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Digital Twin Consensus for Blockchain-Enabled Intelligent Transportation Systems in Smart Cities

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***Abstract*— Digital Twin (DT) has become the key technology in the Intelligent Transportation Systems (ITS) in smart cities to keep the health and reliability of various DT requesters, such as private vehicles, public transportation, energy systems, etc. The combination of DT and ITS can further release the potential of participants in smart cities and guarantee their efficiency and reliability. Despite the advantages of DT-enabled ITS, not all requesters need the same level of DT service due to the highly dynamic nature of ITS. Safe and reliable matching between DT and ITS still needs to be resolved. To address these issues, we propose the blockchain-enabled Digital Twin as a Service (DTaaS) for ITS. First, we propose an on-demand DTaaS architecture to fully utilize the sensing capabilities of ITS and the macro perspective of DT. Second, a double-auction model and a price adjustment algorithm are proposed to realize the optimal DT matching for ITS requesters and ensure the benefits of participants. Third, a permissioned blockchain and a novel DT-DPoS consensus mechanism are established to enhance the security and efficiency of DTaaS. Simulation shows that the proposed DTaaS and double-auction can efficiently stimulate and facilitate DT transactions. The proposed DT-DPoS also has obvious advantages.**

***Index Terms*— Digital Twin, blockchain, intelligent transportation systems, consensus mechanism, auction.**

I. Introduction

THE development of Intelligent transportation systems (ITS) have huge potential and capabilities in future smart cities, which can help construct smart, efficient and safe transportation. Followed by complex interactions and massive traffic data generated by ITS, the difficulty of system management and control continues to increase [1]. Therefore, fully integrating the massive data of ITS with the computation, communication, and control (3C) capabilities of the possible ITS managers can improve the service quality, stability, and reliability of ITS [2]. To enable the intelligence with the digital replication of physical systems in cyberspace, the Digital Twin (DT) concept can be utilized for better ITS services. DT technology is the mapping of the physical system into the digital world. The advantages of DT-related technologies in ITS mainly lie in full life cycle service, real-time and accurate response, and bidirectional communication. For unified scheduling and management, DT can be deployed for ITS to map complex and changeable intelligent transportation subsystems, such as private vehicles, public transportation, energy systems, etc. In this way, DT can make full use of physical models and sensing data to continuously predict the health, lifespan, and critical security events of the system [3].

The DT is an accurate model description of the actual production system. DT must first perceive and model, then analyze a large amount of various data and publish control strategies for the ITS [4]. The basic idea of DT realizes the bidirectional interaction between the physical system in reality and the digital model of the cyber space. DT can obtain massive sensing data from the ITS to get a global perspective, while the ITS can get a vision related to the future of the system with the assistance of the powerful computation, communication, and control of DT [5]. In this way, it is possible to truly realize the coordination of the digital world and the physical system within the entire life cycle of the ITS. Various simulations, analyses, data accumulation, data mining, and even some artificial intelligence (AI) based on digital models can ensure the applicability of DT and physical systems [6].

However, the variability of equipment location and affiliation is an important and distinctive feature of ITS, which brings complex and dynamic requirements to many subsystems of ITS. Such diversification and complex application services of ITS subsystems put forward the need for on-demand customization of DT services. Obviously, not all ITS requesters require the same level of DT services. On the other hand, many current DT service models lack sufficient flexibility, which hinders the efficiency and further promotion of DT in ITS. A demand-oriented DT service architecture for future ITS is urgently needed

As a distributed data structure, the blockchain can be replicated and shared among the system participants, which

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has also been applied to DT-related application scenarios [7]. Because of the decentralized and immutable characteristics of blockchain, the secure and efficient DT service transactions of ITS, including computing, communication, and control can be guaranteed [8]. However, the obvious weaknesses of traditional blockchain in terms of energy, speed and scalability will hinder its application in DT systems [9]. Therefore, the advantages of permissioned blockchain in terms of efficiency and flexibility are considered for the blockchain-enabled ITS sensing and control systems. Transactions in the blockchain can be either digital currency or digital assets such as debt, equity, copyright, etc [10]. This greatly reduces the trust cost and accounting cost of real transactions, and provides the possibility to redefine the property rights system of the ITS.

The goal of our work is to provide a detailed description of how the proposed DT consensus work to support the secure and on-demand DT services for future ITS. Therefore, by introducing the DT service brokers, we exploit the blockchain-related technologies for the DT service transactions between ITS in smart cities and DT service providers (e.g. edge servers, cloud data centers, etc.). The demand-oriented DT services are fully considered in this paper. The contributions of this paper are the following:

- This paper proposes the on-demand Digital Twin as a Service (DTaaS) architecture for the various DT requirements in ITS. The specific details of DT services are analyzed, so the dynamic DT requirements of ITS can be fully considered and responded as needed.
- A permissioned blockchain is established for DT service transactions for the dynamic service matching between ITS in smart cities and DT service providers. An improved consensus mechanism DT-DPoS is proposed.
- A double-auction scheme and a price adjustment algorithm are proposed to ensure the benefits of the demand-oriented DT service participants. An optimal matching method between DT servers and ITS is proposed for the double-auction mechanism.

The remainder of this paper is organized as follows. The related work and the strengths of the proposed DTaaS are given in section II. The proposed DT consensus and the double-auction model for ITS are presented in Section III. Both the auction process of DTaaS scheme for ITS and the proposed algorithm for DT service price adjusting are provided in Section IV. Simulation results are shown in Section V to illustrate the performance of the double-auction model and algorithms. Section VI comes to the final conclusion.

II. Related Work

Acting as a measurement of designing virtual models based on physical entities, DT has a great potential in improving the security and resiliency of all aspects in smart cities, including ITS [11], [12]. DT can form information models that are completely equivalent to physical entities in cyberspace, and can simulate, analyze and optimize physical entities. Authors of [4] provide a state-of-the-art survey of DT in the industry to show comprehensive insights.

By combining edge computing with DT-enabled Internet of Vehicles (IoV), the authors analyzed a multi-user edge computing offloading system By combining edge computing with DT-enabled Internet of Vehicles (IoV), the authors analyzed a multi-user edge computing offloading system with deep learning [13]. In [14], a vehicle edge caching mechanism based on social perception is fully considered. As important equipment in ITS, the caching capabilities of roadside units (RSUs) and smart vehicles are fully rearranged according to user preferences.

