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Construction of Large-Scale Low-Cost Delivery Infrastructure Using Vehicular Networks

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ABSTRACT Vehicular ad-hoc networks, as one of the major components of Internet of Things in smart cities, have enormous idle transportation capability due to the huge number of vehicles. This paper argues that it is feasible to employ a large number of mobile vehicles in smart city to construct a large-scale low-cost delivery infrastructure using opportunistic routing to improve the city's social welfare. To this end, a low-cost good delivery system (LCGDS) with opportunistic relay is proposed to meet the requirements of good delivery. In LCGDS, an enormous number of mobile vehicles constitute a stable, highly reliable, low-cost infrastructure with large transportation capabilities, called the mobile Internet of mission-critical things (M-IoMCT). The main contributions of the LCGDS are: 1) demonstrate the technological feasibility of M-IoMCT for delivering goods through mobile vehicles in a "ride-sharing" fashion with low costs and 2) in order to increase the reliability of goods transmission, the LCGDS proposes mobile vehicle selection algorithm which effectively selects a vehicle with higher probability of arriving at the destination. Both theoretical and experimental simulation results show that the performance of the LCGDS outperforms those of other solutions. Compared with other solutions, our results demonstrate that the costs in the LCGDS are only about 24% of the costs in the origin goods transmission scheme.

INDEX TERMS Mobile vehicular networks, mobile Internet of mission-critical things, low cost, reliability.

I. INTRODUCTION

Vehicular ad hoc networks, as one of the major components of Internet of Things, can facilitate many new promising applications [1]–[5]. Vehicular ad hoc networks [5]–[7] consist of a large number of vehicles. They can be called the Mobile Internet of Things (MIoT), since vehicles are embedded with a variety of smart sensors, and they constantly move in the city [8]–[13]. On one hand, vehicles can monitor the key structures through smart sensors [14]–[17]. On the other hand, vehicles are capable of transporting goods and moving, and thus they can perform search and rescue works [1], [2], [6], [18]. Meanwhile, since the number of vehicles in the city is extremely large [2], [6], [18], they can cooperate with each other to form a huge overlay network to achieve a full range of monitoring [19]–[24] for critical infrastructure or missions. Therefore, they are called M-IoMCT.

Due to the important role of the vehicular ad hoc networks, they have attracted numerous research efforts focused on sensing of the environment, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [1], [2], [6], [7], [18], data gathering [25]–[27], security and privacy protection [28]–[32], etc. Vehicular ad hoc networks are often used as a delay tolerant network (DTN) [23], [27], [33] in which each vehicle is considered to be a peer carrying data and can communicate with each other when two peers meet. As one component of the M-IoMCTs, vehicular ad hoc networks play a significant role in acting as data communication mules. Furthermore, they can also serve as goods delivery mules with the development of the logistics industry and the large transportation capability of vehicular networks [1], [6], [7], [18]. Additionally, if we can make full use of these idle transportation capacities, we can meet the increasing demand for logistics and reduce the number of vehicles needed, thus relieving the traffic congestion and improving the city's social welfare. This paper argues that it is feasible to employ a large number of mobile vehicles in smart city to construct a large-scale, low-cost delivery infrastructure using opportunistic routing to improve the city's social welfare. To this end, a Low-Cost Good Deliver System (LCGDS) with the opportunistic relay is proposed to meet the requirements of good delivery in a cost efficient manner. In the LCGDS, an enormous number of mobile vehicles constitute a stable, highly reliable, low-cost infrastructure with large transportation capabilities, namely the M-IoMCT, and can effectively improve the quality of life in smart cities. The contributions of this paper are as follows.

(1) A high-reliability and low-cost architecture called the M-IoMCT is proposed. Each component and the functionality of the M-IoMCT architecture are presented in details. The effectiveness and feasibility of the proposed architecture are also demonstrated.

(2) LCGDS with opportunistic relay is also proposed to meet the requirements of goods delivery with low cost and high reliability.

(3) Through extensive theoretical analysis and simulations, we demonstrate the feasibility of the M-IoMCT architecture. Moreover, the proposed LCGDS can achieve great transportation volume and guarantee high reliability.

The rest of this paper is organized as follows: In Section II, the related works are reviewed. The system model and problem statement are presented in Section III. In Section IV, a novel M-IoMCT architecture is presented. The performance analysis of the LCGDS is provided in Section V. Section VI gives the experimental results and makes comparisons. We conclude in section VII.

II. RELATED WORKS

There have been numerous research works on mobile vehicular networks. The research works related to this paper are categorized as follows:

(1) Communication is one of the earliest research interests in vehicular networks. It mainly involves vehicular sensing [34], [35], communications [36], [37], integrated vehicular networks [38], program code dissemination [39], data collection [40]–[42] as well as computing and control. Most of the research works mainly focus on the improvement of quality in the communication between the components of the vehicular network. For instance, one component is how to share music and other entertainment media between vehicles [6], [7].

(2) Each vehicle in the mobile vehicular network can be considered a peer, and many of these vehicles constitute the mobile peer-to-peer network. Some researches have taken the mobile vehicular network as an overlay for the peer-to-peer network [11] and mainly studied the data transmission and relay between vehicles. Their research is somewhat similar to our work in this paper. However, to the best of our knowledge, previous research works only investigated communication and relay for data dissemination. There is no research on how to generalize the peer-to-peer network for data communication to the overlay network for similar physical object delivery, and none of the corresponding architecture is proposed.

(3) Bonola *et al.* [43] proposed a data collection strategy that utilizes vehicles as data mules. They presented the sensed data from many sensor devices that are too difficult or costly to be connected to wired networks in the smart cities but can be efficiently and economically collected via taxi fleets as data carriers. For example, intelligent garbage cans with embedded smart sensors can monitor their trash levels, and street lights equipped with intelligent sensors can sense the status of the street lights. All of these sensing devices are characterized by their deployment in remote areas, frequent changes, and the cost of connecting these devices to the wired or wireless networks is prohibitive, and even impossible in some cases, such as urban greening, lawn monitoring, etc. [44]–[46]. Thus, if the sensing devices transmit the data to a vehicle passing by in a short distance, the data can be collected in a cost-effective manner. Based on the work in [43], Tang *et al.* [47] advocated that the vehicles should determine if further data collection is needed when the storage capacities of the vehicles are full due to their limited capacity. Furthermore, Tang *et al.* [47] proposed an SWDCP-SCmules scheme that ensures that the higher-priority data can be transferred to the data center first by defining the priority of the data. Xu *et al.* [48] further stated that the data collected by the data center should cover the entire city. They then proposed a latency and coverage optimized data collection (LCODC) scheme to collect data in smart cities to solve this problem.

(4) The work by Tang *et al.* [49] is most closely related to our work. They proposed using multiple vehicles as the physical relay to collaboratively forward data to the destination. The tasks are completed by selected collaborative trusted vehicles. However, they have not systematically proposed a collaborative architecture. In this paper, we propose a M-IoMCT architecture from the system level. Thus, data transmission in previous works is generalized to both physical objects and data transmission, which can improve the social welfare in the city.

III. THE SYSTEM MODEL AND PROBLEM STATEMENT

A. THE SYSTEM MODEL

In this paper, we mainly consider the transmission of goods that are less sensitive to time and whose weights are not too heavy. Thus, people are glad to carry goods. Therefore, the costs of transferring goods from one mobile vehicle to another mobile vehicle are not considered in this paper. Considering that since the mobile vehicles can obtain some fees when they move around the green city, those mobile vehicles are glad to carry goods.

There are four components. They include (1) the sender of the goods, (2) the goods' collection tanks with intelligent devices, (3) the mobile vehicles with intelligent devices, and (4) the receiver of the goods.

(1) The senders or receivers of the goods are the ones who hold the smartphone. These senders may be walking

on the road or people in a house. Assume that there are m senders of goods in the smart city, which comprises a set $\mathcal{S} = \{S_1, S_2, \ldots, S_m\}$. In this paper, the senders may publish the task for transmitting goods at any time, and they can move at any time. When they want to send goods to a destination, they make an order on the phone that includes the destination for the goods and the costs for the goods' transmission. When mobile vehicles with smart devices are around the customer, they will be aware of their goods' transmission information, and they will pick up the goods according to the transmission rules.

