Secure and Efficient Stigmergy-Empowered Blockchain Framework for Heterogeneous Collaborative Services in the Internet of Vehicles

Yuntao Liu, Daoxun Li, Rongpeng Li, Zhifeng Zhao, Yongdong Zhu, and Honggang Zhang

The authors propose a stigmergy-empowered blockchain framework called SEB, which enables untrusted IoV entities to perform heterogeneous collaborative services conveniently, securely, and efficiently.

ABSTRACT

The Internet of Vehicles (IoV) is expected to address the significant problems of modern transportation through collaboration among various entities. It is crucial to establish a collaborative mechanism for untrusted entities to achieve the full potential of IoV. Blockchain is a promising solution for building a credible environment for entities. However, because of the difference and complexity of services, using a classical blockchain system to support heterogeneous collaborative services in IoV causes some challenges in smart contract support, system security, and computational efficiency. In this article, we propose a stigmergy-empowered blockchain framework called SEB, which enables untrusted IoV entities to perform heterogeneous collaborative services conveniently, securely, and efficiently. Specifically, we first explore the characteristics of collaborative services and analyze the challenges of existing blockchain systems. Furthermore, we introduce the stigmergy of swarm intelligence into blockchain and integrate the stigmergy into SEB by designing a new transaction data structure, a digital pheromone and transaction selection rules, and a new transaction selection algorithm. Simulation experiments demonstrate that compared with IOTA, SEB reduces smart contract transaction sorting searches by approximately 56%, increases the average chain length by up to approximately 87%, and decreases the computation time of the transaction selection algorithm by up to approximately 98%.

INTRODUCTION

The Internet of Vehicles (IoV) has evolved from traditional vehicular ad hoc networks and is crucial for achieving intelligent transportation systems. It is expected to improve traffic safety, mitigate congestion, and reduce fuel consumption and pollution, which are the significant challenges of modern transportation [1]. It incorporates numerous entities, such as vehicles, base stations, satellites, road-side units (RSUs), unmanned aerial vehicles (UAVs), multi-access edge computing (MEC), and cloud providers. The collaborations among these entities are of utmost importance for achieving intelligent services. However, these entities are difficult to collaborate in practice. First, entities belonging to different stakeholders usually have independent interests. Second, numerous privacy and security data are involved in collaboration and entities are likely to distrust each other in the long run. Third, ensuring that the data involved have not been tampered with or falsified is troublesome.

An authority center provides an intuitive answer for establishing a collaborative mechanism. Nevertheless, it is difficult for distributed entities to allow one center to govern the entire system. On the other hand, blockchains have received extensive attention as a distributed ledger technology. Several studies have been conducted on leveraging blockchain to explore collaborative services for IoV scenarios, such as data sharing [2], computation offloading [3], location-based service [4] and privacy-preserving [5]. These studies have conducted excellent and professional research on dedicated services. A real IoV scenario encompasses multiple collaborative services. For example, a vehicle can provide data sharing services with other vehicles or RSUs. Meanwhile, it may receive context and computation offloading services from MECs. Building a dedicated blockchain system for each service is unrealistic, considering energy and computational overhead. Alternatively, designing a framework using only one blockchain system to support heterogeneous services is more flexible. Table 1 demonstrates how our work differs from related works. It can be observed that we support heterogeneous services, while other works focus on dedicated services. To the best of our knowledge, there is currently little related research on using a blockchain system to support heterogeneous IoV collaborative services.

Considering the large number of entities in IoV, traditional linear structure blockchain suffers from low transactions per second (TPS) and cannot be applied to IoV collaborative services. In contrast, using the directed acyclic graph (DAG) idea to improve blockchain TPS performance was first introduced in Ethereum's GHOST [6] and incorporated into many implementations in the community. For example, IOTA (a cryptocurrency for Internet of Things industry) tangle is a well-known DAG blockchain and has been widely verified in numerous scenarios [7]. For simplicity, we will use IOTA to represent the IOTA tangle and ignore the differences.

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Work	Service	Blockchain Framework	Blockchain Structure	Smart Contract
[2]	Data sharing	PermiDAG	DAG	N/A
[3]	Computation offloading	BlockEdge	Single-chain	Yes
[4]	Location-based service	Conflux	DAG	N/A
[5]	Privacy-preserving	SecFly	N/A	N/A
Our work	Heterogeneous services	SEB	DAG	Yes

TABLE 1. Comparison of related work.