In [15], the authors point out the key security requirements for DT-based data sharing and control and that the proposed state synchronization meets the expected DT synchronization requirements. As a new type of smart city application, the author proposes to deploy a digital twin box on the road, which consists of a camera and on-board computer and continuously sends real-time data to the edge/cloud [16]. By modeling the digital twins of vehicles and drivers in the cloud server, the merging cooperation between vehicles is improved, and safety and sustainability are ensured with acceptable communication delays. [17].

On the other hand, the blockchain can be regarded as a huge leap forward for distributed databases [8], [18]. The obvious benefits of blockchain in terms of secure and efficient transaction records can provide an appropriate platform for DT-related service. To solve the data decentralized sharing requirement in DT, a prototype EtherTwin is proposed to deal with the problems of distribution, integrity and confidentiality [19]. Similarly, the authors of [20] studied the applicability of distributed ledgers to protect digital twin data sharing to overcome current infrastructure challenges. Due to the traceability of transactions, the authors of [21] propose to authenticate and monitor the entire component production process of the product through the blockchain, and conducted in-depth research using metal additive in the aviation industry as an example. For the complex life cycle of products and large amounts of data, a DT-enabled data management method based on blockchain technology is proposed to improve the efficiency of data sharing between participants [22].

Although some related studies introduce the advantages of DT ideas into the ITS-related issues, they hardly involve the on-demand response of DT service for different ITS requesters. Therefore, compared with the existing work, the strengths of our work lie in the following aspects. First, we have fully considered the dynamic demand of ITS subsystems for DT services. Second, to ensure the security of service transactions, the advantages of the permissioned blockchain are fully utilized and a DT consensus is proposed. Third, for better ITS utility, we design a double-auction model and a price adjustment algorithm to support the blockchain-enabled DTaaS proposed in this paper, and the transactions are recorded in the blockchain.

III. Basic Architecture

A. Basic Scene of Blockchain-Enabled DTaaS for ITS

In the ITS of a smart city, various subsystems are constantly serving the smart and efficient transportation of the city.

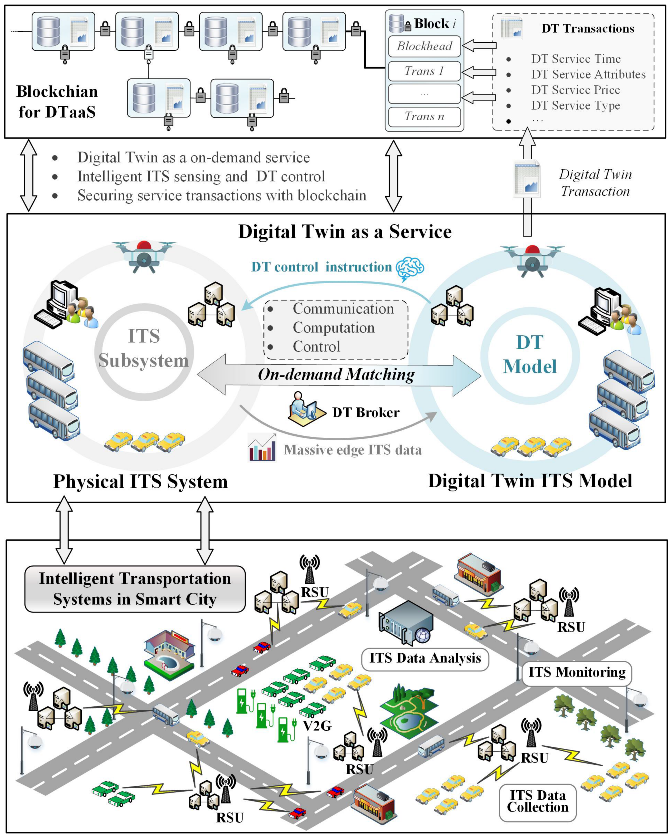


Fig. 1. Blockchain-enabled Digital Twin as a Service for ITS in Smart Cities.

When the number of moving devices/vehicles and the amount of ITS data become larger, its management and maintenance will become increasingly complicated, thereby reducing the safety and reliability of the transportation systems in the smart cities. ITS is a complex and large-scale system composed of multiple functional subsystems and corresponding physical equipments (e.g., traffic information collection systems, data processing and analysis systems, and information publication systems). Therefore, we introduce the DT servers to provide a guarantee for the stable and efficient operation of the ITS-related subsystems in the smart city, shown in Fig.1. The DT server needs to be capable of providing control, communication, and computation functions. As the requesters of DT service, the different subsystems of ITS manage a large number of vehicles and traffic-related equipments. Therefore, an on-demand DT service model will ensure a better service for the overall ITS system. To improve the system efficiency and reliability, the DT server shown in Fig.1 with computation, communication and control capabilities can provide early warning and optimization of health status, system stability, and security events. However, changes in DT requirements in ITS are often unpredictable, resulting in huge difficulty and workload for DT service management. So it is necessary to introduce an on-demand DTaaS scheme. In the DTaaS scheme, different DT service providers will perform optimal resource transactions with the ITS subsystems. DT servers will establish corresponding models for ITS subsystems to provide real-time and detailed guarantees. The permissioned blockchain we deployed consists of DT servers that meet

TABLE I

MAIN SYMBOLS AND EXPLANATIONS

Symbols	*Explains*
i, j, k	ITS subsystem i, DT server j, DT broker k
$\mathbb{I}, \mathbb{J}, \mathbb{K}$	The set of ITS subsystem, DT server, DT broker
$s\%$	User satisfaction of DT service
$Tok_{DT,j}$	Total cumulative token amount
$R_{i,j}$	DT service level obtained by ITS
θ, γ	Indicate the ITS scale and the demand for DT
ap_{ij}, bp_{ij}	Asking price of seller, bidding price of buyer
α, β	Correspondence between 3C resources
T_{ij}	Total service time of $i - j$
f_{ij}	Total service frequency of $i - j$
ω, μ	Price adjustment parameters
η, ε	Communication resource parameters
a, b, c	Computation resource parameters
$\sigma/1-\sigma$	Proportion of auction cost of buyers/sellers
N	Total auction rounds
λ	The cost of each auction
$\delta_{i,j}^k$	Buyer and seller $i - j$ are trading on broker k

the basic conditions of DT services. Together they maintain distributed DT service transactions. The service transactions of ITS and DT nodes are recorded in the blockchain to ensure security and efficiency. The ITS subsystems will then send their key sensing data and information to the DT service providers and the DT will contribute its computation, control and communication resources to provide services for ITS.