(2) The goods collection tanks are deployed in the smart city for collecting goods. Let $\{K_1, K_2, \ldots K_{\mathcal{M}}\}$ denote a set of $\mathcal{M}$ goods collection tanks in the smart city. The goods collection tanks are equipped with enough intelligent devices that can sense goods information. When the sender of the goods transmits goods to the collection tank, the intelligent devices can sense the information of the goods. When a mobile vehicle is passing the goods collection tank, it can sense whether there are some goods to be transmitted. If there are goods in the collection tank for transportation, the vehicle will piggyback the goods.

(3) Mobile vehicles are the mobile nodes in the smart city (for example, taxies or pedestrians). These nodes that move in the city every day could act as IoT mobile nodes. Cabs cover an extensive area of the city with somewhat random paths (with respect to buses that move only on main streets) and work. Suppose there are n vehicles in the smart city that are expressed as $\mathbb{C} = \{v_1, v_2, \ldots, v_n\}$, and vehicles know their locations through GPS. Mobile vehicles are equipped with transceivers that enable them to opportunistically communicate with nearby mobile vehicles or goods collection tanks.

(4) The receivers of goods are the destination nodes. In this paper, the receiver of goods can also be the sender of goods. Usually, the goods are transported through the mobile vehicle with intelligent devices to the goods collection tank near the destination. Then, the receiver of the goods uses the sensing devices (such as a cell phone) to sense the arrival of the goods and then quickly obtains them.

In the paper, we only considering lighter goods. Thus, citizens are glad to carry goods from one mobile vehicle to another mobile vehicle.

B. PROBLEM STATEMENT

In this paper, the research problems can be summarized into the following three aspects.

(1) Minimization of total costs Φ

d_i is the distance from the source location of good i to the destination. c_i denotes the costs for transmitting good i in one unit distance. In this paper, the goal is to minimize the total costs Φ of transmitting goods. $\mathbb{Z}$ represents the total number of goods in the smart city. The minimization of total costs for transmitting goods can be expressed as follows:

$$\min(\Phi) = \min\Big(\sum\nolimits_{i=0}^{\mathbb{Z}} d_i c_i\Big) \tag{1}$$

TABLE 1. Network parameters.

Parameter	meaning
$D_{i,k}^{ave}$	The average distance of mobile vehicle i to the destination in time slots t
$\mathcal{F}_i$	The distance of current location of mobile vehicle $\mathbb{N}_i$ to destination
c_{total}	The total costs c_{total} paid by sender of goods
L_A	The moving distance for transmitting good A
α	The arrival ratio of goods to their destinations
N_{tot}	The number of goods that is transmitted to destination

(2) Maximization of arrival rate η

The arrival rate η refers to the ratio of the number of goods that arrive at their destinations to the total number of goods in the smart city. ϖ denotes the number of goods that arrive at their destinations. The maximization of arrival rate η can be expressed as follows.

$$\max(\eta) = \max(\varpi/\mathbb{Z}) \tag{2}$$

(3) Minimization of transmission time

In the process of transmitting goods, the transmission time should be as small as possible. t_b denotes the start time for transmitting goods, and t_e represents the end time for transmitting good. The minimization of transmission time τ is regarded as follows.

$$\min(\tau) = \min(t_e - t_b) \tag{3}$$

Ultimately, we should guarantee the minimization of total costs Φ, the maximization of arrival rate η, and the minimization of transmission time τ. In sum, the optimization goals in this paper are as follows:

$$\begin{cases} \min(\Phi) = \min\Big(\sum\nolimits_{i=0}^{\mathbb{Z}} d_i c_i\Big) \\ \max(\eta) = \max(\varpi/\mathbb{Z}) \\ \min(\tau) = \min(t_e - t_b) \end{cases} \tag{4}$$

There are some parameters in this paper, and the table 1 is given to show the meaning of parameters.

IV. THE M-IOMCT ARCHITECTURE DESIGN

A. MOTIVATION

(1) Large goods transmission costs

There are few previous strategic studies that address the low-cost transmission of goods to the destination. In the traditional scheme, when citizens want to transmit goods to a destination, they usually use couriers to transmit the goods. However, this brings high costs. In this paper, we employ the mobile vehicles in the smart city as transmission tools. When people need to send goods to a destination, the mobile vehicle in the mobile vehicle network can be used to transmit the goods to a destination rather than using a dedicated courier to transmit the goods. The advantage is that the user can spend

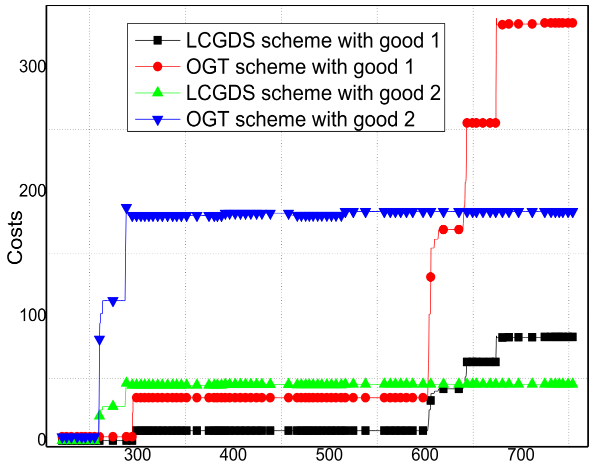

FIGURE 1. The cost in different schemes.

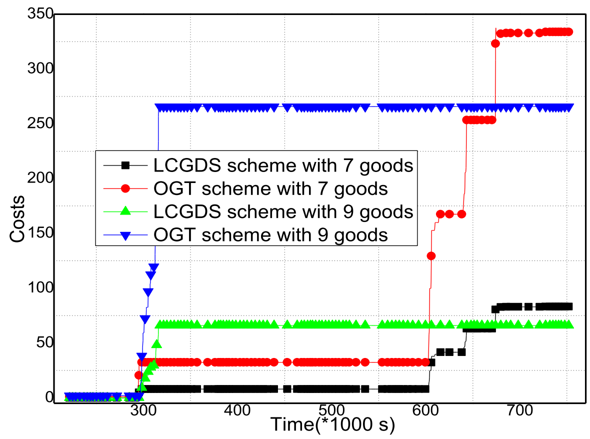

FIGURE 2. The cost of transmitting different number of goods.

less money to deliver the goods to the destination. Since these mobile vehicles are not intended to transmit the goods, but piggyback the goods when they pass the goods collection tank and sense that there are goods in the collection tank to be delivered. In this way, it does not cost too much for users to transmit the goods to the destination. For the mobile vehicles, this is extra income. As seen from Figs. 1 and 2, this scheme proposed in our paper can significantly reduce the costs of goods transmission.

(2) Previous schemes simply collect and transmit data, without any support for physical object collection and transmission. In this paper, transmission is mainly targeted for goods. In the process of data collection in previous schemes, when the mobile vehicle passes the area with the information to be transmitted, the mobile vehicle will collect the information. When the vehicle passes the data center, it will transmit the data to the data center. However, due to the motion randomness of the mobile vehicle, the mobile vehicle taking the received data may not pass the destination (data center), thus the data will not be sent to the data center, leading to the information loss and low arrival rate. By contrast, the proposed scheme in our paper can improve the arrival rate of the goods at lower costs. When the vehicle passes the goods collection tank and there are goods to be transported, the vehicle will piggyback the goods. Thus, our scheme can enhance the arrival rate of goods.

B. OVERVIEW

Most previous schemes utilized the mobile vehicles in the mobile vehicular network to collect information about the intelligent devices in the smart city and then transmit the information to the destination. However, this only transmits data information. This paper, from a new perspective, proposes a novel scheme to transport goods to destinations with lower costs and high probability.

In the mobile vehicular network, the topology of the smart city is given in Fig. 4. The senders of goods are citizens holding smart mobile phones in the smart city. They can be moving pedestrians or people sitting in an office. The goods collection tank is used to collect the goods. The intelligent devices are self-powered devices embedded in the goods collection tank and mobile vehicles in the smart city to enhance their functionality and productivity. The receiver of the goods receives the goods in the smart city. In the mobile vehicular network, the receiver of goods is regarded as the destination of goods. The process of goods transmission is described as follows.