We analyze the impact of collaborative services on the blockchain system from two dimensions: transaction volume and transaction arrival rate.

Unfortunately, IOTA is not fully applicable to collaborative services in IoV. First, DAG blockchains, including IOTA, do not effectively support smart contracts because of the nonlinear order of transactions [6]. Second, the transactions in IOTA are arbitrarily distributed in the ledger, which weakens the system's security [8]. Third, entities with limited power resources in IoV are sensitive to computational overhead. As one of the core algorithms in IOTA, the overhead of the tip selection algorithm (TSA) increases rapidly as the number of transactions increases [9].

Based on the idea in [10], we take inspiration from swarm intelligence to address the shortages encountered using DAG blockchain, particularly IOTA, for heterogeneous collaborative services. The individuals in swarm intelligence only need to follow simple rules to achieve group intelligence with a low computational overhead [11]. For example, as a realization of swarm intelligence, stigmergy uses pheromones to trigger specific individual behavior and ultimately achieve intelligent behavior in an ant colony [12]. Ants move randomly between their nest and food when they forage. Nevertheless, the ant colony can eventually find the shortest path between the nest and food through pheromones. We consider that the disorganized transactions in the DAG blockchain have some inherent correlations, similar to the movement of ants. Specifically, the transactions of heterogeneous services are interleaved in the DAG ledger. There is no correlation among transactions, but transactions belonging to the same service are related. Therefore, we introduce stigmergy into the DAG blockchain and design a pheromone similar to that in [13] for the blockchain system. Disordered transactions still retain their inherent association in the ledger under the guidance of the pheromone. This association can be fully used by smart contracts and the core algorithms of the blockchain system to solve or alleviate the problems in IOTA.

This article establishes a collaborative mechanism for untrusted distributed entities to realize the full potential of IoV. The main contributions of this article are summarized as follows:

1. We explore and analyze collaborative services from the perspective of blockchain, which provides a basis for the research and analysis of using one blockchain to support heterogeneous services.
2. We provide a new paradigm for designing and optimizing blockchain systems using swarm intelligence. Specifically, we introduce the stigmergy of swarm intelligence into the blockchain and propose an innovative framework called SEB (Stigmergy-Empowered Blockchain) for heterogeneous collaborative services in IoV.
3. We design a new transaction data structure, a digital pheromone, transaction selection rules, and a new transaction selection algorithm named TSPS (Transaction Selection by Pheromone of Stigmergy) for SEB to improve smart contract support, enhance system security, and decrease computational overhead.
4. We build an IoV heterogeneous collaborative services prototype system and demonstrate that SEB is superior to IOTA in terms of smart contract support, system security, and computational efficiency.

The remainder of this article is organized as follows. We discuss the blockchain system for heterogeneous collaborative services. We elaborates on our proposed blockchain framework SEB. Next, we conduct simulation experiments to verify the performance of SEB. Finally, we conclude this article with a summary.

Blockchain for Heterogeneous Collaborative Services

In this section, we first explore the characteristics of heterogeneous collaborative services and then analyze the challenges of existing blockchain systems. Based on the introduction of the stigmergy of swarm intelligence, we further present our idea of integrating the stigmergy into blockchain to solve the challenges.

Characteristics of Heterogeneous Collaborative Services

IoV has numerous heterogeneous entities. Since vehicles are the most essential and numerous entities in IoV, we consider the examples of collaborative services related to vehicles and explore their characteristics.

Different collaborative services have different requirements for the blockchain system. We analyze the impact of collaborative services on the blockchain system from two dimensions: transaction volume and transaction arrival rate. We list four typical collaborative services in Fig. 1. These four services correspond to scenarios with different transaction volumes and transaction arrival rates in the blockchain system. For example, *Type 1* represents scenarios with low transaction arrival rates and transaction volumes, while *Type 4* represents scenarios with high transaction arrival rates and transaction volumes. Furthermore, collaborative services have other inherent characteristics. First, heterogeneous entities have different computing performances. Second, many collaborative services have complex business logic. Third, entities are more likely to collaborate with others with specific correlations.