B. Improved DT-DPoS Consensus Mechanism for Blockchain-Enabled Digital Twin

To enhance the security and reliability of the DTaaS scheme for ITS, a permissioned blockchain model is established for the system. The permission blockchain sets clear and detailed requirements for the nodes participating in the blockchain, so it can further guarantee the security and quality of DT services. DT servers are regarded as nodes of the permissioned blockchain and maintain the operation of the blockchain. To facilitate the explanation of the mathematical models of this paper, the main symbols used in this paper and their corresponding meaning are shown in Table I.

In terms of the consensus mechanism, certain improvements to the traditional Delegated Proof of Stake (DPoS) are a potential feasible solution for the DTaaS mechanism. Therefore, this paper proposes a DT-DPoS consensus suitable for ITS and digital twin scenarios, which also retains the efficiency and speed of traditional DPoS. Since each DT node needs a corresponding complete ITS subsystem model for the customized service, DT nodes are natural representative nodes to participate in the consensus. To ensure the security and efficiency of the permissioned blockchain, token holders in DT-DPoS will select several representative nodes to operate the network. Since the DTaaS scheme has certain per-

Algorithm 1 DT-DPoS Consensus Algorithm in DTaaS

Input: The set of all DT nodes $\mathbb{R}$, the current token of each node $Tok_{DT,j}$, and the service satisfaction of ITS $s\%$
Output: Validator V^* and backup validators V^b.

```
Search for newly added DT nodes
  if New nodes meet the joining conditions then
    Update the nodes list of the permission blockchain
    DT nodes choose the total amount of token invested
  end if
  for all t_i ∈ T do
    Calculate cumulative tokens according to Eq.(1)
  end for
  for all node DT_j do
    if DT_j ∈ ℝ then
      Update service satisfaction s%
      Calculate P(DT_j, Rep) according to Eq.(2)
    else
      P(DT_j, Rep)=0
  end for
Choose representative V* according to probability P(DT_j, Rep)
V* pay the deposit and verify the block
Update the set of compliant nodes
Recalculate the cumulative token of each node over time
```

formance requirements for the computation, communication, and security of DT nodes, DT nodes for the permissioned blockchain can be regarded as a representative elected by the ITS subsystems. Further, the DPoS consensus will select a certain number of representatives to be responsible for the production of blocks. One of its best advantages is that the time for reaching consensus is relatively much shorter. Meanwhile, in the blockchain-enabled DTaaS system, if the block validator is incompetent, it may be voted out by other DT nodes at any time, and other backup nodes will perform their duties. Part of the rewards will also be given to the validators and voters of the network maintenance node as a reward for community maintenance.

To fit the actual scenario of DTaaS, we also made customized improvements to DPoS so that it can promote the utility of DT nodes, which is called DT-DPoS. Although DT nodes can obtain benefits by providing services for ITS subsystems, we have also taken into account the feedback of ITS subsystems on services during their specific consensus process. Therefore, we designed the following token calculation method for DT-DPoS.

In our DT-DPoS consensus mechanism, when a node obtains the accounting right, its accumulated token will be cleared. Otherwise, the token will accumulate over time to increase the probability of the node obtaining the accounting right. The total cumulative token amount $Tok_{DT,j}$ of the DT service provider j will be counted.

$$Tok_{DT,j} = \sum_{t_i \in \mathbb{T}} \tau_{DT,j} \cdot s\% \quad (j \in \mathbb{J} \quad t_i \in \mathbb{T}) \tag{1}$$

In the above $Eq.(1)$, t_i denotes each time period of DT server and $\mathbb{T}$ is the cumulative time period. Therefore, we can

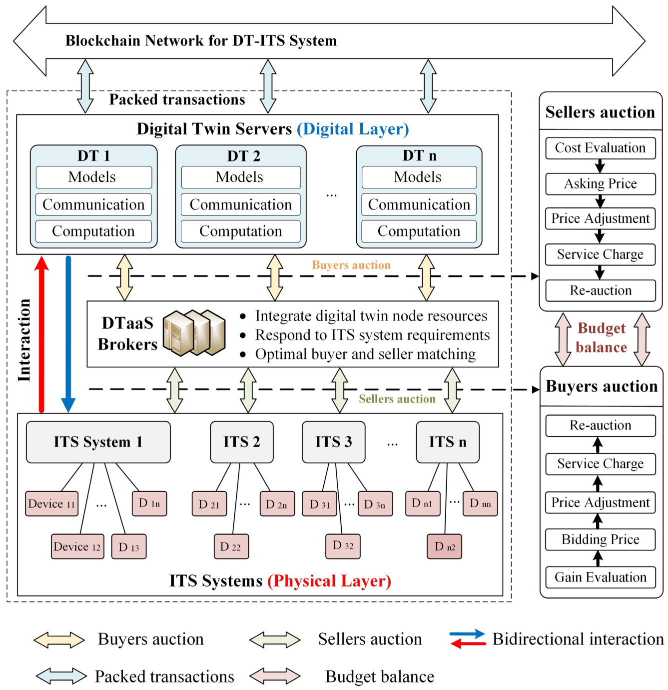


Fig. 2. The Double-auction Process for the Matching of ITS Subsystems and DT Servers.

calculate the probability that each DT server becomes the chosen block validator as the following $Eq.(2)$.

$$P(DT_j, Rep) = \frac{Tok_{DT,j}}{\sum_{j \in \mathbb{J}} Tok_{DT,j} \cdot \chi_j} \begin{cases} \chi_j = 0 & DT_j \in \mathbb{R} \\ \chi_j = 1 & DT_j \notin \mathbb{R} \end{cases} \tag{2}$$

In $Eq.(2)$, χ_j is a 0-1 variable and $\mathbb{R}$ is the collection of all compliant nodes. The specific DT-DPoS consensus mechanism process we proposed can be expressed by the following Algorithm 1.

