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A Leader-Follower Model with Communication Delay for Platooning Control in Highway Scenario

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Abstract—**The development of the intelligent transportation system has the potential to improve traffic management considerably. This paper research the car-following control of the autonomous vehicle in high way scenario. The given traditional car-following model does not consider the lateral lane change of the leader vehicle; Besides, the traditional control directly takes the related motion in the platoon of the leader vehicle as the system input of the following vehicle. But this paper combines the lateral and longitudinal movement of the vehicle as to the following control method. In addition, vehicle communication is taken as the way of platoon exchange between vehicles. Therefore, considering the influence of communication delay on the following control of vehicle platoon. The relevant simulation is carried out through Matlab/Simulink.**

Keywords—Vehicle Platooning; Car-following Control; Communication Delay

I. INTRODUCTION

Due to the increase in the number of vehicles, traffic accidents in cities have become increasingly complex. Fortunately, with the progress and development of technology, intelligent transportation system provides several methods to solve the problem. It can combine emerging network communication technology, big data technology. Meanwhile, with the improvement of hardware computing power, we can deal with the vast amounts of data from our transportation systems more efficiently. As computers gradually replace manual, management efficiency and road safety are guaranteed. In the Intelligent Transportation System research, improving road utilization rate and saving energy consumption are the problems to be considered. Meanwhile, the accumulation of technologies in vehicle dynamics and the advent of deep learning have led to breakthroughs in computer vision.

Among the numerous research, the Connected Vehicle technology has attracted the attention of many universities, scientific research institutions. The technology includes Vehicle to Vehicle (V2V), Vehicle to Road Infrastructure (V2I) and Vehicle to Pedestrian (V2P) and other real-time communication technologies. In recent years, many countries have strongly supported 5G communication technology to promote intelligent transportation systems further. 5G communication technology can support a considerable amount of data exchange between humans, vehicles and roads. Therefore, it can realize complex vehicle interaction technology, such as vehicle platoon.

Vehicle platoon can control the following vehicle into the wake zone of the head vehicle, reduce the overall average air resistance of the platoon, and improve the fuel economy in the process of high-speed driving[1]. Moreover, the platoon form can improve the road utilization rate because of the small gap between vehicles and the close connection within the platoon. Besides, autonomous driving technology and intelligent transportation systems can make vehicle management scientific, and reducing human operation can improve safety.

It is fundamentally different from that of common ground mobile robots, and the road scenario of vehicle driving has its unique limitations on vehicle driving planning. This article presents a vehicle platoon model that considers the delay caused by the workshop communication and deeply researches the platoon following control of vehicles. That requires the rationality of the maximum acceleration of the vehicle, the angular acceleration and the maximum deceleration speed when emergency braking, and adjusts the orientation, position, and speed of the vehicle body in a short time to avoid violating the corresponding traffic laws and regulations.

The rest of this paper is structured as follows: related work is introduced in Section 2. In Section 3, the framework system of automatic driving vehicles used in this paper is established. In Section 4, a longitudinal and lateral vehicle following model is proposed. Section 5 shows the simulation. Finally, section 6 provides the conclusion.

II. RELATED WORK

Autonomous vehicle technology is a comprehensive technical challenge, including several vital technologies and difficulties. In this paper, some of the current hot technologies have been applied in the industry, including positioning path planning of technology and vehicle platoon technology.

Positioning technology finds the self's position relative to the reference frame, which is crucial for an autonomous

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vehicle. In addition, positioning technology is also an essential requirement of global navigation[2]. Zhang et al. proposed to combine GPS. and IMU data platoon for positioning[3]. Its main principle is to use the inertial measurement unit to eliminate errors. G.P.S. errors will gradually accumulate over time so that the vehicle's position will shift; IMU can combine the measured vehicle acceleration and angular velocity to assist G.P.S. to eliminate errors. The platoon can be used to calculate the vehicle's trajectory. Elfes et al. grid the surrounding environment of mobile robots or vehicles to facilitate the perception and navigation of robots[4]. By deploying probability sensors to interpret the model and random field representation scheme. Many research ideas on map gridding applied to vehicle perception and navigation direction are based on the research results of the above paper[5]. For example, Tiancheng Li et al. proposed establishing a fan-shaped raster map model[6] based on the radius problem of circular wave propagation. This model was established based on the polar coordinate system and could solve the circular wave propagation algorithm.