(1) In the mobile vehicular network, if some citizens holding smart mobile phones want to send goods to another citizen, the citizens will send the goods to the goods collection tank near the sender of goods. Intelligent devices in the goods collection tank sense the information about the goods. Then, the information is stored in the memory of the intelligent devices in the goods collection tank. The mobile vehicle (including taxis, private vehicles, and buses) in the smart city move at any time, and they are equipped with transceivers that enable them to opportunistically communicate with nearby nodes (including intelligent devices and mobile vehicle). When a mobile vehicle passes a nearby goods collection tank, smart devices detect the existence of goods and incidentally pick them up. The stored information in the intelligent device will be transmitted to the intelligent vehicle in the mobile vehicle.

When a mobile vehicle with goods passes the goods collection tank near the destination, the mobile vehicle will place the goods into the collection tank. Then, the information about the goods is also transmitted to the intelligent devices in the goods collection tank. When the information of the goods is stored in the goods collection tank of destination, the smart mobile phone for the receiver of goods (citizens) will sense the information about the good's arrival.

As shown in Fig. 3, when the mobile vehicle passes the nearby goods collection tank, the intelligent devices in the mobile vehicle will be switched into sensing states since they will sense the message about goods in the goods collection tank. If goods S in the goods collection tank need to be transmitted, the intelligent devices in mobile vehicle A will be switched into transmitting states. The goods in the goods

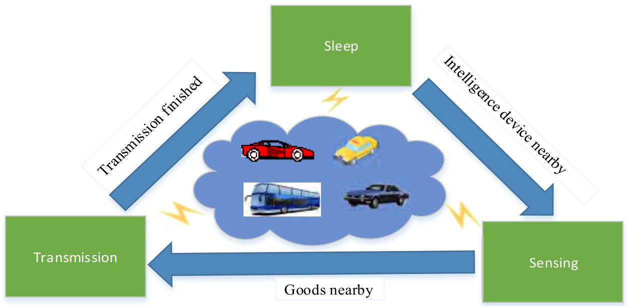

FIGURE 3. The state diagram of intelligent devices.

FIGURE 4. A concrete example of LCGDS scheme.

collection tank will be picked up by mobile vehicle. If mobile vehicle B moves toward mobile vehicle A and if the distance from a point moved by node A to the destination is longer than the distance from a point moved by node B to destination, mobile vehicle B will carry goods S. Otherwise, goods S will continue to be transported to the collection tank closest to the destination until the goods arrive at the destination.

The intelligent devices have two main functionalities: detecting the status of the infrastructures and communicating via short-range wireless networks. To save the energy of moving nodes, intelligent devices in a smart city have three states, as shown in Fig. 3: the sensing state, the transmission sate, and the sleep state. If no mobile vehicle passes the intelligent devices, the intelligent devices are in the sleep state. When the mobile vehicle passes the nearby goods collection tank, the intelligent devices in the mobile vehicle will be switched into sensing states since they will sense the message about goods in the goods collection tank. If goods S in the goods collection tank need to be transmitted, the intelligent devices in mobile vehicle will be switched into transmitting states.

C. GOODS TO GOODS COLLECTION TANK

When citizens send goods to destinations, the citizens need to send goods to goods collection tank. For example, when citizens want to send clothes, books and other goods, they will cost more money and time for users to using courier delivery or rent a car to transmit goods with relatively low time demand. In this paper, we use mobile vehicles to transmit goods to save costs.

When citizens send goods to destinations in the Fig. 4, smart mobile phones of citizens will sense message of intelligent devices, which includes the location and weight. Intelligent devices access their location via GPS. If intelligent devices are in the transmission range of citizens, citizens holding smart mobile phone will send goods to goods collection tanks, and the information about goods is also recorded in the intelligence devices of goods collection tanks. In the process of goods transmission, goods are transmitted through mobile vehicles. However, due to the motion randomness of mobile vehicles, goods may be transmitted to a point far from their destination. To transport goods to their destinations in a given period of time, the maximal transmission time allowed of goods transmission should be stored in the memory of intelligence devices when citizens place goods into goods collection tanks. The cost for goods transmission in a unit distance to mobile vehicle is usually lower than the price for transmitting goods directly.

When citizens place goods into goods collection tank, they use smart mobile phones to record the information about the movement trajectory and the running time, so that they can monitor the moving position of goods in real time. If the running time of goods reaches the maximum value, then citizens can cancel this transaction and place a new order with a higher price to transport the goods to destination.

The citizens can transmit goods to mobile vehicle directly, if the mobile vehicle pass by the citizens and carry goods to a location near to the destination. And we have added the detailed discussion in the paper, please seen the revised paper.

D. GOODS COLLECTION TANK TO VEHICLE

Mobile vehicles in smart city move at any time, and they are equipped with transceivers which enable them to opportunistically communicate with another nodes. It can be seen from Fig. 1 that the sensing device in mobile vehicles can sense the surrounding information when they are in the sensing state. When mobile vehicles transmit goods, we consider that mobile vehicles can access to its location via GPS, and each mobile vehicle trustable when carrying goods. Once goods are carried, mobile vehicles transport goods to goods collection tank near their destinations or even directly to their destinations. We also consider using the movement trajectory of mobile vehicles in the past period of time to predict the future trajectory and weight of mobile vehicles.

When mobile vehicles move to goods collection tank in the transmission range, they will detect the message whether goods are in goods collection tanks. If yes, the weight of mobile vehicles are calculated by intelligent devices. If the weight is less than 1, it represents that the distance from mobile vehicles to their destination is shorter. If mobile vehicles accept costs given by citizens, mobile vehicles will piggyback goods, and the message about goods will be transmitted to mobile vehicles.

After mobile vehicle carry goods from goods collection tanks, goods information stored in intelligent devices will be cleared. The pseudo-code of goods transmission between vehicle (intelligent devices) and mobile vehicle is presented as algorithm 1.

Algorithm 1 Goods Collection Tank to Mobile Vehicle Transmission

1: **When** mobile vehicles move to the area near goods collection tanks
2: **If** mobile vehicles pass goods collection tank **then**
3: switch into dumping state;
4: **If** there are goods in goods collection tank;
5: transmitting goods to mobile vehicles
6: **End**
7: **If** finishing transmitting
8: clear internal memory;
9: **Else**
10: attempt to transmit at next time slot;
11: go to step 5;
12: **End**
13: switch into collecting state;
14: **End**
15: **End**

E. MOBILE VEHICLE TO MOBILE VEHICLE

The scheme proposed in this paper considers the reliable delivery of goods to the destination. The paper employs the transmission from goods collection tanks to mobile vehicles and the transmission from one mobile vehicle to another mobile vehicle.

In this paper, mobile vehicles obtain the moving location using GPS. Each mobile vehicle stores the location information and the arrived destination. Assume $P_{i,k}$ denotes the weight of transmission for good k in mobile vehicle i. In this paper, using the distance of the intelligent device to the destination during past t time slots to predict the weight of the intelligent device for mobile vehicle i. The weight is used to measure the probability whether intelligent devices reach their destinations.

The movement trajectory of mobile vehicle i in the past t time slots is denoted by $\{\mathbb{Q}_1, \mathbb{Q}_2, \ldots \mathbb{Q}_t\}$. For good k, the distance of mobile vehicle to the destination in time Υ is d_Υ. Thus, the distance in the last t time slots can be calculated as follows:

$$\mathrm{D}_i^k \triangleq \left\{d_1^k, d_2^k, \ldots, d_t^k\right\}$$

Then, the average distance of mobile vehicle i to the destination in time slots t can be calculated as follows.

$$D_{i,k}^{ave} = \begin{cases} \sum_{y=1}^{w} d_y^k \times \hbar(y)/t, & t \neq 0 \\ 1, & t = 0 \end{cases} \quad (5)$$

Where $\hbar(y)$ is an attenuation function that can be shown as follows.

$$\hbar(y) = \begin{cases} 1, & y = t \\ \hbar(y-1) = \hbar(y) - 1/t, & 1 \leq y \leq t \end{cases} \quad (6)$$

When the system calculates the distance of intelligent devices, it considers the most recent w time's evaluation results. $\hbar(y)$ ensures that the recent distance evaluation results have a higher weight [6].