C. A DT Service Auction for the Proposed DT Consensus

For better service matching of various DT services and the requirements of ITS subsystems, this paper proposes a double auction method in which buyers and sellers determine prices through open competition. The double auction is a model in which buyers and sellers seek the optimal match in the open market [23]. For the optimal matching, competition between buyers and sellers coexist. As shown in Fig.2, diversified DT service providers and ITS subsystems seek the optimal matching through DT brokers to achieve the better matching of DT services and requirements. The DT server acts as a seller to measure its specific cost and then give an asking price. Each ITS subsystem acts as a buyer to measure the benefits of the specific resources that the DT server can provide, and then gives the bidding price. The two parties reach a deal or fail to match in the continuous price adjustment, and DT broker charges a certain fee through the auction process. As the organizer of the auction, DT brokers play a bidirectional matching role. On the one hand, it integrates the resources of DT service providers, and on the other hand, it responds to requests from ITS subsystems. In the DTaaS mechanism proposed in this paper, DT brokers are intermediate service nodes with high reputation and need to undergo strict inspection and supervision. The transaction process and payment of fees will be protected and guaranteed by the aforementioned permissioned blockchain system. In addition, compliant DT servers will maintain the transactions and contracts generated during this matching process through the consensus mechanism mentioned above.

IV. Proposed Scheme and Algorithms

A. The Double Auction Model for DTaaS

Unlike traditional British auctions, double auctions are more suitable for multiple service providers and multiple demanders, where there is competition between buyers and sellers. The main advantage of double auction for DT service transactions in ITS is that participants can bid at any time and the transaction can be quickly concluded. We formulate the DT service market in the blockchain-enabled DTaaS scheme with a double-auction process to satisfy incentive compatibility. The DT service market is composed of compliant DT servers and different subsystems of the ITS. Both buyers and sellers can continuously give their own prices to brokers in order to seek completion of the transaction, and the brokers will charge a certain amount of auction fees. There are several assumptions in the proposed auction process as follows:

- All DT service provider have reasonable resources to serve different ITS subsystems, and only differs in costs and service utility. They and sells the equivalent DT service to different ITS subsystems.
- DT brokers only match those DT services from DT servers that satisfy requests of ITS subsystems. During the double-auction process, some related constraints are always satisfied (e.g. time delay, energy consumption, etc.
- Through the double-auction, ITS buyers can purchase any satisfying DT service from the DT market. There is a one-to-one correspondence between DT service providers and ITS subsystems.

1) Resource Evaluation for DT Service: In the DTaaS scheme, the main resources involved in the DT service include computation resources, communication resources and control resources. These three types of resources are highly interrelated.

- Computation resources: Mainly used to ensure the foundation of all computing power related to DT services.
- Communication resources: Support bidirectional communication between the DT server and the ITS subsystem, including the acquisition of real-time data and the issuance of control strategies.
- Control resources: Indicates the ability of the DT server to model the ITS subsystem. A better modeling level can support more precise and better control strategies.

To ensure a efficient DT service, control resources mainly lie in the establishment of models, computing resources mainly lie in the calculation of data-based models, and communication resources lie in maintaining frequent interaction with ITS subsystems. Taking into account the quality of service of the DT and the efficiency of the blockchain system, we have also set a minimum threshold for the resources of the DT server. To better evaluate the resources of the DT server, we assume the following resource correspondence.

$$Rcp_{m,n} = \alpha \cdot Rcm_{m,n} = \beta \cdot Rmd_{m,n} \quad (\alpha, \beta > 0) \tag{3}$$

where α and β represent the corresponding weights between computing resource and other resources. Through the above formula, we can calculate how much computing and communication resources are needed for a certain scale of DT model. In addition, whether a service provider can join the DT market should be determined by its minimum resources, which is $R_{i,j} \geq R_{threshold}$. For the DT service provider j and corresponding ITS subsystem i, we have the following formula.

$$\begin{aligned} R_{i,j} &= min\left\{Rcp'_{i,j}, Rcm'_{i,j}, Rmd'_{i,j}\right\} \\ &= min\left\{Rcp_{i,j}, \frac{1}{\alpha}Rcm_{i,j}, \frac{1}{\beta}Rmd_{i,j}\right\} \end{aligned} \tag{4}$$

That is, for a DT server, the measurement of its resources is determined by the shortcomings of its computing, communication and modeling resources.

2) Utility of ITS Subsystems: The ITS subsystem's measurement of service utility is its estimate of the value of DT services. In this paper, the utility of the ITS subsystem is set as an exponential function to get closer to the actual situation. Similar to common service satisfaction models, the increase in service utility will slow down as DT service resources increase, which can be expressed by the following formula.

$$G_{ITS,i} = \frac{1}{\theta_i} \cdot log(1 + \gamma_i \cdot R_{i,j}) \cdot \mu_{i,j} \cdot T_{i,j} \quad (i, j \in \mathbb{I}, \mathbb{J}) \tag{5}$$

In the above formula, both θ are used to represent the model scale after DT has modeled ITS and γ is a parameter of the sensitivity of the ITS subsystem to DT resources. The increase of θ and the decrease of γ (larger model scale and lower resource sensitivity level) will hinder the utility of ITS for corresponding resources. On the other hand, the total cost of the ITS subsystem is the following product of the service unit price and the total service time.

$$C_{ITS,i} = bp_{i,j} \cdot T_{i,j} \quad (i, j \in \mathbb{I}, \mathbb{J}) \tag{6}$$

Therefore, the specific utility of ITS is the difference between the benefits derived from DT services and the total cost paid. It is worth noting that if the DT service buyer fails to match the ITS seller, the utility of the ITS is zero.

$$\begin{aligned} U_{ITS,i} &= G_{ITS,i} - C_{ITS,i} \\ &= \sum_{t \in T_{i,j}} (\frac{1}{\theta_i} \cdot log(1 + \gamma_i \cdot R_{i,j}) \cdot \lambda_{i,j} - bp_{i,j}) \end{aligned} \tag{7}$$

3) Utility of DT Service Providers: The utility of DT service providers is also measured by the difference between its benefits and costs. It can be measured by the product of the unit price of the service asking price and the service time. The following equation shows that the revenue of the DT server is the difference between the price paid by the ITS and the auction fee.

$$G_{DT,j} = C_{ITS,j} - G_{broker} = ap_{i,j} \cdot T_{i,j} \quad (i, j \in \mathbb{I}, \mathbb{J}) \tag{8}$$

On the other hand, the cost of DT service providers can be refined into the following three aspects: computation cost $C_{cp,j}$, communication cost $C_{cm,j}$ and control cost $C_{md,j}$.

$$\begin{cases} C_{md,j} = r_j \cdot \theta_i + d_j & \text{(9a)} \\ C_{cm,j} = \dfrac{T_{i,j}}{f_{i,j}}(\eta_j \cdot e^{\varepsilon_j C_{md,j}} - 1) & \text{(9b)} \\ C_{cp,j} = \dfrac{T_{i,j}}{f_{i,j}}(a_j \cdot C_{md,j}^2 + b_j \cdot C_{md,j} + c_j) & \text{(9c)} \end{cases}$$

In the above formula, since the DT model is a reflection of the real IST system, control cost $C_{md,j}$ is considered to be linearly related to the scale parameter of the IST. $\frac{T_{i,j}}{f_{i,j}}$ represents the number of interactions between the two parties. Since a larger communication bandwidth occupancy will lead to a rapid decline in the quality of communication services, the cost of communication $C_{cm,j}$ is set as an exponential function. The specific computation cost is closely related to the complexity of the specific algorithm used. In this model, the computation cost $C_{cp,j}$ is set to a common polynomial form.