Path planning plays a significant role in the autonomous vehicle system architecture, which belongs to decision control. Although this technology is not the focus of this article, it is an integral part of autonomous driving. It can be divided into two sub-tasks: global route planning and local route planning[7]. The primary method of finding the shortest path is named Dijkstra algorithm[8], proposed by E.W.Dijkstra in 1959. This algorithm adopts the greedy strategy. By maintaining a priority queue of ordered vertices, the next vertex selected in each iteration is the nearest sub-vertex of the current vertex. Thus, the shortest route obtained after each iteration is guaranteed. But to ensure the shortest path of the final result, we need to traverse all the vertices. McNaughton et al. proposed a motion planning method for highway driving[9], which presents a search space that enables the search algorithm to scan in real-time. Ziegler et al. proposed a motion planning method for moving obstacles in dynamic road scenes[10]. The algorithm works by sampling and modelling a geometric graph from a pipe that combines time and configuration space.

Vehicle platoon technology involves workshop communication[11], multi-vehicle cooperative control and obstacle avoidance strategy in the platoon and is an application on autonomous driving technology. The combination of IEEE 802.11p and IEEE 1609 protocol suites are represented as Wireless Access in Vehicular Environments (WAVE). Paden's team[12] classified vehicle control technologies in many platooning technologies: path stability, trajectory tracking, predictive control, and linear parameter variable controller. Peppard et al. proposed that a vital performance standard of the longitudinal control system of moving vehicles is the chord stability in the face of disturbances in the movement of a single vehicle[13], and designed a platoon controller based on P.I.D. to realize the chord stability by simultaneously using forward and backward separation measurements.

In terms of vehicle platoon control, there are many research results[14]. At present, relatively mature platoon control methods include:

In the displacement-based configuration control method, each vehicle can sense its neighbouring vehicles relative to the global coordinates and control the displacement of its neighbouring vehicles to control the configuration. The desired configuration is determined by the expected displacement of each vehicle concerning the global coordinate system, assuming that each vehicle is aware of the relative position of its neighbours in the global coordinate system.

In the distance-based configuration control method, the required configuration is realized by actively controlling the distance between vehicles, and it is required to assume that each vehicle can perceive the relative position of its neighbouring vehicles relative to its local coordinate system[15].

III. ROAD COLLABORATION FRAMEWORK

The concept of an intelligent driving vehicle mainly refers to the ability of a single vehicle to drive itself. But it has its inevitable defects: blind area, perceived distance limit, trapped in local, cost and so on. Therefore, it is necessary to construct a cooperative vehicle system to construct a safe and economic autonomous driving system. The overall framework adopted in this paper is a three-layer distributed control system of a core-edge cloud-vehicle terminal. This technology is accessed through 5G communication, and this framework has a low delay and high reliability. The conceptual framework shows in Figure 1.

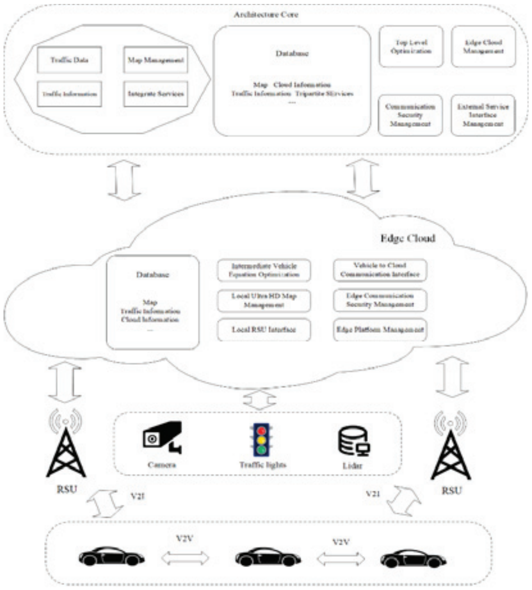


Fig. 1. Core-MEC-V2X three layers structure

A. Core Layer

As the core of the whole architecture, the core layer is mainly responsible for the standard access request service and real-time update of road data of each module. For the platoon of vehicles, the core layer pays attention to the destination, optimal route, current vehicle position and macro vehicle state, such as the vehicle in the automatic driving state, remote control state, platoon following state or personnel control state, etc. Moreover, the core layer can assist the driver in providing the optimal global route and the velocity planning to be optimized. The edge cloud calculates the detailed velocity planning. This speed plan to be optimized can provide a reference value when the vehicle enters the freeway scene and is following.