Time slots can be denoted as $t \triangleq \{t_0, t_1, t_2, \ldots, t_n\}$. Let $D_{i,k}^{ave}$ denote the average distance of mobile device i in time slot t_j. $P_{i,k}$ is the weight of mobile device i for good k in time slot t, which is calculated as follows:

$$P_{i,k} = D_{i,k}^{ave}/D_{tot} \quad (7)$$

D_{tot} is the distance from source of good k to destination of good k. In mobile vehicular network, intelligent devices' weight information and location information are stored in the memory of intelligent devices. In case of sleep state, intelligent devices will be switched to sensing state when they detect their neighboring device. Besides, intelligent devices use the beacon message to have access to the information of neighboring intelligent devices, including its location and weight.

Algorithm 2 Mobile Vehicle to Mobile Vehicle Transmission (Sender S_i)

1: **While** mobile vehicles move in the smart city
2: switch into sensing state, detect neighboring mobile vehicle υ.
3: find $min(P_\upsilon)$ according to beacon messages;
// P_υ is weight of mobile vehicle υ for all goods in this time.
4: **If** $P_\upsilon < 1$
5: transmit goods and information of goods to mobile vehicle υ;
6: clear information of goods;
7: **Else**
8: continuing moving;
9: **End**
10: **End**

In the LCGDS scheme, if the distance from a point moved by node A to the destination is longer than the distance from location of goods to destination, there is no need to transmit the goods to mobile vehicle A. If mobile vehicle B's weight is smaller than that of mobile vehicle A, mobile vehicle B will pick the goods from mobile vehicle A.

In goods transmission from a mobile vehicle to another mobile vehicle, the pseudo-code of goods transmission by mobile vehicle is given by algorithm 2. The pseudo-code of transmission for receiver mobile vehicle is by algorithm 3.

Algorithm 3 Vehicle to Vehicle Transmission (Receiver S_υ)

```
While true
    If detecting goods from other intelligent devices
        If mobile vehicle S_υ receives good k then
            mobile vehicle S_υ stores good k and
            information of good k.
        End
    End
End
```

F. MOBILE VEHICLE TO GOODS COLLECTION TANK OR DESTINATION

After the mobile vehicle brings the goods, if the distance from the mobile vehicle to the destination is less than the threshold, the mobile vehicle will put goods in the current goods collection tank. The time for transmitting the goods is recorded in the intelligent devices of the goods collection tank. The time and location can be known by the sender of the goods using their mobile phone. When goods are delivered, the sender of the goods can immediately cancel the transaction and pay for the transaction at a predetermined price. The information stored in the intelligent device will be cleared. Then, the surrounding intelligent devices cannot detect goods in this goods collection tank. Although the goods have not been transferred to the destination, they can be transmitted to the place close to the destination through the above method. This is mainly because mobile vehicles are moving throughout the green city at different trajectories according to [43]. Mobile vehicles only piggyback the goods when they pass the goods collection tank and then transport the goods to the goods collection tank. For a mobile vehicle, it obtains the appropriate profits. For citizens, they pay less to transport goods to the destination.

The pseudo-code of transmission between intelligent devices from mobile vehicle $\mathbb{N}_i$ to goods collection tanks or destination is as algorithm 4:

When a mobile vehicle brings goods from the source location, the message about the destination of goods is also stored in the memory of the mobile vehicle. Thus, the mobile vehicle can transport goods to the destination. When mobile vehicles that carries goods move to their destinations, mobile vehicles will be switched into transmitting state, then the goods and information about goods will be transferred into goods collection tanks. According to the recorded destination, the receiver of goods will be informed of the arrival of the goods, and pick up the goods. When goods arrive at the destination, citizens who send the goods can know the goods has been safely delivered to the destination. Thus, citizens can pay costs in accordance with the transmission distance. Finally, this order is completed.

V. PERFORMANCE ANALYSIS

The aim of this paper is to transport goods to their destinations with lower costs, and the performance of proposed scheme is discussed theoretically.

Algorithm 4 Vehicle to Goods Collection Tank or Destination

```
If mobile vehicle ℕ_i that brings goods passes goods
        collection tank then
    Calculate the distance ℱ_i of current location of mobile
            vehicle ℕ_i to destination
    If ℱ_i is smaller than the distance of next
            movement location of mobile vehicle ℕ_i
            to destination then
        mobile vehicle ℕ_i will place goods into goods
        collection tank; the information of goods is
        transmitted to intelligent devices of goods
        collection tanks.
    mobile vehicle ℕ_i clears information of goods;
    Else
        continue moving;
    End
    Else if mobile vehicle ℕ_i that brings goods passes
            by destination then
        mobile vehicle ℕ_i places goods into goods
            collection tank near destination, and the
            message of goods is transmitted to goods
            collection tank;
        the message of goods in the memory of mobile
            vehicle ℕ_i is cleared.
End
```

Theorem 1: In the LCGDS approach, if n goods need to be transmitted to their destinations, the distance of n goods from their destinations are denoted by $\{d_1, d_2, d_3 \ldots d_n\}$. The arrival ratio of goods is α, the costs paid for mobile vehicle in unit distance is c, and the total costs c_{total} paid by sender of goods is as follows.

$$c_{total} = c\alpha(d_1 + d_2 + \cdots d_n) \tag{8}$$

Proof: According to formula 5, if n goods need to be transmitted to their destinations, and if the distance for transmitting one goods from source of goods to destination is d_1. The costs paid for mobile vehicle in unit distance is c, the total costs c_1 paid for transmitting goods is as follows.

$$c_1 = cd_1 \tag{9}$$

Since n goods need to be transmitted to their destinations, the total costs c_{mid} for transmitting n goods are as follows if all goods are transmitted to destinations successfully:

$$c_{mid} = c(d_1 + +d_2 + \cdots d_n) \tag{10}$$

The arrival ratio of goods is α, thus the total costs c_{total} for transmitting goods are as follows.

$$c_{total} = c\alpha(d_1 + d_2 + \cdots d_n) \tag{11}$$

Theorem 2: Assume movement trajectory of mobile vehicle i in the period of time τ is $\{x_1, x_2, \ldots, x_\tau\}$, and each trajectory is stored in the memory of mobile vehicles.

There are N movement trajectories. For mobile vehicle i in the time τ, ζ movement trajectories are near goods collection tank y (within the transmission range). Suppose good A is transmitted from goods collection tank GA to destination S, the moving distance L_A for transmitting good A is as follows.

$$L_A = \sum_i \varphi_i d_i \tag{12}$$

Where i refers to mobile vehicle i that passes the area near goods (whether goods are in goods collection tanks or in mobile vehicles). The average distance calculated according to the past τ period of time is longer than the average distance calculated for all mobile vehicles that pass the area near goods.

Proof: According to the discussion above, when the senders of the goods place goods into goods collection tanks, if a mobile vehicle passes goods collection tank and is able to place the goods into a point closer to the destination, the mobile vehicle will piggyback goods. If another mobile vehicle has a greater probability of transferring the goods to the destination, then the goods are transferred to another mobile vehicle. Otherwise, the goods are placed in good collection tank nearest to the destination.

Assume there are w movement trajectories. For mobile vehicle i in the time τ, ζ movement trajectories are near goods collection tank y that store goods. Thus, the probability that mobile vehicle i passes goods collection tank y or passes mobile vehicle z carrying goods is $\varphi_i = \frac{\zeta}{w}$. Within the period of time τ, the average movement trajectory of mobile vehicle i is $d_i = \frac{x_1+x_2,\ldots+x_\tau}{\tau}$. For mobile vehicle i, the moving distance is $\varphi_i d_i$. In the process of goods transmission, as long as a mobile vehicle passes goods (within transmission range), and its distance from the destination is shorter, the goods can be piggybacked by this mobile vehicle. Thus, the moving distance of goods are $L_A = \sum_i \varphi_i d_i$. ∎

Theorem 3: In the LCGDS approach, if n goods need to be transmitted to their destinations $\{1, 2, 3 \ldots n\}$, the distance for n goods to destinations are $\{d_1, d_2, d_3 \ldots d_n\}$. The arrival ratio of goods to their destinations is α as follows.

$$\alpha = \frac{\sum_{i=1}^{n} h}{n} h = \begin{cases} 1 & if \ (L_i = d_i) \\ 0 & else \end{cases} \tag{13}$$