Similarly, the specific utility of a DT service provider is the difference between its benefits and costs.

$$\begin{aligned} U_{DT,j} &= G_{DT,j} - C_{md,j} - C_{cm,j} - C_{cp,j} \\ &= ap_{i,j} \cdot T_{i,j} - k \cdot \theta - d \\ &\quad - \frac{T_{i,j}}{f_{i,j}}(a \cdot C_{md,j}^2 + b \cdot C_{md,j} + c + \eta \cdot e^{\varepsilon C_{md,j}} - 1) \end{aligned} \tag{10}$$

That is, the DT's income is the total asking price income of the paid resources minus the cost of its resources in three aspects.

4) Problem Formulation of the Double Auction: During the auction process, DT puts forward an asking price for the resources it will pay, and ITS puts forward a bidding price for the resources in order to obtain services of DT. In the end, the DT broker that facilitates the transaction will determine a hammer price. In the double-auction process, both buyers and sellers have certain requirements on the hammer price [24].

$$\begin{cases} G_{ITS,i} \geqslant p_i^k \cdot T_{i,j} \geqslant bp_i^k \cdot T_{i,j} & \text{(11a)} \\ ap_j^k \cdot T_{i,j} \geqslant p_j^k \cdot T_{i,j} \geqslant C_{md,j} + C_{cm,j} + C_{cp,j} & \text{(11b)} \end{cases}$$

The above Eq. (11) shows that both parties involved in buying and selling are rational, and it shows a clear relationship between price, income and cost.

For the broker, the income it obtains comes from the difference between the prices of the two parties, and from the transaction fees obtained by the auction. We assume that the fees paid by the ITS subsystem and the DT server are $\sigma \cdot \lambda$ and $(1-\sigma) \cdot \lambda$ respectively. Thus, the profit of the DT broker is as follows:

$$U_b = \sum_{i \in \mathbb{I}} \sum_{j \in \mathbb{J}} \sum_{k \in \mathbb{K}} (bp_i^k - ap_j^k) \cdot \delta_{i,j}^k + N \cdot \lambda \tag{12}$$

Algorithm 2 Double-Auction Algorithm of DTaaS Scheme

Input: The set of ITS buyers, DT sellers and brokers, the demand and cost of buyers and sellers.

Output: The profit.

```
Initialize the ITS buyers 𝕀, DT sellers 𝕁 and brokers 𝕂
  for all i ∈ 𝕀 and j ∈ 𝕁 do
    Calculate cost and utility by Eq.(7) and Eq.(10)
    Check condition C3 and C4
    if min{ap_j} ⩽ max{bp_i} then
      i' = argmax{bp_i} and j' = argmin{ap_j}
      The broker decide a p_{i,j} ∈ [a_{j'}, b_{i'}]
      δ^k_{i,j} = 1
      N = N + 1
    else
      Price adjustment of the sellers and buyers
    end if
    Brokerprofit+ = (bp*_i − ap*_j) · δ^k_{i,j} + λ
  end for
Transactions are packaged into blocks to be verified
```

To satisfy all requests of the auction, we assume that at least one ITS subsystem offers a bidding price bp_i that is higher than the minimum asking price ap_j of DT server. So we have

$$\exists i \in \mathbb{I}, j \in \mathbb{J} \quad min\{ap_j\} \leqslant max\{bp_i\} \tag{13}$$

Therefore, the profit optimization of the double auction in the proposed DTaaS scheme is given as follows:

$$\max: \; U_b = \sum_{i \in \mathbb{I}} \sum_{j \in \mathbb{J}} \sum_{k \in \mathbb{K}} (bp_i^k - ap_j^k) \cdot \delta_{i,j}^k + N \cdot \lambda \tag{14}$$

$$\max: \; U_{ITS} = \sum_{i \in \mathbb{I}} \sum_{k \in \mathbb{K}} G_{ITS,i} - C_{ITS,i} \quad i \in \mathbb{I}, j \in \mathbb{J} \tag{15}$$

$$\max: \; \delta_{total} = \sum_{i \in \mathbb{I}} \sum_{j \in \mathbb{J}} \sum_{k \in \mathbb{K}} \delta_{i,j} \quad i \in \mathbb{I}, j \in \mathbb{J}, k \in \mathbb{K} \tag{16}$$

$$s.t. \begin{cases} C_1: \sum_{i \in \mathbb{I}} \sum_{k \in \mathbb{K}} G_{ITS,i} - C_{ITS,i} - \sigma \cdot N \cdot \lambda \geqslant 0 \\ C_2: \sum_{j \in \mathbb{J}} \sum_{k \in \mathbb{K}} G_{DT,j} - C_{md,j} - C_{cm,j} \\ \qquad\qquad -C_{cp,j} - (1-\sigma) \cdot N \cdot \lambda \geqslant 0 \\ C_3: G_{ITS,i} \geqslant p_i^k \cdot T_{i,j} \geqslant bp_i^k \cdot T_{i,j} \\ C_4: ap_j^k \cdot T_{i,j} \geqslant p_j^k \cdot T_{i,j} \geqslant C_{md,j} + C_{cm,j} + C_{cp,j} \\ C_5: \delta_{i,j}^k \in \{0, 1\} \qquad \forall i \in \mathbb{I}, j \in \mathbb{J}, k \in \mathbb{K} \end{cases} \tag{17}$$