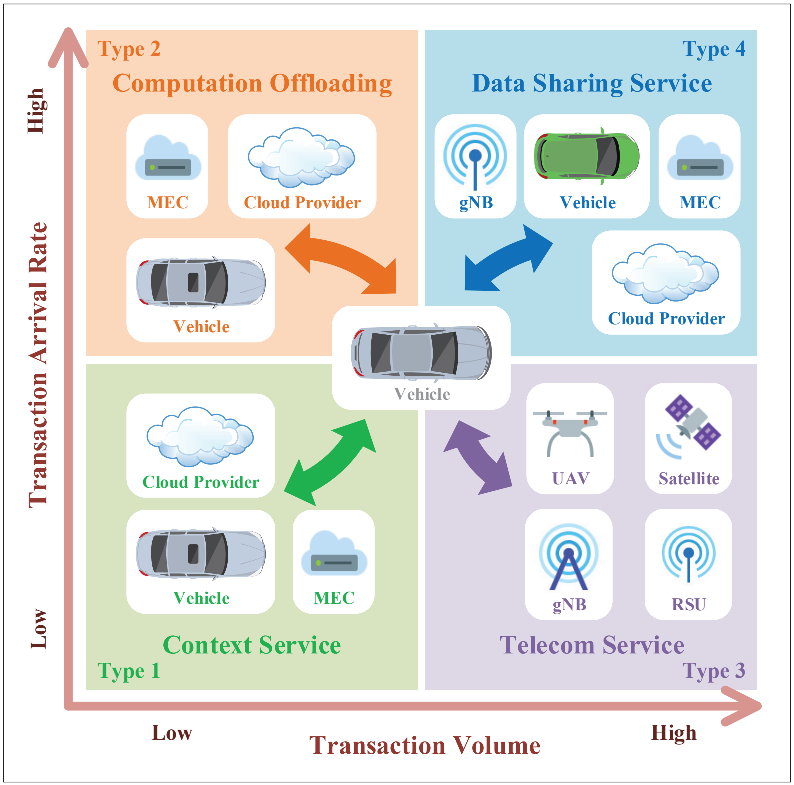

FIGURE 1. Typical heterogeneous collaborative services in IoV.

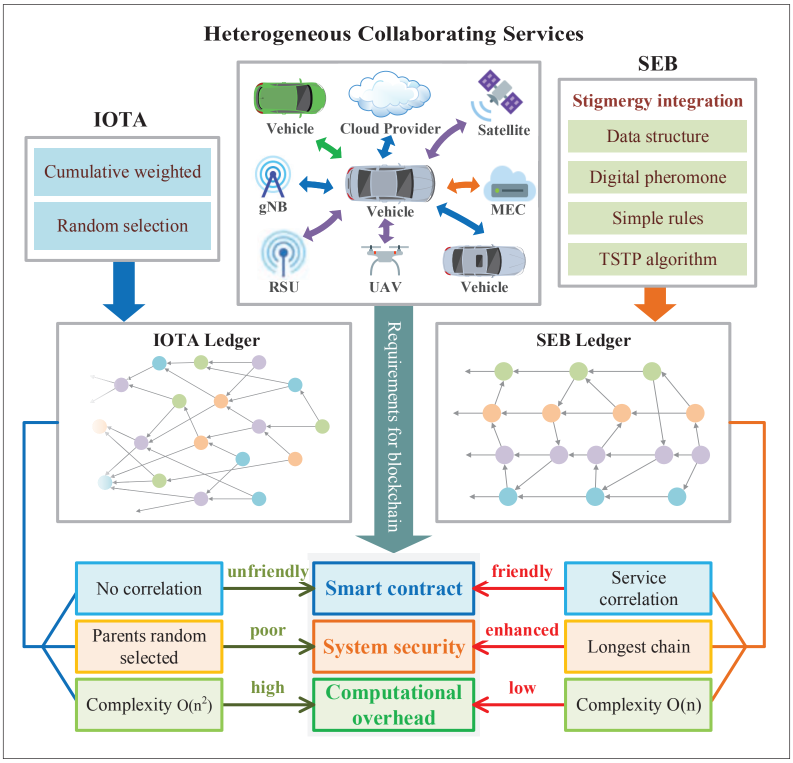

FIGURE 2. SEB vs. IOTA in supporting heterogeneous collaborative services.

CHALLENGES OF BLOCKCHAINS

As analyzed above, IoV has several scenarios that require the blockchain system to support high transaction arrival rates and transaction volumes. IOTA is an optional solution, which is a well-known DAG blockchain. However, IOTA is not fully applicable to IoV collaborative services. In the left part of Fig. 2, we list the difficulties of IOTA in supporting heterogeneous collaborative services.