Proof: The arrival ratio of goods is the ratio of number of goods that is transmitted to destination successfully to the total number of goods in the smart city. According to theorem 2, for goods i, the moving distance for goods i is L_i, and the distance from source location of goods i to destination is d_i. If $L_i = d_i$, it shows that goods i is transmitted to destination, thus the number of goods that is transmitted to destination adds 1. For n goods, the number of goods that is transmitted to destination is as follows.

$$N_{tot} = \sum_{i=1}^{n} h \quad h = \begin{cases} 1 & if \ (L_i = d_i) \\ 0 & else \end{cases} \tag{14}$$

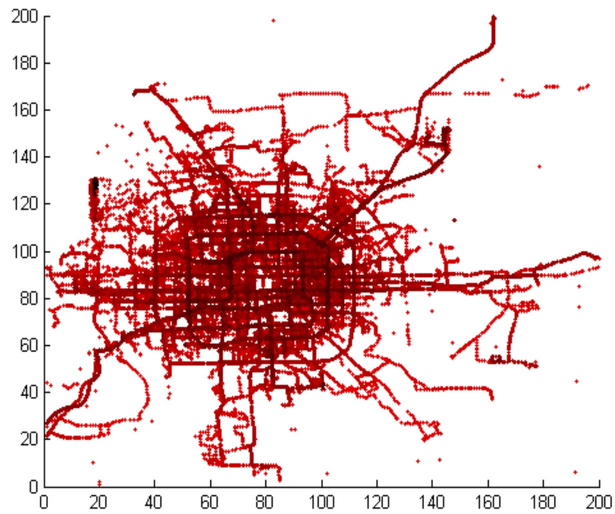

FIGURE 5. Visualization of T-Drive trajectory dataset.

There are n goods in the smart city, thus the arrival rate of goods is as follows.

$$\alpha = \frac{\sum_{i=1}^{n} h}{n} \quad h = \begin{cases} 1 & if \ (L_i = d_i) \\ 0 & else \end{cases} \tag{15}$$

∎

Theorem 4: Considering goods A is transmitted from goods collection tank GA to destination S. Within the period of time τ, the probability that mobile vehicle i passes goods collection tank y that stores goods or mobile vehicle z carrying goods is φ_i. The average movement trajectory of mobile vehicle i is d_i. The distance of goods transmission from source of goods to destination is d_A. After goods is piggybacked by mobile vehicle, the distance from goods to destination is:

$$\varpi_A = d_A - \sum_i \varphi_i d_i \tag{16}$$

Proof: According to theorem 2, the moving distance L_A for transmitting good A is $L_A = \sum_i \varphi_i d_i$. The distance from source location of good i to distance is d_i. After good i is piggybacked by mobile vehicle, the distance from the destination is $\varpi_A = d_A - L_A = d_A - \sum_i \varphi_i d_i$. ∎

VI. EXPERIMENTAL RESULT

In this paper, in order to prove the effectiveness of the scheme, we use the T-Drive trajectory dataset, which is provided by the MSRA [50]. Fig. 5 illustrates the dataset, and the different colors reflect different density distributions of the GPS waypoints.

The T-Drive trajectory dataset contains GPS trajectories of 10357 taxis during the period of Feb. 2 to Feb. 8, 2008, in Beijing. The number of GPS waypoints in this dataset reaches up to 15 million, the total distance of the trajectories reaches up to 9 million kilometers. Citizens paid one Yuan per kilometer to people who driving vehicle. There are

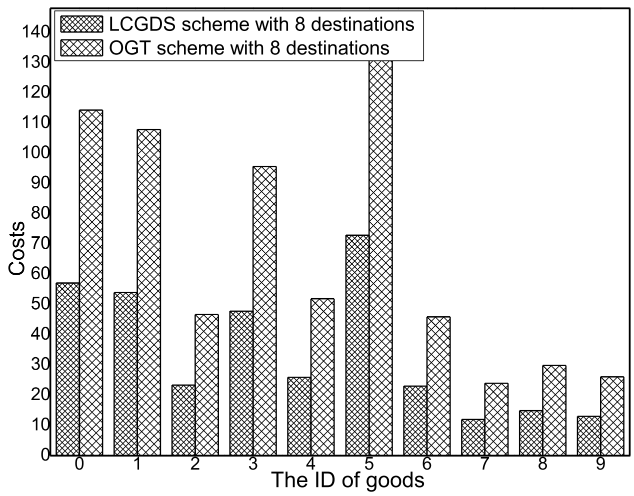

FIGURE 6. The cost of transmitting different goods for a different number of destinations.

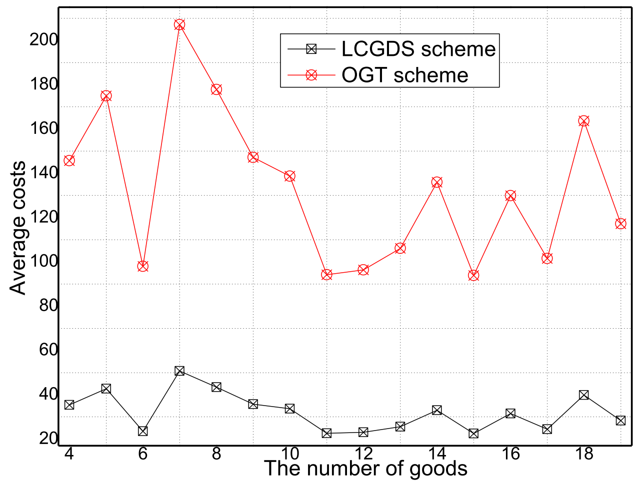

FIGURE 7. The cost of transmitting a different number of goods.

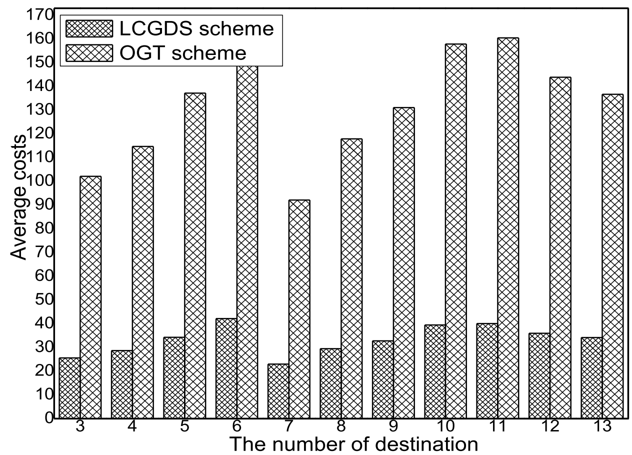

FIGURE 8. The average cost of transmitting different goods for a different number of destinations.

3 destinations in the process of goods transmission. There are 3 goods in the city.

The Origin Goods Transmission (OGT) scheme is used for comparison with our proposed scheme. The main idea of this scheme is that when citizens transmit goods, they use mobile vehicle to transmit the goods to their destinations.

The metrics in this paper include cost, distance of goods to destination, moving distance and arrival rates. The cost is used to show the cost for citizen in proposed scheme and previous scheme. It shows that LCGDS has lower costs. Distance of goods, mobbing distance and arrival ratio of goods are used to show that goods can be transmitted to destination successfully. Those results show that LCGDS scheme has better scheme.

A. COST

The costs for sending different goods to different destinations are given in Fig. 6. It can be observed that (1) the costs in the LCGDS scheme are less than the costs in the OGT scheme, and (2) the costs for transmitting different goods is different in the two schemes. The main reason is that in the LCGDS scheme, when citizens holding smart mobile phones transmit goods, they put the goods in nearby goods collection tanks and record the relevant information of the goods. When the mobile vehicle passes the goods collection tank, it will take the goods and then transmit the goods to the location nearest to the destination of the goods. In the LCGDS scheme, goods can only be carried by mobile vehicles when a mobile vehicle passes the goods collection tank, and it does not lose the mobile vehicle's original interest. Thus, citizens pay lower costs. The costs for transmitting different numbers of goods are shown in Fig. 7. The average costs of the LCGDS scheme do not change. Additionally, the costs in the LCGDS scheme are lower than the costs in the OGT scheme, which demonstrates the effectiveness of the LCGDS scheme.

The average cost of transmitting goods under different numbers of destinations and the average costs of transmitting goods with the change in time are given in Fig. 8 and Fig. 9, respectively. In Fig. 8, although the number of destinations increases, the costs paid by citizens in the LCGDS scheme is always less than that in the OGT scheme. It can be seen from Fig. 9 that the costs paid by citizens in two schemes increase with time.