In the above optimization problem, we hope to protect the best interests of brokers, the maximum utility of the ITS, and promote as far as possible all ITS subsystems to reach transactions with DT service providers. In the above equations, Eq.(14) and Eq.(15) respectively represent the utility of DT service providers and ITS subsystems. The optimization goal of Eq.(16) is to promote as many transactions as possible. The protection of the benefits of brokers is actually the maintenance of the long-term resource trading platform for both DT and ITS. We also believe that in specific ITS of a smart city, the DT servers need to sell their own services as much as possible, and the ITS subsystems hope to obtain higher resource benefits. In the conditions of the optimization

Algorithm 3 Price Adjustment Algorithm of the DTaaS Double-Auction

Input: The bidding price bp_i and asking price ap_j of ITS subsystem i and DT service provider j

Output: The adjusted bidding price bp_i^* asking price ap_j^* of ITS subsystem i and DT service provider j

```
1: Initialize the price of the node that failed to complete the auction in the last round
2: Get the adjustment sets 𝕀′ and 𝕁′
3:     for all i ∈ 𝕀′ do
4:         if bp_i(n) ⩽ Uit_i then
5:             bp_i′(n + 1) = bp_i(n) · (1 + ω_b^{μ_b} · e^{−ω_b} / μ_b!
6:         if bp_i(n + 1) ⩾ Uit_i − λ then
7:             bp_i(n + 1) = Uit_i − λ
8:         end if
9:     end for
10:    for all j ∈ 𝕁′ do
11:        if ap_j(n) ⩾ Cost_j then
12:            ap_j′(n + 1) = ap_j(n) · (1 + ω_a^{μ_a} · e^{−ω_a} / μ_a!)
13:        if ap_j(n + 1) ⩾ Cost_j + λ then
14:            ap_j(n + 1) = Cost_j + λ
15:        end if
16:    end for
17: The adjusted price enters the next round of auctions
```

problem, C_1 and C_2 respectively limit the utility of both the buyers and sellers of the resource to be non-negative, while C_3 and C_4 are the price relationship restrictions in the auction process. In addition, C_5 shows that $\delta_{i,j}^k$ is a 0-1 variable. Algorithm 2 shows the specific process of DTaaS double auction. Double-auction is a process in which many sellers face many buyers. Among them, there is competition between ITS buyers and DT sellers. With Algorithm 2, we can conduct a double-auction between the DT service provider and the ITS requester. The corresponding price adjustment will be introduced in detail in the next section.

B. Price Adjustment Algorithm

In the process of double-auction, a suitable hammer price is not always easy to reach, and it requires continuous adjustment of the price by both parties. The buyer will gradually increase its bidding price, and the seller will lower its asking price to meet the conditions described in Eq.(13) and complete the transaction. Since the double auction issue in DTaaS involves the interests of multiple parties, we propose a price adjustment algorithm to ensure the benefits of ITS subsystems, DT servers and brokers. If the bidding price of ITS buyer is higher than the sum of its estimated service price and broker service fee, the transaction between the two parties will be terminated and the two parties cannot reach a cooperative relationship. If the asking price of the DT service provider is higher than the difference between its cost and the auction charge of the broker, the auction will also be closed. To achieve efficient price matching between buyers and sellers, we propose the

Algorithm 4 Optimal Buyer and Seller Matching Algorithm for DTaaS Scheme

Input: Buyers $\mathbb{I}$, sellers $\mathbb{J}$, suppose that $|\mathbb{I}| \leqslant |\mathbb{J}|$, pre-auction final results ap_{ij} and bp_{ij}, weight adjustment parameters $\Delta_{buyer}/\Delta_{seller}$.

Output: Optimal buying and selling matching strategy.

```
1: Construct buyer node 𝕀 and seller node 𝕁 into a bipartite graph G(E, V)
2:   for all edge e_ij  i ∈ 𝕀 and j ∈ 𝕁
3:     if i and j reach a pre-auction
4:       The value of e_ij is the profit obtained by the broker
5:       e_ij = ap_ij − bp_ij.
6:     else
7:     e_ij = 0
8:   end for
9:   for all vertex υ_i and υ_j  i ∈ 𝕀 and j ∈ 𝕁
10:    υi = max{e_i1, e_i2, ..., e_imaxj} and υj = 0
11:  end for
12:  for current node υ_i
13:    if υj unmatched
14:      eij = argmax{υi}
15:    if υj matched
16:      υi− = Δ_buyer
17:      υj+ = Δ_seller
18:    repeat line 12-17
19:    until all buyer i find DT servers
20:  end for
```

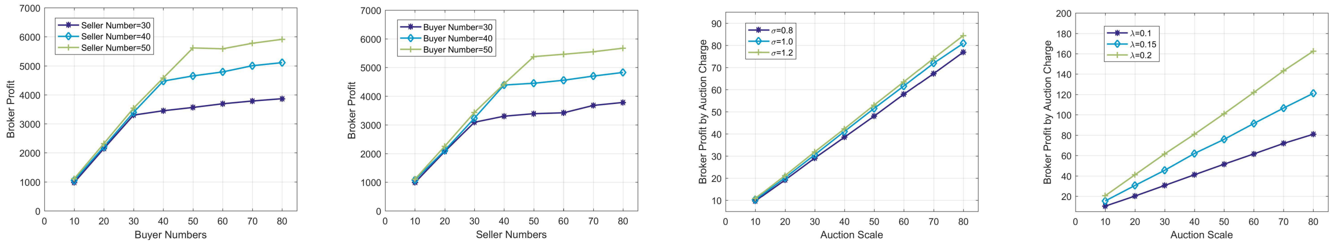
following efficient price adjustment formula.

$$
\begin{cases}
bp_i{}'(n+1) = bp_i(n) \cdot (1 + \dfrac{\omega_b^{\mu_b} \cdot e^{-\omega_b}}{\mu_b!}) & \text{(18a)} \\
ap_j{}'(n+1) = ap_j(n) \cdot (1 + \dfrac{\omega_a^{\mu_a} \cdot e^{-\omega_a}}{\mu_a!}) & \text{(18b)}
\end{cases}
$$

In the above Eq.(14), $f(\omega, \mu) = \omega^{\mu} \cdot e^{-\omega}/\mu!$ is a Poisson distribution. The characteristics of these two parameters of the Poisson distribution will help both parties to determine the mean and variance of each price adjustment. By setting ω and μ, both buyers and sellers can set appropriate price adjustment strategies. The specific adjustment algorithm of bidding and asking price is as follows. In Algorithm 3, we adjust the prices of buyers and sellers in consideration of service fees. Due to the characteristics of the Poisson distribution, buyers and sellers can flexibly set their price adjustment expectations and variance. Meanwhile, the algorithm will dynamically determine the accumulated auction cost and the profits of both buyers and sellers, and will not execute transactions that make any party lose.