First, almost all DAG blockchains, including IOTA, do not effectively support smart contracts. The transactions in DAG blockchains are linked in a directed graph instead of a chain. Thus, DAG blockchains have partially ordered sets of transactions. Nevertheless, the execution of a smart contract highly depends on the total order of its transactions. To support smart contract, DAG blockchains must sort transactions to achieve a linear order of transactions [6]. For example, IOTA sorts transactions in an L2 blockchain component. Since transactions are randomly distributed and have no correlation in IOTA's ledger, the sorting process in a DAG-structured ledger is computationally expensive.

Second, the transactions in IOTA are arbitrarily distributed on the ledger, which weakens the system's security. Random selection of parent transactions makes the chains in the ledger easy to fork. Consequently, it is difficult for the ledger to keep long chains, thereby reducing the system's security.

Third, the computational overhead of IOTA becomes excessively high when the number of transactions is large. As a core algorithm in IOTA, TSA uses Markov Chain Monte Carlo (MCMC) to select two parent transactions. In MCMC, all transactions' cumulative weight (CW) must be recalculated whenever a new transaction is added to the ledger. Given a graph with n-vertex and the complexity of graph traversal is $O(n)$, then the complexity of calculating the CW is $O(n^2)$ [9]. The computational overhead of the TSA is unacceptable for limited power resource devices such as RSUs, especially when the transaction volume is large.

INSPIRED BY STIGMERGY OF SWARM INTELLIGENCE

Swarm intelligence has some distinctive features [11], which include the following:

1. The control method is mainly distributed rather than centralized;
2. The communication between individuals is indirect rather than direct;
3. The individuals have limited abilities and simple behavior;
4. The group is formed spontaneously, and the system shows self-organization.

Based on the idea in [10], we further tentatively put forward that a blockchain system is a form of swarm intelligence since they share similar features. First, a blockchain system is distributed, and each participant is a peer. Second, participants can synchronize the ledger and other information without communicating directly. Third, enforcing each participant's capabilities or contributions to the system is impossible. Finally, all participants are spontaneous, and a blockchain system can self-manage and self-maintain itself without any center controller.

Thus, based on the stigmergy of swarm intelligence, the disorganized transactions in the DAG blockchain have several inherent correlations, similar to the movement of ants. Given the shortcomings in IOTA addressed in the previous subsection, it is reasonable to introduce swarm intelligence elements into the blockchains. Therefore, we design a digital pheromone similar to that in [13] to express the inherent correlations of transactions and further learn from stigmergy to design a more intelligent algorithm for blockchain.

SEB: A Stigmergy-Empowered Blockchain Framework

This section describes the design details of SEB, a stigmergy-empowered blockchain framework for heterogeneous collaborative services in IoV. Furthermore, we analyze how our innovative designs enable SEB to address the challenges of supporting heterogeneous collaboration services.

Overview of SEB

Figure 3 illustrates the overview of SEB. The left side of Fig. 3 shows the entities of an IoV physical world, and the right side illustrates the architecture of SEB.

We use nodes instead of entities to maintain consistency with blockchain terminology. Each node is an independent economic stakeholder, which includes one or more entities. Furthermore, we use transactions and smart contracts to map the collaboration of entities in the IoV physical world into a blockchain system. We can directly transform collaborative services into transactions when the business logic is simple. For more complex business logic, we rely on smart contracts. References [3] and [14] present numerous studies using smart contracts to achieve complex logic collaborative services.

Then, the heterogeneous collaborative services in IoV are abstracted into transactions conducted by a set of independent nodes. SEB inherits the architecture of IOTA, and there are no professional miners. However, each node performs the role of a miner to maintain the blockchain system. Additional details can be found in [7]. When a node generates a new transaction, it employs the transaction selection algorithm to select two previous transactions as its parent transactions. The selection also implies that the node approves the parent transactions. Conversely, transactions that have not been approved by other transactions are called orphan transactions, or orphans for short. We set the two parents as service-parent and security-parent, respectively. Furthermore, we design two rules to select the two parents according to the service characteristics and system security separately, and devise a new transaction selection algorithm, i.e., TSPS, to integrate the two rules. These two rules and TSPS are described in detail in Section III-B and III-C. As each transaction has two parents, there are multiple paths from one transaction to the genesis transaction. We define the height of a transaction as the number of transactions from the longest path to the genesis transaction.

Integrating Stigmergy into SEB

Figure 2 shows that SEB incorporates the stigmergy of swarm intelligence. To integrate stigmergy into SEB, we create some new designs for SEB as follows.