The ratio of paid costs for transmitting goods in the LCGDS scheme to the OGT scheme is given in Fig. 10. In Fig. 10, with the change of time, when 9 goods need to be transferred in smart city, the costs paid in the LCGDS scheme is only around 24% of the costs of the OGT scheme. It demonstrates the effectiveness of the LCGDS scheme.

B. DISTANCE OF GOODS TO DESTINATIONS

Fig. 11 shows the distance of different goods to destinations with the change in time. This mainly shows that the strategy proposed in this paper can transfer goods to their destinations. It can be seen from the figure that for time-tolerant

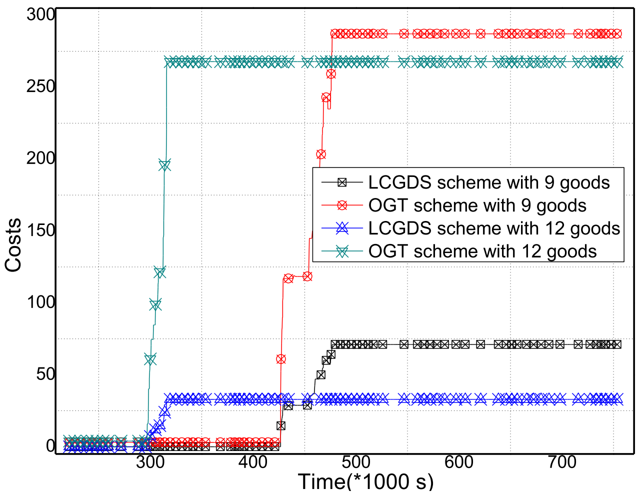

FIGURE 9. The average cost of transmitting different goods with time.

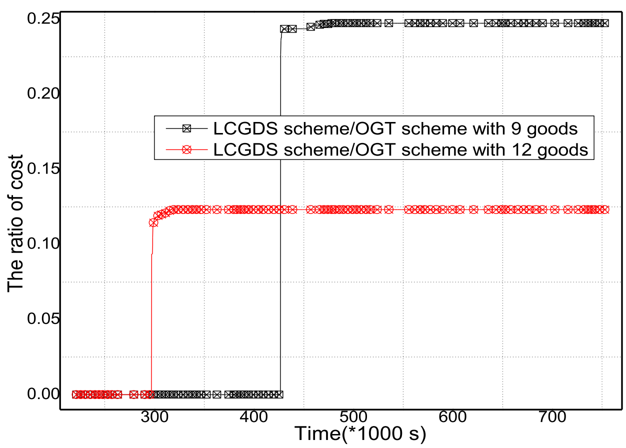

FIGURE 10. The ratio of costs in the LCGDS scheme to the OGT scheme with different numbers of goods.

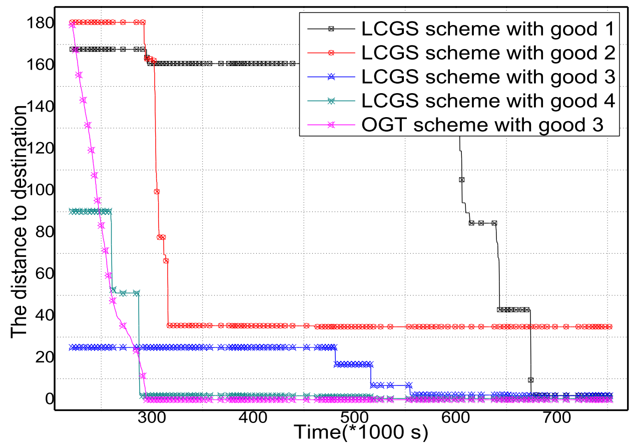

FIGURE 11. The distances of different goods to their destinations with time.

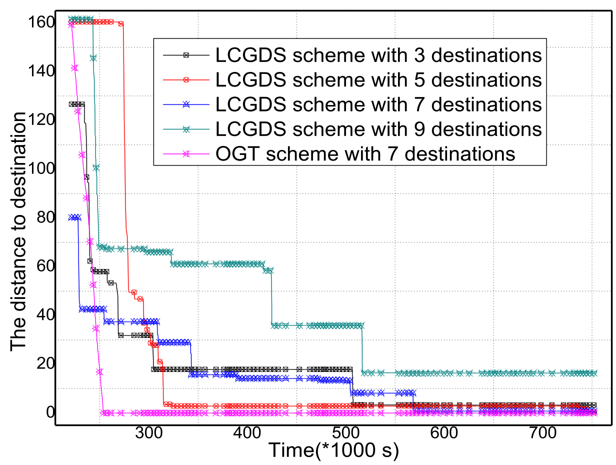

FIGURE 12. The distances of different goods with different numbers of destinations with time.

goods deliveries, after a period of transmission, goods will be transmitted to destinations with lower costs. In previous schemes, when users transmit goods to destinations using a courier or a mobile vehicle to deliver the goods, they must pay more money. To better save time and money, this paper uses mobile vehicles to send goods. It can be seen from the figure that over time, some goods are located relatively far away from the destination. This is mainly because when users want to transmit goods to the destination, the goods will be placed in a nearby goods collection tank. When a mobile vehicle moves to the vicinity of the collection tank, if the mobile vehicle can carry the goods to a location closer to the destination, the mobile vehicle can piggyback the goods and deliver goods to a better collection tank or destination in order to save costs.

Fig. 12 shows the distances of goods with the different numbers of destinations to the destination over time. It can be seen that the distances of all goods to their destinations have declined in a relatively short period of time. In the end, the distance of all goods is less than 20 m, and the distance of some goods to destinations is close to 0. As long as one mobile vehicle passes by the location of the goods, the mobile vehicle will piggyback the goods.

The distance of different goods to different destinations are given in Fig. 13. It can be seen that (1) most goods can be transmitted to the location near their destinations, then the receiver of goods can pick up goods easily, and (2) With the increase of the number of goods, the distance of goods to destinations increases. The average distance from goods to destinations in different numbers of destinations is shown in Fig. 14. The distance of goods to their destinations decreases with time. When the distance of goods near the destination is long, the declining speed of the distance of goods to destination is faster. This is because mobile vehicles will carry goods as long as they passes goods.

The average distance of goods to destinations in the different numbers of goods and different numbers of destinations are given in Fig. 15 and Fig. 16, respectively. In general, the distance of goods with different numbers of goods is

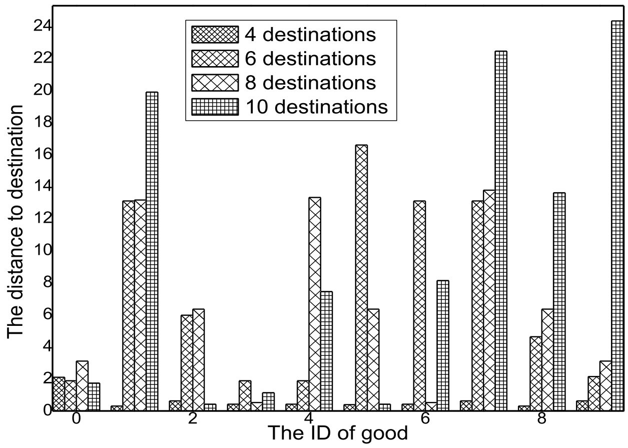

FIGURE 13. **The distances of different goods with different destinations to destinations.**

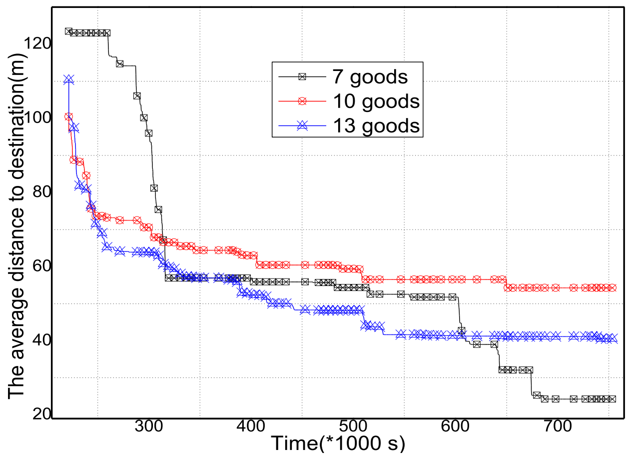

FIGURE 14. **The average distance of different goods to destinations with different numbers of goods over time.**