C. Optimal Matching Algorithm of the DTaaS Scheme

In this section, we propose an algorithm that can search for the optimal solution for the aforementioned optimization problem. In this algorithm, the auction process is traversed first between buyers and sellers. Therefore, we can get the broker income after each auction and use this as the weight of the auction. Then our goal has become how to match buyers and



(a) The impact of buyers (b) The impact of sellers (c) The impact of different price strategies (d) The impact of auction charge

Fig. 3. Comparison of DT broker profit under different trading conditions.

sellers to obtain the maximum sum of the weights. Algorithm 4 shows how to calculate the maximum weight and obtain the corresponding matching strategy. The algorithm constructs a bipartite graph for buyers and sellers, and regards the best match between buyers and sellers as solving the combinatorial optimization problem. It can continuously iterate the results of the current best matching to get the final best matching strategy. The algorithm shows how to divide buyers and sellers into bipartite graphs and find the optimal matching process of the graphs.

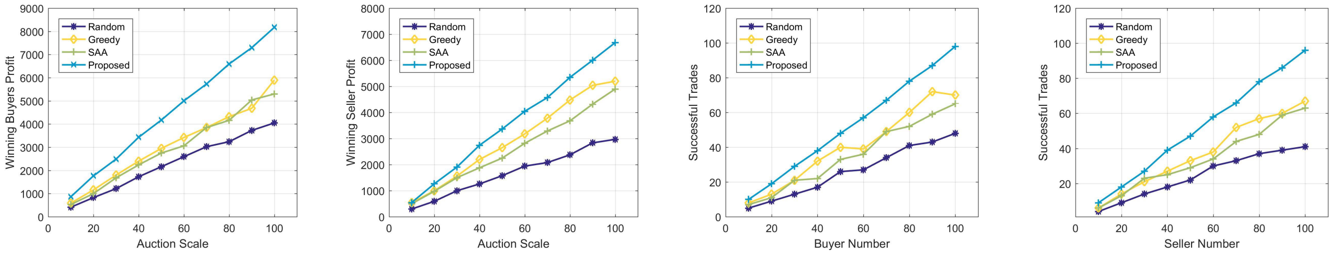
V. Experiments and Analysis

In this section, we carried out detailed simulations and experiments to show the effectiveness of the proposed algorithms and DTaaS scheme. We compare the results of a series of experiments to show the efficiency of the proposed blockchain-enabled DTaaS scheme. The corresponding internal reasons are explained in detail. Specific comparison indicators include the profit of auction participants, the number of successful transactions, the comparison of various resources under different consensus mechanisms, and the performance of different algorithms. Our scheme and algorithms are simulated on a server with Intel i7 6700 CPU and 16G RAM. The main content of the simulation and experiment in this section includes 1) verification of the effectiveness of the double auction scheme designed in this paper, 2) parameter sensitivity analysis of brokers to buyers and sellers, 3) performance comparison between the matching algorithm designed in this paper and common algorithms, and 4) comparison between the proposed DT-DPoS consensus and the traditional consensus mechanism

For the rationality of experimental setup, we assume that there are some ITS subsystems in smart cities that require DT services, and a considerable number of edge computing servers can be used to provide DT services for these subsystems. In the experiment, both parties are in a state of roughly matching resources and scale, and are willing to reach a transaction through the auction of DT brokers. For the DT servers in the DT service market, we have set up dedicated token accounts for participating in the consensus mechanism. Each individual of the buyers and sellers will ask or bid according to their own strategies, and brokers will charge a small amount of auction fees. The setting of communication resources and computing resources is based on the existing mainstream edge computing servers [25], [26].

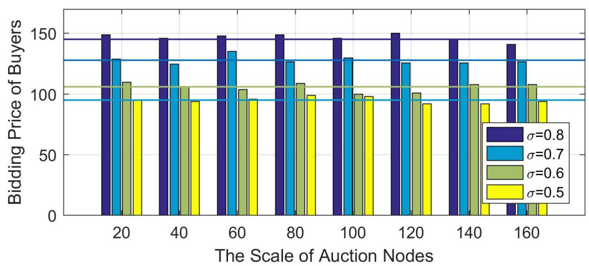
First, we compare the profits of brokers in different situations to analyze the main influencing factors. In Fig. 3(a) and Fig. 3(b), we compare the broker profit under different numbers of buyers and sellers. We can clearly see that the profit of the broker will increase as the number of buyers/sellers increases. With the same number of buyers, a larger number of sellers can provide the broker with more matching options to obtain higher revenue. The same conclusion can be reached when the number of sellers remains unchanged. We observe that the curves in Fig. 3(a) and Fig. 3(b) have experienced a process of first growing faster and then slowing down. This is due to the small number of sellers/buyers in the first half of the curve. Therefore, newly concluded transactions can be quickly reflected in the profits of brokers. When the number of transaction matches reaches the saturation level, only higher-quality transactions and efficient auctions can increase the profits of brokers. Fig. 3(c) compares the influence of different price adjustment strategies of nodes on broker profit. We increased the auction scale when the number of buyers and sellers were equal, and the profit of the broker was improved. The larger the ω, the higher the broker's profit. This is because the larger the price adjustment range, the larger the difference between the bidding price and the asking price. But this gap is not obvious. This is because a larger price adjustment will bring about a reduction in auction fees, as shown in Fig. 3(d). The broker profit under different auction fees λ is compared in Fig. 3(d). We can see that higher fees can significantly increase profits of the broker. Therefore, for buyers and sellers, out of consideration for their interests, the fee λ will affect their price adjustment strategies.