In other cases, such as the planned route appears to be obstacles or short-time traffic flow increase caused by the traffic jam, then the core layer can give full play to the advantages of overall planning and timely adjust the vehicle's route.

The optimal route is not necessarily the route with the shortest driving distance. There will be different routes according to different minimization criteria. For example, expressways can significantly reduce the travel time, but the journey may have a longer detour. With the architecture system's continuously rollout, the road data platoon will be more detailed and specific. In the future, based on extensive data, it even can be based on the vehicle's engine parameters and tire wear, road pavement temperature, humidity, airflow direction and speed, etc., planning out a current optimal save gas or power method.

B. Cloud Layer

The idea behind Edge Cloud, or Multi-Access Edge Computing (M.E.C.), is to reduce the increasing operating pressure on core network equipment and allow operators to create unique customer experiences. M.E.C. nodes can be placed near the base station of the cellular network. This new M.E.C. technology enables edge nodes to have strong computing power, enriching the whole communication network structure.

Compared with the technology based on the cloud server, M.E.C. technology can significantly reduce the communication delay with users due to reducing the actual physical distance and simplifying the complexity of the cloud server system. At the same time, the application of edge cloud technology has been extensively expanded in combination with services such as computing task unloading, intelligent transportation and dynamic content optimization, including Internet of vehicles applications.

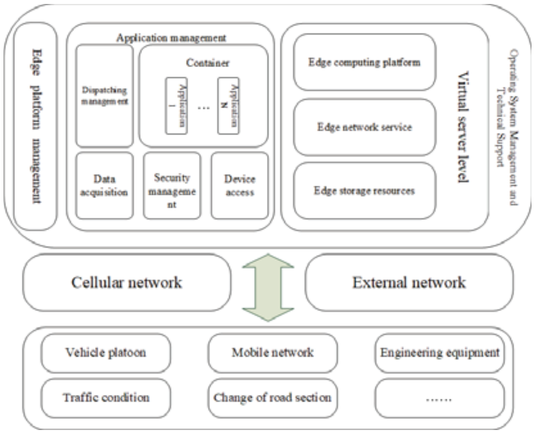


Fig. 2. General service architecture of MEC

MEC provides excellent local services to vehicles in the vehicle platoon system by calculating and optimizing local road sections' paths, calculating and controlling the traffic flow, etc. Virdis et al. adopted LTE-advanced network communication to realize the platoon framework of M.E.C. auxiliary vehicles[16]. Edge cloud technology is also gradually playing more and more broad and powerful advantages.

C. Terminal Layer

The path planning and following control of vehicle platoon studied in this paper involve the global path planning module and motion planning module of the terminal layer of vehicle road in the above structure. The vehicle-road terminal includes the vehicle terminal and the road terminal. The vehicle terminal's On-Board Unit (O.B.U.) is responsible for integrating the vehicle's real-time platoon, including the vehicle's primary platoon, the driving platoon of the vehicle, the movement platoon of the vehicle, and the position platoon of the vehicle. At the same time, it uploads them to the Road Side Unit(R.S.U.). The R.S.U. The roadside is responsible for the real-time processing of the messages uploaded by the vehicle. Meanwhile, the Basic Safety Message (B.S.M.) is fused with other sensors' data, such as lidar, camera, and so on, to realize the fusion and processing of multiple data.

Global planning needs to get the coordinate row of vehicle G.P.S. positioning system and plan path based on local map data. In addition, command and coordination should be conducted to the upper server to avoid the unique control of the road sections such as long roads, frequent up and down of the highway, road congestion, etc.

The motion planning module needs the instruction of the behaviour decision module to guide the vehicle's response or countermeasures in the face of a certain environment. The environment perception module helps build real-time environment information around the vehicle, local map data, and the decision-making layer of influencing behaviour. This locally collected information will be uploaded to the upper server and then assist other vehicles.