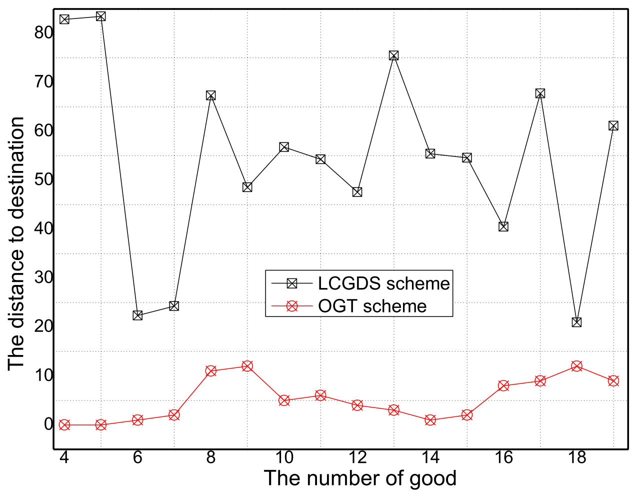

FIGURE 15. **The distance of different goods to destinations in different numbers of goods.**

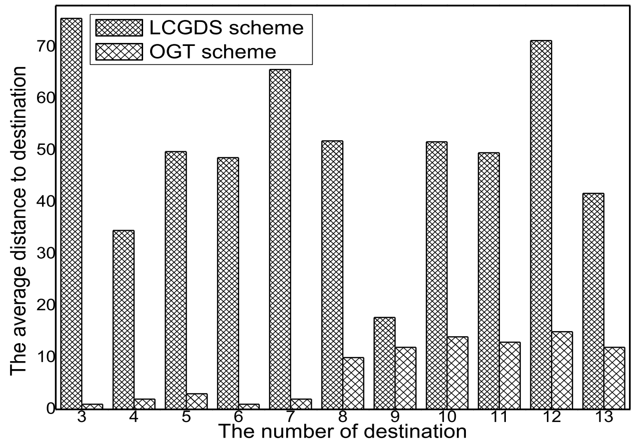

FIGURE 16. **The distances of different goods to destinations in different numbers of destinations.**

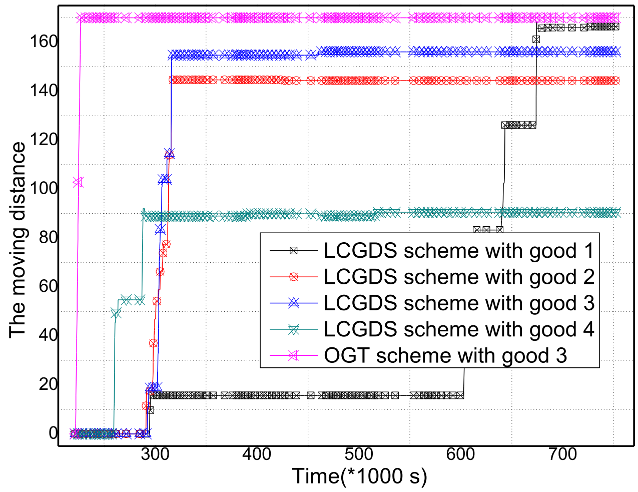

FIGURE 17. **The moving distance of different goods with time.**

about 40-50m. However, the distance of goods with the different numbers of destinations are about 45-55m. The main reason is that (1) the distance of individual goods to destination decreases over time. However, the arrival rate of goods cannot be 100% due to the movement uncertainty of mobile vehicles. (2) Goods near the destination may not be transmitted to destination because few mobile vehicles pass the location of goods. However, the receivers of goods will obtain goods near destination, it will save costs. As shown in Fig. 16, the distance from locations of goods to their destinations are constantly declining, which also proves the validity of this scheme.

C. MOVING DISTANCE

Fig. 17 shows the moving distance of different goods with the change in time. The main goal of this paper is to reduce the costs of goods transmission. In this paper, if goods do not need be transmitted to destinations quickly, they can be transmitted to their destinations using the proposed scheme. For mobile vehicle, it just piggybacks the goods, and then get the benefit. For users, this scheme reduces paid costs greatly. For goods, as long as there is the opportunity for the mobile

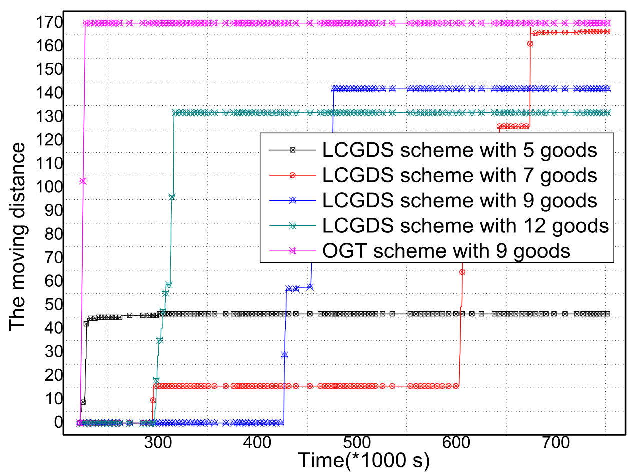

FIGURE 18. The moving distance of different goods and different numbers of goods.

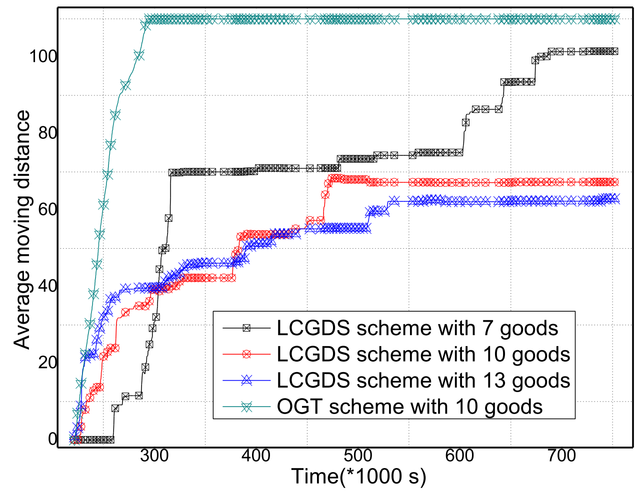

FIGURE 20. The average moving distance of different goods in different numbers of goods with time.

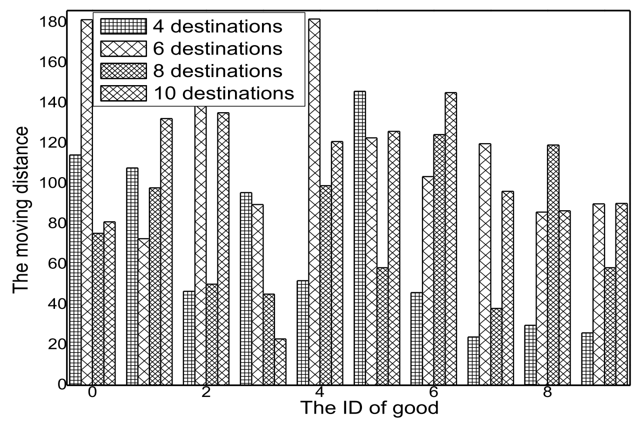

FIGURE 19. The moving distance of different goods in different numbers of destinations.

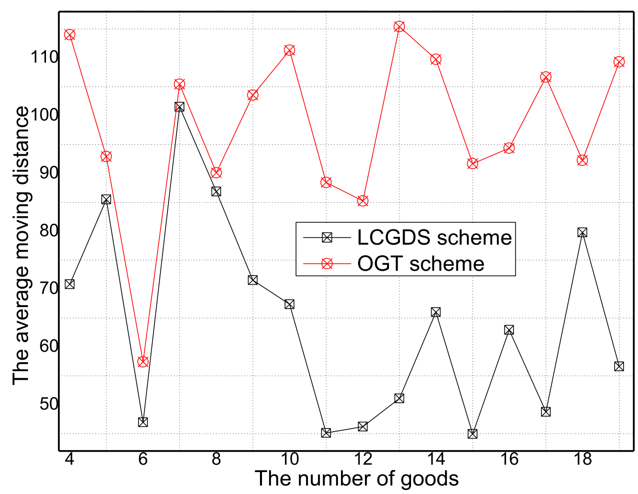

FIGURE 21. The average moving distance of different goods in different numbers of goods.

vehicle piggybacking of goods, the goods can be transmitted to locations near their destination and eventually to the destination itself through several rounds of transmission. Thus, the proposed scheme achieves better performance.