Second, we simulated the optimal strategy search algorithm proposed in this paper and compared it with some traditional methods for solving combinatorial optimization problems. Our comparison benchmark algorithm includes the following. 1) Random node matching: Randomly matching nodes that can establish potential transactions; 2) Greedy algorithm: Constantly prioritize the strategy that can bring the maximum profit to the broker at the current moment; and 3) Simulated Annealing Algorithm (SAA): a classic heuristic algorithm can realize the continuous optimization of the strategy. The profit of winning buyers/sellers and the number of successful transactions we compared can well reflect the pros and cons of the transaction matching algorithm. When a better algorithm is adopted, the number of transactions reached will inevitably be greater, and it will also increase the profits of both buyers and sellers. In Fig. 4(a) and Fig. 4(b), we compare the changes in the profits of buyers and sellers with the number of auction nodes. We can see that the profits of buyers and sellers increase with the increase in the number of nodes. Meanwhile, the algorithm proposed in this paper is significantly better than

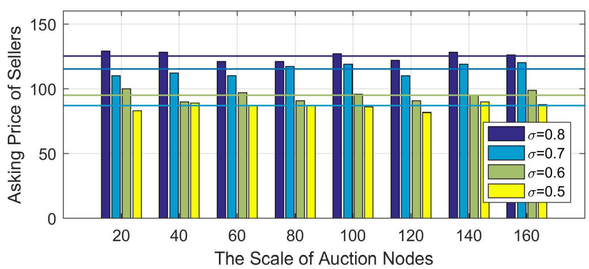


(a) Average winning buyer profit (b) Average winning seller profit (c) Successful trades with buyer scale (d) Successful trades with seller scale

Fig. 4. The performance of the proposed algorithm evaluation under different conditions.

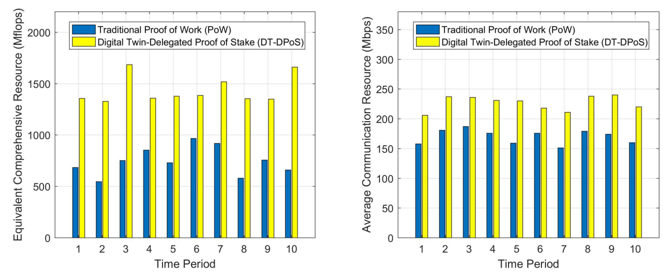


(a) Average bidding price of buyers

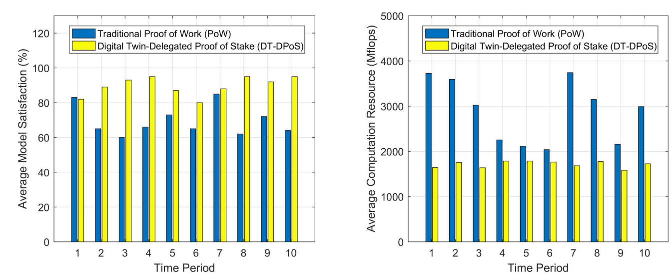


(b) Average asking price of sellers

Fig. 5. The effect of broker charge ratio on the price of buyers and sellers.



(a) Comprehensive DT resources (b) Communication resources



(c) DT model satisfaction (d) Computation resources

Fig. 6. Block validator resources of the proposed DT-DPoS.

the comparison algorithms. Fig. 4(c) and Fig. 4(d) show the number of successful trades as the number of buyers and sellers increase. Similarly, the proposed algorithm can stably obtain a better matching strategy. Although the traditional greedy algorithm and heuristic algorithm can also obtain better results than random matching, the results obtained are not stable. From the experimental results, the random method has greater uncertainty, and it is very likely that there are not enough effective transactions between buyers and sellers. However, heuristic algorithms and greedy algorithms tend to overlook better overall matching methods due to their own limitations. The algorithm proposed in this paper is generally better than the benchmark algorithms, but the running time of the algorithm is relatively long.

Third, to consider the influence of brokers on buyers and sellers, we compare the effect of different ratios of auction fees between buyers and sellers on bidding/asking prices of them, shown in Fig. 5. Since the buyers and sellers of each round of transactions need to pay a certain fee to the broker that organizes the auction, the proportion of the costs borne by both parties will affect the bidding strategy of both parties, and thus the final asking price and bidding price. We can see from the results of the experiment that when the auction fee for a party is reduced, the final price will be more favorable to it. When the auction fee is high, the cost consideration of the node will increase the price adjustment range, to achieve the transaction in a smaller number of auction rounds. Fig. 5 shows the changes between the asking price of sellers and the bidding price of the buyers under different auction fee ratios. The horizontal line represents the average value of the corresponding data. For sellers, a smaller proportion of auction fees will increase the asking price. For the buyer, when its auction cost is low, the resources can be auctioned at a lower price. Such experimental results show that when the auction costs to be borne by one party are reduced, the final price will be more favourable to it. When the auction fee is high, the node will increase the price adjustment range due to cost considerations to achieve the transaction in a smaller number of auction rounds. Since the buyers and sellers of each round of transactions need to pay a certain fee to the broker that organizes the auction, the proportion of the costs borne by both parties will affect the bidding strategy of both parties, and thus the final asking price and bidding price.

Besides, we also simulate the DT-DPoS proposed in this paper and compare its performance in terms of various resources with the traditional Proof-of-Work (PoW) consensus. We mainly consider whether the proposed consensus mechanism can promote the on-demand matching between DT and ITS. Fig. 6(a) shows the actual comprehensive DT resources provided by the nodes selected by the consensus mechanism. Since the main measurement indicators of DT-DPoS proposed in this paper are the benefits brought by DT services and the specific user satisfaction, the elected nodes do not need to pay actual computing resources to obtain the accounting rights like traditional PoW. Therefore, in Fig. 6(b) and Fig. 6(c), the nodes elected by DT-DPoS also have certain advantages over traditional PoW. But in Fig. 6(d), we compared the computing resources of the nodes selected by the two consensus mechanisms. The PoW consensus mechanism has obvious advantages in terms of computing resources. But on the whole, DT-DPoS is a more suitable consensus mechanism for the DT system. The selected block verifier has better DT resources, and the corresponding DT server can also profit without consuming too many additional resources.

VI. Conclusion And Future Work

In this paper, we mainly focused on how to respond to dynamic DT requests for ITS subsystems in an on-demand method to fully realize the advantages of DT. As the requester of DT service, ITS subsystems will conduct corresponding service transactions with DT service providers through optimal matching. We modeled the matching process of buyers and sellers through the double auction process, and designed algorithms to obtain the optimal matching results. The successful DT trades are recorded and protected by the permissioned blockchain and an improved DT-DPoS consensus mechanism is proposed for ITS. The simulations showed the superiority of the DTaaS scheme, the DT-DPoS consensus mechanism and specific algorithms proposed in this paper.

For future work, we plan to further consider the fine-grained service details of Internet of Vehicles (IoV). Fine-grained service details will make the problem studied in this paper more complicated, and further problem modeling is required. In addition, how to achieve high-quality digital twin services with a smaller energy cost is also a question worth considering.

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