IV. CAR-FOLLOWING MODEL

The car-following control technology is one of the core technologies of the vehicle platoon. The quality of car-following strategy plays a crucial role in the safety and comfort of vehicle platoon driving. In this section, we will directly improve it instead of introducing the traditional I.D.M. model.

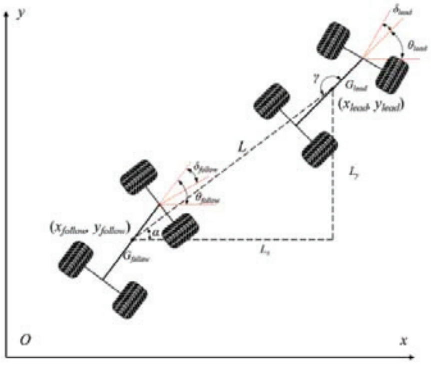


Fig. 3. Leader-follower vehicle model

Figure 3 shows the model of the leading vehicle and the following vehicle[17], in which the lower left is the following vehicle and the upper right is the leading vehicle. G_{lead} and G_{follow} are the centroids of the leading vehicle and the following vehicle, respectively. The distance between the centroids of the two vehicles is L, and the angle between the connection and the X-axis is α. The angle between the driving direction of the body of the leader vehicle and the connection L between the centre of mass of the two vehicles is defined as γ. The line is decomposed into L_x and L_y by orthogonal global coordinates.

As can be seen from the figure, the distance between two cars can be expressed as:

$$L = \sqrt{L_x^2 + L_y^2} \tag{1}$$

The angle between the connection and the X-axis can be expressed as:

$$\alpha = arctan\frac{L_y}{L_x} \tag{2}$$

The angle γ can be expressed as:

$$\gamma = arctan\frac{L_y}{L_x} - \theta_{follow} + \pi \tag{3}$$

Then, L_x and L_y obtained by using two vehicles coordinates to represent the orthogonal decomposition are as follows:

$$\begin{cases} L_x = x_{lead} - x_{follow} \\ L_y = y_{lead} - y_{follow} \end{cases} \tag{4}$$

To know the relationship between L and time t need to take the derivative of L using the symbol $\dot{L}$ to indicate this:

$$\dot{L} = \frac{L_x \dot{L}_x + L_y \dot{L}_y}{L} \tag{5}$$

$$\begin{cases} \dot{L}_x = \dot{x}_{lead} - \dot{x}_{follow} \\ \dot{L}_y = \dot{y}_{lead} - \dot{y}_{follow} \end{cases} \tag{6}$$

Finally, the experimental results $\dot{L}$ were given:

$$\dot{L} = \frac{(x_{lead} - x_{follow})(\dot{x}_{lead} - \dot{x}_{follow}) + (y_{lead} - y_{follow})(\dot{y}_{lead} - \dot{y}_{follow})}{\sqrt{(x_{lead} - x_{follow})^2 + (y_{lead} - y_{follow})^2}} \tag{7}$$

Meaning of each parameter:

$$\begin{cases} \dot{x}_{lead} = v_{lead} cos(\delta_{lead} + \theta_{lead}) \\ \dot{y}_{lead} = v_{lead} sin(\delta_{lead} + \theta_{lead}) \\ \dot{x}_{follow} = v_{follow} cos(\delta_{follow} + \theta_{follow}) \\ \dot{y}_{follow} = v_{follow} sin(\delta_{follow} + \theta_{follow}) \end{cases} \tag{8}$$

For vehicle following, correlation analysis is needed for three variables: lateral distance error, vertical distance error and front-wheel deflection angle between the following vehicle and the navigating vehicle. Second-order systems are used for analysis, including displacement and velocity information. L_x and L_y As values obtained through coordinate trans platoon are controllable variables used in the control method.

Error variables e_x Were defined to represent X axis and Y axis errors of the following vehicle's position in the global coordinate system.

$$\begin{cases} e_x = L_x - L_x^D = x_{follow} - x_{follow}^D \\ e_y = L_y - L_y^D = y_{follow} - y_{follow}^D \end{cases} \tag{9}$$

L_x^D and L_y^D respectively represent the expected value of L_x and $(x_{follow}^D, y_{follow}^D)$ are the coordinates of the expected position points of the following vehicles. The desired position is set in the same direction as the leader-vehicle and the distance $k_1 v_{lead}$ behind it, where the safety distance coefficient k_1 is greater than 0.