Fig. 18 shows the moving distance of goods with different destinations. It can be seen that the moving distance of all goods increases over time, and the time that each good moves are different. The reason is that different goods have different positions, and the movement uncertainty of the mobile vehicle causes the time that each good moves to not be the same. We can see that goods can move longer in a shorter period of time in the OGT scheme, but users need to pay higher costs. Although the time for transmitting goods to destinations are longer in the LCGDS scheme, users pay less costs and do not affect the performance.

The distances of different goods to different destinations in the different numbers of destinations are given in Fig.19. The average moving distance of goods in the different numbers of goods is shown in Fig. 20. From Fig. 20, the moving distance of goods increases over time, and the moving distance of individual good can reach about 170, but the average moving distances of goods is reduced. The reason is that the moving distance of goods is longer due to the higher frequency that mobile vehicle passes locations of goods. However, the moving distance of some goods is smaller due to the lower frequency. With the change in time, the range of area where mobile vehicle arrive is wide, and the probability that mobile vehicle carries goods is higher, which can increase the moving distance of goods. Thus, goods can be transmitted to destinations.

The average moving distance of goods in the different numbers of goods and in the different numbers of destinations are given in Fig. 21 and Fig. 22, respectively. Generally speaking, the average moving distance of goods to destinations is about 60-75m in different numbers of goods, but the paid costs in the LCGDS scheme is less than that of the OGT scheme. In the LCGDS scheme, when goods are

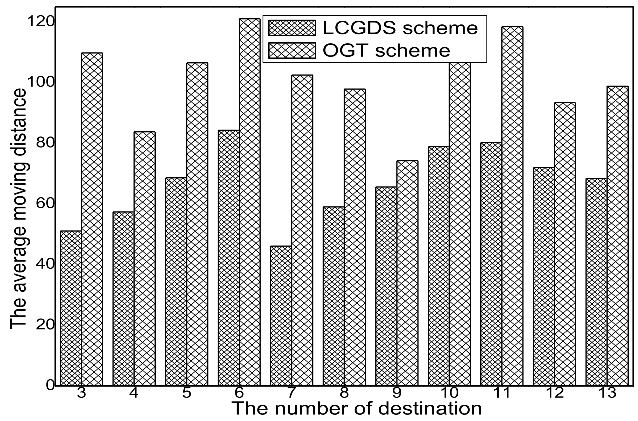

FIGURE 22. **The average moving distance of different goods in different numbers of destinations.**

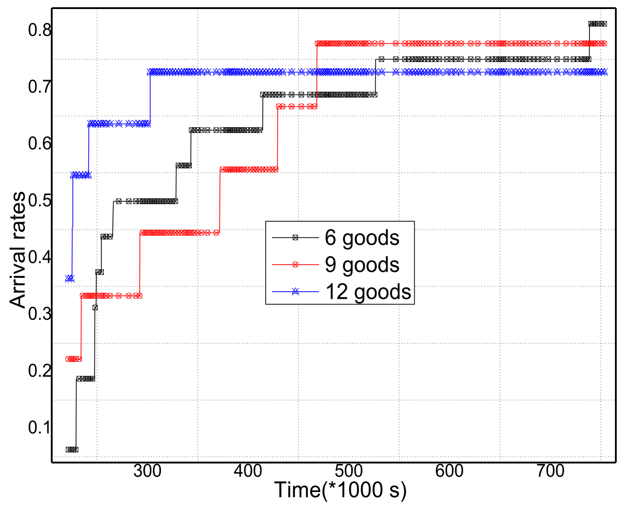

FIGURE 23. **The arrival ratio of different goods with time.**

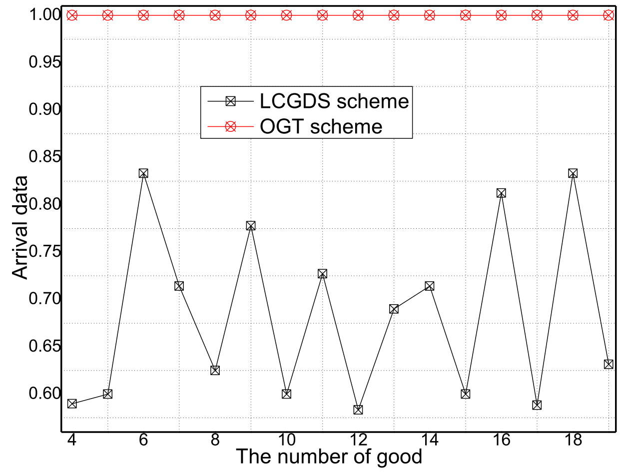

FIGURE 24. **The arrival ratio under different numbers of goods.**

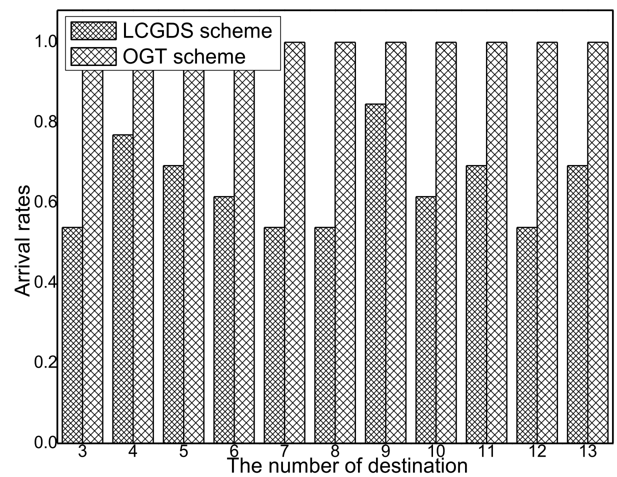

FIGURE 25. **The arrival ratio of different goods in different numbers of destinations.**

transmitted to location near the destination, the senders of the goods can also directly send goods to destinations using mobile vehicles, it will not affect the performance. Thus, the proposed scheme can save costs.

D. ARRIVAL RATES

The arrival ratio of goods at different times is given in Fig. 23. The arrival rate of goods refers to the ratio of goods that arrive at the destination to the number of goods in the smart city. It can be seen that the arrival ratio of goods increases with time.

Fig. 24 and Fig. 25 show the arrival ratios of goods at the different numbers of goods and the different numbers of destinations, respectively. For different numbers of goods, the arrival ratio of goods reach above 0.6, and the highest arrival ratio of goods is 0.84615 at the different numbers of destinations. We can see that the arrival ratio in the OGT scheme can reach 1. The main reason is that users pay higher costs to directly transmit goods to destinations using mobile vehicles or couriers. However, if the goods transmission has a low time requirement, it is unnecessary to transmit the goods using the OGT scheme. Since its costs are usually several times higher than those of the proposed scheme. Although the arrival rate of the proposed scheme does not reach 100% in the LCGDS scheme, the goods are transmitted to the location near the destinations. Then, goods senders can also select a mobile vehicle to transmit goods to the destination. Thus, this can also reduce costs.

VII. CONCLUSION

Most previous works in vehicular networks focus on data transmission. In this work, we leverage vehicular networks to efficiently delivery goods in smart city. The rationale is that when time is not the primary consideration factor, it is expensive for citizens to transport heavy goods to their destinations using express delivery. To provide low-cost goods transportation, a Low-Cost Good Delivery Scheme (LCGDS) with an Opportunistic Relay Style is proposed to transmit goods. Compared to the previous schemes, the LCGDS uses mobile vehicle to deliver goods to their destinations. In this scheme, mobile vehicles randomly move in the smart city. When a mobile vehicle passes the goods collection tank, it will piggyback goods and transport the goods to their destinations. In the process of carrying goods, mobile vehicles transfer goods to another mobile vehicle if another mobile vehicle is closer to the destination. In this way, the goods can be transferred to the destination quickly. Thus, we can achieve lower costs and minimum transmission time for goods delivery.

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