Transaction Data Structure: In order to make the internal correlations of the transactions more explicit, we devise a new transaction data structure. A transaction still consists of a head and body, similar to traditional blockchains. However, we add a service property item to the transaction header. A service property item contains a *type*, *indicator*, and *index*. Specifically, the *type* represents the type of collaborative service. The *indicator* represents whether a transaction is a regular or smart contract transaction. The *index* is the serial number of a transaction in a specific type and indicator. A smart contract is simply concerned with the total order of its transactions. Therefore, this new structure allows transactions belonging to a smart contract or specific collaborative service to have the same or similar service properties.

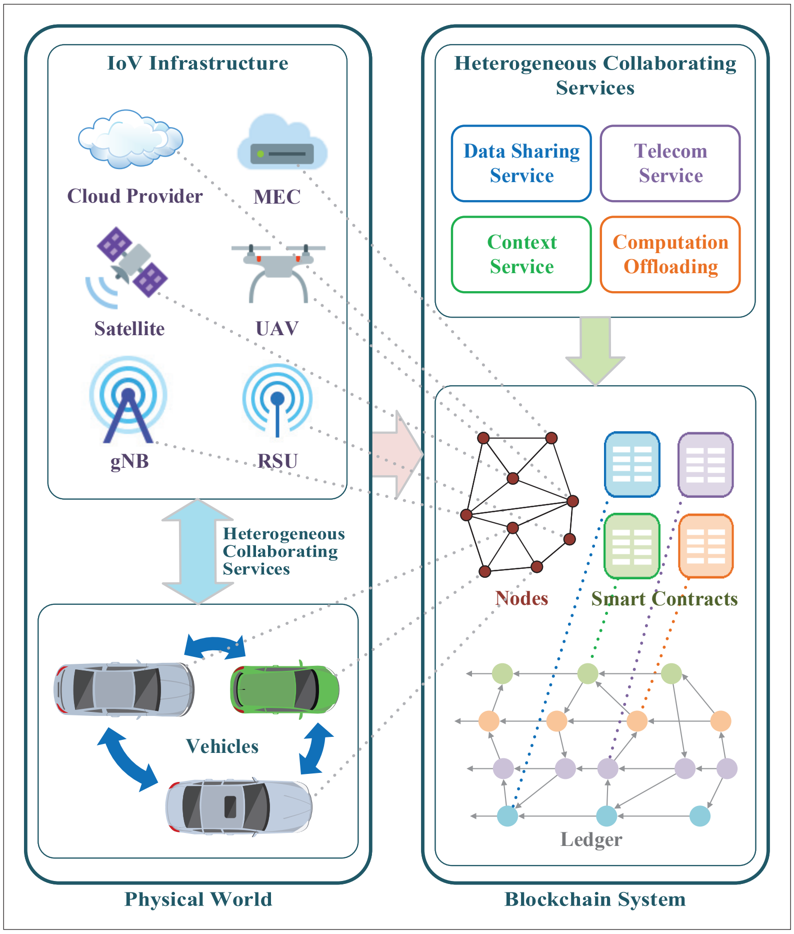

FIGURE 3. Overview of the proposed framework for IoV.

Digital Pheromone: We introduce *service-attraction* as a digital pheromone for SEB to describe the service correlation between a transaction and a newly generated transaction. Like the natural pheromone, *service-attraction* also has diffusion, accumulation, and time-decay characteristics [12]. These characteristics are described as follows:

1. *Diffusion*: the *service-attraction* of a transaction can diffuse to its service-parent, and so on backward;
2. *Accumulation*: the *service-attraction*value of a transaction is the sum of the *transaction-attraction* values of all transactions within its diffusion range, where *transaction-attraction* denotes the transaction correlation between a transaction and a newly generated transaction;
3. *Time-decay*: older transactions have lower weight when calculating the *service-attraction* value of a transaction within the diffusion range. Since the DAG blockchain can fork at any time, older transactions may appear on multiple chains. Giving greater weight values to newer transactions can allow the chain always to represent the latest service trend. Transactions are more intelligently distributed in the DAG ledger under the guidance of *service-attraction*, thus allowing transactions to retain their intrinsic correlations.

Rules: We define two rules for nodes to select a service-parent and a security-parent for their newly generated transaction. The first rule aims to select a previous transaction with the maximum *service-attraction* value as its service-parent. This rule helps increase the probability of transactions with similar service properties to be placed on the same chain or closer. As a direct benefit, implementing smart contracts is more convenient since transaction sorting for a smart contract does not need to traverse the entire graph, thus significantly reducing computational overhead. To improve system security, we introduce the Nakamoto chain rule (the longest chain rule) as the second rule to select a transaction with the maximum height value as its security-parent. The longest chain, similar to bitcoin, is the most secure. All transactions must attempt to connect to the longest chain.