Therefore, the position coordinates of the following vehicles can be expressed as:

$$\begin{cases} x_{follow}^D = x_{lead} - k_1 v_{lead} cos\theta_{lead} \\ y_{follow}^D = y_{lead} - k_1 v_{lead} sin\theta_{lead} \end{cases} \tag{10}$$

Therefore, the error variable can be transformed into the following formula:

$$\begin{cases} e_x = x_{follow} - x_{lead} + k_1 v_{lead} cos\theta_{lead} \\ e_y = y_{follow} - y_{lead} + k_1 v_{lead} sin\theta_{lead} \end{cases} \tag{11}$$

The following controller is designed for vehicle platoon:

$$\begin{cases} \dot{x}_{follow} = k_2 e_x + k_3 \int_0^t e_x dt + v_{lead} cos(\delta_{lead} + \theta_{lead}) \\ \dot{y}_{follow} = k_4 e_y + k_5 \int_0^t e_y dt + v_{lead} sin(\delta_{lead} + \theta_{lead}) \end{cases} \tag{12}$$

K_2、 K_3、 K_4 and K_5 are gain coefficients respectively.

V. SIMULATION

MATLAB R2019A and its corresponding version Simulink were used as simulation tools concerning Vehicle Dynamics Blockset and Model Predictive Control Toolbox.

According to the model parameters of the adaptive cruise control system in the predictive control model toolbox module, a linear model from vehicle longitudinal acceleration to longitudinal velocity is selected. Its transfer function parameter is $tf = ([1,[0.5,1.0]])$. As shown in Figure 4, the acceleration and speed limits are increased.

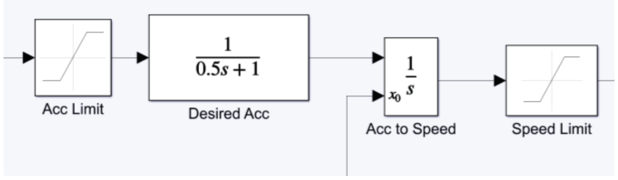


Fig. 4. Block diagram of vehicle's velocity control system

The final model of the navigating vehicle is shown in Figure 5. The upper part is the longitudinal vehicle control, and the lower part is the lateral control. Horizontal control adjusts the vehicle front wheel angle through the integral link and adjusts the speed direction and numerical size through the trigonometric function relationship.

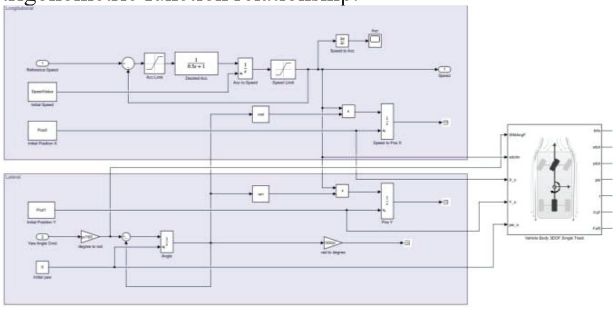


Fig. 5. Block diagram of vehicle control system

The vehicle body model uses the library of the vehicle dynamics module and the three degrees of freedom model. The control includes information such as the rotation angle of the vehicle's wheel and vehicle speed.

Other relevant parameter values include body mass of *2000 kg*; The distance between front-wheel and vehicle centroid is *1.4m*; The distance between rear-wheel and vehicle centroid is 1.6m; The body moment of inertia is $4000 kg \cdot m^2$.

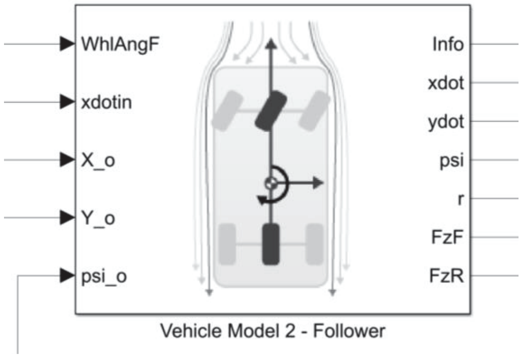


Fig. 6. Block of the body of a vehicle

The coefficients were set K_1 as 0.1, K_2and K_4 as 10-5, K_3andK_5 10-7. In-vehicle initialization setting, the initial speed of the pilot vehicle is set as 5m/s, the target speed is 10m/s, the initial position coordinate is (20,0), and the turning angle is set as 0. The initial speed of the following vehicle is set as 15m/s, and the initial position coordinate is (0, -6).

