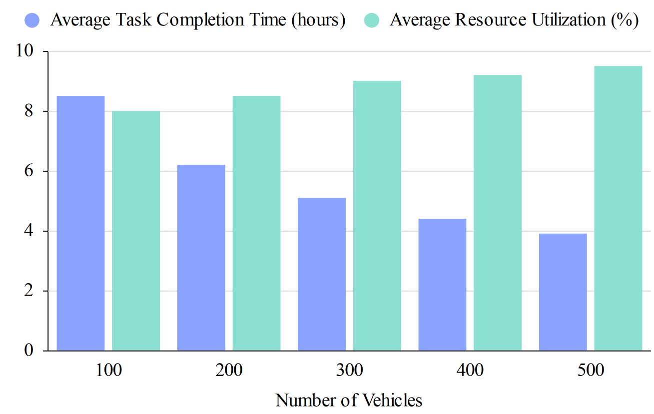

Figure 6. Scalability and performance.

Experiment results demonstrate the efficiency of the proposed framework on task allocation, cooperation, and incentive mechanisms. The greedy algorithm was efficient in distributing general tasks, and this resulted in low completion times of tasks and high resource utilization. The time-window-based cooperation approach for the emergency tasks guaranteed that the emergent tasks were processed on time by collaboratively acquiring vehicles with free resources. Moreover, the incentive mechanism in the blockchain environment not only helped to guarantee proportional financial rewards but also enabled a fair and transparent payment distribution, in which vehicles were rewarded according to their fair contribution. In overall, the system exhibited good scalability, availability, and performance that was able to efficiently support larger networks of vehicles and tasks.

Table 3. Average entropy values for fairness evaluation in reward distribution.

Task Type	Average Entropy (Fairness Index)
General Tasks	0.75
Emergent Tasks	0.82

7.6 Discussion

The performance of the system is impacted by network characteristics like channel latency and vehicle velocity. We also demonstrated that communication delays, particularly for large-scale deployments, contributed to latency in whether a task is allocated and completed, especially for tasks with tight deadlines. Cars with faster connection speeds responded more promptly, whereas cars with a low response rate or having a weak connection coverage experienced a longer delay time. These findings highlight the need for adaptive scheduling strategies that consider network dynamics and vehicle behaviour. It was also observed that the system performed well up to 500 vehicles within the tested range; however, based on the increasing communication overhead and scheduling complexity observed as the network approached this threshold, it is anticipated that performance would deteriorate at densities beyond 500 vehicles due to increased delay and congestion. Future research will be directed toward improving the blockchain framework to handle bigger networks and task scheduling algorithms in a wide range of conditions.

Despite the effectiveness of the proposed framework under moderate-density conditions, high-density urban IoV scenarios bring significant challenges with additional vehicles and messages, resulting in communication delay, congestion, and competition for resources. These overheads may, however, slow down task assignment and resource coordination dynamically, especially for instance, emergent tasks. In order to overcome these issues, future studies will scale the blockchain framework and optimize the communication protocols. Moreover, the challenge-response incentive complicates the process of transaction cost, because the blockchain-based incentive mechanism naturally involves transaction fees, in particular in public blockchains such as Ethereum. The overhead can be tolerated for small to medium-sized deployments, but it might not be feasible for hundreds to thousands of nodes. To address this, the work will investigate the more efficient consensus mechanisms such as PoS and the Layer 2 solution, as well as private blockchain to reduce the overhead of the transactions while still being naturally secure and transparent.

8 Conclusion and future work

In this paper, we proposed a blockchain-enabled Internet of Vehicles (IoV) cooperative task allocation mechanism for highly dynamic IoV systems to achieve effective task allocation and resource sharing. Through the greedy scheduling algorithm for general tasks and the dynamic scheduling algorithm for emergency tasks, the system can maximize the utilization of resources and ensure the fairness, security, and transparency in the reward distribution by using blockchain technology. Experiments demonstrate that the system is efficient and the system greatly enhances scalability, resource utilization, and the balance between rewards and compensation based on existing methods. The proposed framework was especially efficient in performing fast and secure task completion; however work shall be done in reducing energy consumption for task processing and blockchain transactions.

The proposed framework based on blockchain technology presents a new and effective approach for IoV systems to incorporate blockchain technology to support transparency, fairness, and security in task assignment. It achieves competitive resource utilization across multiple vehicles and demonstrates strong scalability, making it well-suited for integration in smart cities where large numbers of vehicles are deployed. Although energy efficiency remains an area for improvement, the system demonstrates strong scalability and overall performance. In the future, we will work on reducing energy consumption by applying energy-efficient algorithms, optimizing task allocation, and studying low-power communication protocols. Furthermore, we will also improve the blockchain scalability using sharding or layer-2 solutions to optimize the performance in the large-scale IoV systems.

Keeping privacy is vital in IoV environment as the critical vehicle and driver data is shared all the time. Future work will be directed towards the inclusion of privacy-preserving technologies such as zero-knowledge proofs and homomorphic encryption in order to protect the vehicle data from untrusted entities which enabling a transparent operation of the system. Finally, the potential of the framework for a real-world pilot is investigated to assess its practical feasibility for dynamic urban traffic management or a smart city. This deployment will enable us to evaluate the systems performance in practical environments, to optimize its functionality, and to gain more insights on how it will influence urban mobility patterns, emergency response time, and the overall IoV infrastructure.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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