As a direct benefit, implementing smart contracts is more convenient since transaction sorting for a smart contract does not need to traverse the entire graph, thus significantly reducing computational overhead.

TSPS ALGORITHM

The SEB does not have miners and relies on newly generated transactions to validate previous transactions, similar to IOTA. Therefore, the transaction selection algorithm is crucial. We present a transaction selection algorithm TSPS for SEB to replace the native TSA of IOTA, which is used to improve blockchain performance. In addition, to simplify the description of TSPS, we ignore the transaction approval process and assume that all transactions are valid by leveraging the legacy verification in the traditional blockchain systems.

Generally, the TSPS algorithm operates as follows for a new transaction.

First, the node searches for all orphans and saves them as a candidate list. A node approves an orphan if it selects the orphan as the parent of its newly generated transaction. Thus, the orphan is no longer an orphan. Consequently, this design can make the blockchain system more self-managing and self-maintaining. Furthermore, orphans are the endpoints of the DAG ledger, and they can reduce the number of blockchain forks and improve system security if they are selected as the parent transactions.

Second, the node checks whether orphans follow the rules mentioned in the previous subsection and eliminate disloyal ones from the list. Malicious nodes may arbitrarily select parent transactions for their generated transactions instead of following our proposed rules. To further combat these adversarial attacks, we must have a security enhancement. If the *service-attraction* value between an orphan and its service-parent is less than a threshold or if the height of its security-parent is less than expected, the node must remove this orphan from its candidate list. Thus, the orphan is unlikely to be selected as a parent transaction and will permanently remain a real orphan.

Third, the node selects two parent transactions from the candidate list using the two rules mentioned in the previous subsection. Specifically, to calculate the *service-attraction* value, consistent with [13], TSPS uses a one-dimensional Gaussian function to characterize the *time-decay* of *service-attraction* and a similarity function to represent the value of *transaction-attraction*.

ANALYSIS OF SEB

The ledger of SEB has some obvious changes compared with that of IOTA. Each transaction is attached to its service-parent and security-parent. In a sense, each transaction is on two chains: the service chain and the security chain. SEB has significant advantages over IOTA.

First, the service-parent rule can make transactions with the same or similar service properties more likely to be connected on the same chain or close together. Therefore, when SEB performs transaction sorting for a smart contract, it only needs to search on or around a corresponding service chain. The computational overhead of transaction sorting in SEB can be drastically reduced compared with random search in IOTA. Therefore, the implementation of smart contracts is friendly in SEB.

Second, the security of a blockchain system is related to the longest chain in a sense. The longest chain itself is the most secure, according to the rules of the Nakamoto chain. Furthermore, new transactions linked to the longest chain mean that the more times the old transactions are verified and approved, the lower the probability of transactions being tampered with. Transactions in IOTA are randomly attached to the ledger. Therefore, the system security of SEB is significantly improved compared with IOTA.

Third, the TSPS of SEB has less algorithm complexity than the TSA of IOTA. As mentioned above, given transaction number is n, the algorithm complexity of TSA is $O(n^2)$. In contrast, TSPS only needs to traverse the graph. Thus, the algorithm complexity of TSPS is $O(n)$. Therefore, TSPS has more advantages than TSA in computational overhead, especially when the number of transactions is large.

EXPERIMENTAL EVALUATION

To further demonstrate the concept of our proposed SEB, we design a blockchain-based IoV heterogeneous collaborative services prototype system. Moreover, we conduct four experiments, termed as Experiments A, B, C, and D, to compare SEB with IOTA in this prototype system.

Taking account of the complexity of a complete blockchain system, we only implement the blockchain's core modules to guarantee the execution of experiments, including node distribution, transaction generation, transaction arrival latency, transaction selection algorithm, and ledger generation. The entire simulation is consistent with [7, 8, 15] and is implemented using Java. All experiments are executed on an X86 PC station with an Intel TM i7-11700@2.50GHz 8C CPU, 32GB RAM, 1T SSD, and Windows 10. In addition, since Experiments C and D are closely related to the computing device's performance, we also conduct these experiments on an ARM-embedded device with a Cortex-A78AE@2.2GHz 12C CPU, 32G RAM, 1T SSD, and Ubuntu 20.04.