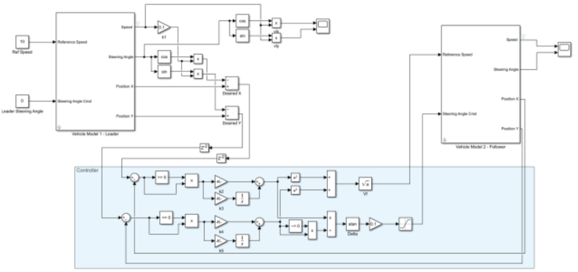
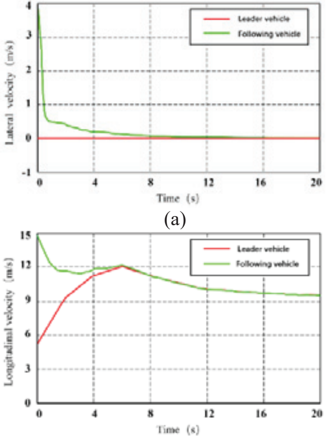


Fig. 7. Vehicle platooning control system

In case of no communication delay:

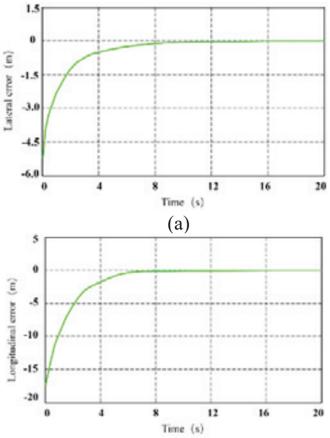


(a)

(b)

Fig. 8. The comparison of the velocity curve. (a) Lateral velocity contrast. (b)Longitudinal velocity contrast

As seen from the figure, the system has been stable from the observed curve for about 6s time.

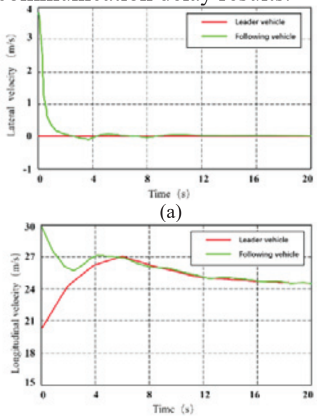


(a)

(b)

Fig. 9. The comparison of the error curve. (a) Lateral position error. (b) Longitudinal position error

Contains communication delay results:

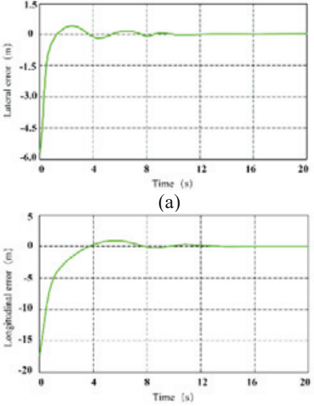


(a)

(b)

Fig. 10. The comparison of velocity curve with delay. (a) Lateral velocity contrast. (b)Longitudinal velocity contrast

As can be seen from the figure, the curve of the system has stabilized in about 10s. The added delay makes the input signal from the pilot vehicle later than that of the following vehicle, making it more time-consuming for the system to become stable than the no-delay state.



(a)

(b)

Fig. 11. The comparison of error curve with delay. (a) Lateral position error. (b) Longitudinal position error

VI. CONCLUSION

This paper studies the realization of the platoon in the case of communication delay. Firstly, the framework scheme of the adopted autonomous driving vehicle is briefly introduced. The whole framework consists of a distributed control system composed of three layers: core, cloud and vehicle terminal. The traditional I.D.M. model can't adjust vehicle lateral, so this paper adopts a comprehensive vehicle following the vertical and horizontal control model. In the case of vehicle communication delay and information transmission delay, the relevant driving conditions of the formation are considered. Section 5 of the paper carries out the relevant simulation. The simulation results show that the proposed model is effective.

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