In addition, for the total number of vehicle nodes N, we evaluate the performance under different values (i.e., 5000, 10000, 15000, and 20000) in Experiments A and B. For Experiments C and D, the performance is studied when N ranges from 2000 to 50000 with a step size of 2000. Moreover, we classify four different services (i.e., *Type* 1, *Type 2*, *Type 3*, and *Type 4*), as shown in Fig. 1. In each round (i.e., every 60s), the transaction arrival rate of *Type 1* and *Type 3* is one transaction per node, while that of *Type 2* and *Type 4* is 3. The transaction volume of *Type 1* and *Type 2* is $0.03N$ in a round, while that of *Type 3* and *Type 4* is $0.12N$. For example, for *Type 1*, 3% of the vehicle nodes are selected randomly as participating nodes, and each participating node can generate one transaction in a 60s period. The time of the transactions generated in

Experiments	Cases	Blockchain	Total number of Transactions						
			100	500	1000	1500	2000	2500	3000
Experiment A number of search transactions	Type 1	SEB	5	22	52	82	110	135	160
		IOTA	75	297	537	788	1019	1260	1508
	Type 2	SEB	4	22	52	83	113	132	151
		IOTA	77	298	555	780	1009	1273	1492
	Type 3	SEB	25	111	192	317	423	549	621
		IOTA	67	287	546	794	1098	1258	1647
	Type 4	SEB	24	106	208	314	425	506	597
		IOTA	68	294	528	818	1055	1319	1612
Experiment B chain length	Gaussian distribution	SEB	13	50	113	186	256	335	428
		IOTA	11	41	92	139	183	229	280
	Uniform distribution	SEB	10	39	80	125	178	238	295
		IOTA	8	25	51	78	102	129	158

TABLE 2. Results of Experiments A and B.

Compared to the uniformly distributed vehicle nodes, a larger proportion of the Gaussian-distributed vehicle nodes are distributed in a closer manner.

each round satisfies a Poisson distribution. This configuration ensures that the four service types have the same combination of transaction volume and arrival rate. Furthermore, according to our simulation experiments and theoretical analysis, increasing the total number of transactions leads to a more obvious advantage of SEB over IOTA. Therefore, we set the maximum number of unapproved transactions in experiments as 3000, refer to [8].

Transaction Sorting Performance for Smart Contracts

In this experiment, we compare the transaction sorting performance for smart contracts to verify SEB and IOTA in supporting smart contracts conveniently. We randomly choose two transactions of a smart contract from SEB and IOTA ledgers. Then, we count the number of transactions that need to be searched to sort out the two transactions. Furthermore, to diminish the randomness, we perform 500 independent runs and adopt their average values to represent the sorting performance.

From Table 2, we can learn that SEB markedly reduces the transaction search times for transaction sorting. Compared with IOTA, SEB reduces the search number of transactions by at least approximately 56% and up to 95% in this experiment. Furthermore, the transaction sorting performance of SEB improves in all service types, especially in *Type 1* and *Type 2*, which have small transaction volumes.

The results are consistent with our expectations. As analyzed in the previous section, transactions in SEB with the same service property are more likely to be on a linear chain or close together in the ledger. SEB can search on a chain or around it to sort transactions for a smart contract, whereas IOTA must traverse the entire graph regardless of the transaction volume for that smart contract. Consequently, SEB can remarkably improve the computational efficiency of transaction sorting, making it more friendly for implementing smart contracts.

System Security from the Perspective of Chain Length

In this experiment, we verify the system security from the perspective of chain length. Based on the Nakamoto chain rule, the longer the chain, the more secure the system. In addition, the distribution of nodes can affect the chain length. We perform this experiment in cases where the distribution of vehicle nodes is Gaussian or uniform.

As shown in Table 2, SEB has a much longer average chain length than IOTA in these two distributions. Moreover, this advantage becomes more obvious as the total number of transactions increases. In our experiment, when the total transactions number is 3000, the average chain length in SEB is about 87% and 53% higher than in IOTA under the vehicle nodes' uniform distribution and Gaussian distribution, respectively. The reason is apparent. In IOTA, newly generated transactions are attached to any other transactions, causing the edges of the DAG ledger to grow continuously. Conversely, the newly generated transaction is attached to its security-parent in SEB. As such, all transactions are linked to the longest chain found, which enables a longer average chain length and better system security.

Furthermore, for both SEB and IOTA, the average chain length under the Gaussian distribution is longer than that under the uniform distribution. Compared to the uniformly distributed vehicle nodes, a larger proportion of the Gaussian-distributed vehicle nodes are distributed in a closer manner. Thus, there is a lower probability of generating forking in the Gaussian case than in the uniform case. As a result, the average chain length is longer under Gaussian distribution.

Computational Efficiency Comparison of TSPS and TSA

In this experiment, we encapsulate TSPS and TSA algorithms as separate modules (objects in Java code) and execute them with the same configurations on the same device to compare computational efficiency. The implementation of TSA is consistent with [7, 8] and [15] as well. In addition, the computation time for executing TSPS and TSA for a single transaction is short and varied. Consequently, we count the total time to execute the algorithms for all transactions generated by vehicle nodes in one minute.

As shown in Fig. 4, TSPS has a conspicuous advantage over TSA, especially when the number of vehicle nodes increases. In our experiment, when the num-

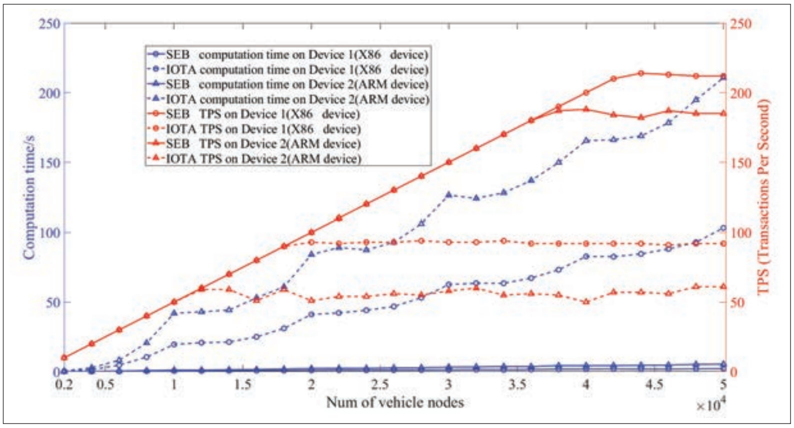

FIGURE 4. Computational efficiency and TPS of SEB and IOTA.

ber of vehicle nodes is 50000, compared with TSA, TSPS can reduce the computing time by about 98%.

As mentioned earlier, assuming the number of transactions is n, the complexity of TSA and TSPS are $O(n^2)$and $O(n)$, respectively. Therefore, TSPS takes less computation time than TSA. The number of transactions generated by vehicle nodes is proportional to the number of vehicle nodes. Therefore, this advantage will become more obvious as the number of vehicle nodes increases.

TPS PERFORMANCE COMPARISON

The TPS is an essential performance metric for a blockchain system. In this experiment, we verify the TPS performance of SEB and IOTA in the same setup with the same parameters. Considering that SEB improvement to IOTA is primarily the transaction selection algorithm, we ignore the time consumed by the transaction verification in this experiment.

As shown in Fig. 4, the maximum TPS of SEB is approximately 134% greater than that of IOTA. When the device can process all transactions in time, TPS increases linearly along with the number of vehicle nodes. However, when the device reaches its peak computing capability, TPS stops increasing. At this stage, TPS fluctuates around the maximum value because the device cannot maintain a stable peak computing capability for a long period. The transaction selection algorithm is the most time-consuming component of processing a transaction. The computation cost of TSPS is less than that of TSA. Thus, the maximum TPS of SEB should be higher than that of IOTA.

CONCLUSION AND FUTURE DIRECTIONS

This article proposes a blockchain-empowered framework SEB for heterogeneous collaborative services in IoV. Without loss of generality, SEB establishes a collaboration mechanism that enables untrusted distributed entities to simultaneously support heterogeneous collaborative services conveniently, securely, and efficiently. Furthermore, this article provides a new paradigm for designing and optimizing blockchain systems using swarm intelligence techniques. The simulation results show that by introducing the stigmergy of swarm intelligence, SEB achieves significant performance improvement over the baseline IOTA in terms of smart contract support, system security, and computational efficiency.

For future work, the proposed SEB still has its limitations. First, it needs to be optimized for node mobility in practical IoV applications. Second, we must study defense strategies and evaluate the performance under malicious attacks. Third, the deployment of SEB on different IoV entities with heterogeneous performance devices at scale should be addressed further. Fourth, applying additional swarm intelligence techniques to blockchain systems should be studied in greater detail.

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