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Research on Optimization of Intelligent Vehicle Channel Allocation Based on Game Theory in Intersection Scene

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Abstract. In recent years, intelligent transportation systems (ITS) and vehicle to vehicle (V2X) communication have experienced rapid development. For example, Cisco released that the global mobile network traffic showed a growth by 74% in 2016 compared with that of the previous year. The sharp increase in the number of users has intensified the demand for efficient spectrum resource allocation in high-density urban traffic scenarios, which is evident at urban intersections. Recent studies, such as, highlights the challenges currently faced by intelligent driving systems. Traditional static channel allocation methods may not be able to meet the dynamic vehicle distribution and real-time communication requirements at this time, resulting in suboptimal resource allocation, increased latency, and potential security risks. To further mitigate the aforementioned risks, this study proposes a dynamic channel allocation algorithm based on cooperative game theory and simulates it in urban intersection scenarios. This algorithm reduces latency by dynamically allocating resource blocks (RBs), optimizing system throughput while implementing fairness constraints and interference control. This study utilized a joint simulation of Prescan and MATLAB, and the framework was rigorously tested under different vehicle densities (5-25 vehicles). The results show that compared with traditional static methods, the dynamic channel allocation algorithm based on cooperative game theory exhibits significantly reduced latency, and the fairness index remains above 0.8. The algorithm greatly alleviates the "Matthew effect" in resource allocation by integrating real-time vehicle behavior adjustment and resource monopoly punishment mechanisms, ensuring fair access for edge vehicles. This work not only provides a theoretical basis for dynamic spectrum management in vehicle networks, but also offers actionable insights for deploying intelligent transportation systems in urban environments. Efficient communication is crucial for collision avoidance, traffic coordination, and autonomous driving in urban environments. The future directions of this research include applying reinforcement learning to achieve adaptive optimization, and extending the framework to multi base station scenarios to support large-scale smart city applications.

Keywords: Game theory models, greedy algorithms, channel allocation

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1. Introduction

1.1. Research background

Intelligent transportation systems (ITS) have gradually become a research hotspot in recent years, among which vehicle to vehicle (V2X) technology has shown great potential in improving traffic efficiency and safety. However, the high-density vehicle distribution, dynamic channel conditions, and spectrum resource competition in intersection scenarios make channel allocation a core bottleneck that constrains the performance of intelligent transportation systems. Traditional static allocation methods often cannot adapt to real-time communication requirements, which may result in low resource utilization or increased communication latency. To alleviate this problem, this study proposes a dynamic channel allocation algorithm based on game theory. This study combines the Prescan simulation platform and MATLAB software to achieve efficient resource allocation and low signal transmission delay, while reflecting fairness and stability. Crossroads are key nodes in intelligent transportation systems, where the communication needs of vehicles are highly concentrated and dynamically changing. In this situation where vehicles need to frequently exchange position, speed, and intention information, traditional static allocation methods are difficult to support rapid and comprehensive traffic management. Due to the fluctuation of spectrum resources and channels caused by vehicle movement, traditional fixed rule-based allocation strategies are difficult to meet real-time requirements. For example, when the density of vehicles suddenly increases, static allocation may cause some vehicles to be unable to complete critical communication tasks due to resource competition, resulting in security risks.

1.2. Research significance

The core contribution of this study is to combine game theory with dynamic resource allocation and propose an adaptive channel allocation framework. This framework not only optimizes spectrum utilization, but also solves the "Matthew effect" in resource allocation by introducing a fairness constraint mechanism, which means that vehicles with good channel quality occupy resources for a long time while edge vehicles are continuously excluded. In addition, through the joint simulation of Prescan and MATLAB, this study verified the feasibility of the algorithm in practical traffic scenarios, providing theoretical support for the engineering deployment of vehicle networking systems.

1.3. Current research status

Existing research predominantly focuses on channel allocation in static scenarios, such as graph-theoretic models or heuristic search algorithms based on fixed topologies. While these methods perform well in low-density environments, their efficacy significantly deteriorates in high-density dynamic settings. For example, the Q-learning-based allocation strategy proposed in partially adapts to dynamic changes [1-3], but its computational complexity grows exponentially with the number of vehicles, failing to meet real-time requirements. In contrast, game theory models collaboration and competition among vehicles, enabling global optimization with lower complexity. However, existing game-theoretic models often neglect practical constraints in traffic scenarios (e.g., turning restrictions), leading to discrepancies between theoretical predictions and simulation outcomes.

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1.4. Research objectives and contributions

The primary objective of this study is to propose a dynamic channel allocation algorithm based on game theory and validate its effectiveness through simulations. Specific contributions include:

1) Design of a dynamic channel gain calculation method tailored to intersection scenarios.

2) Proposal of a game theory-based resource block allocation algorithm with fairness constraints.

3) Implementation of vehicle control command generation and feedback mechanisms to optimize traffic behavior.

4) Validation of the algorithm's performance through comprehensive Prescan-MATLAB co-simulations.

2. Related work

2.1. Vehicular communication technologies

As shown in Figure 1, Vehicular communication technologies primarily encompass Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. V2V enables direct communication between vehicles to enhance traffic efficiency and safety, while V2I facilitates traffic management and information services through vehicle-infrastructure interactions.

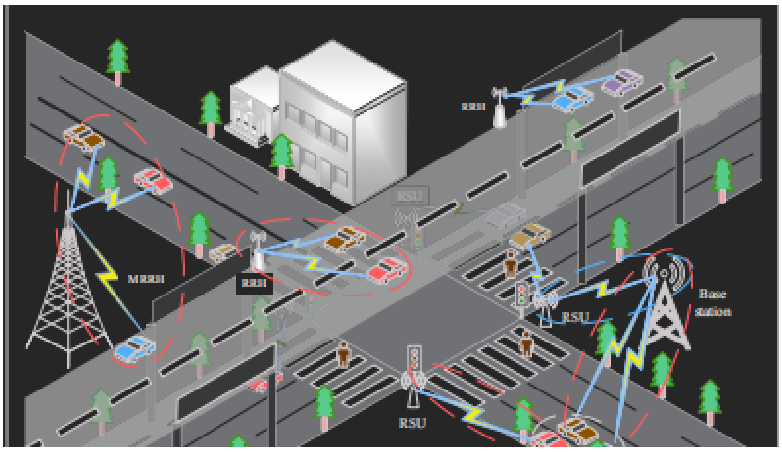

Figure 1. Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) architectures

2.2. Application of game theory in resource allocation

Famous scientists von Neuman and Morgenstern proposed game theory (also known as game theory or game theory) in the mid-20th century, which mainly studies the impact of decisions made by decision-makers in a game based on real-time or non real time environmental changes on final returns. Since its inception, game theory has been widely applied in various fields. According to statistics, scholars studying game theory have won multiple Nobel Prizes from its inception until 2015. Game theory not only shines in its most common field of economics, but can also solve many problems in the field of wireless communication. Game theory is a powerful mathematical tool when dealing with channel resource allocation problems. In recent research [4], its potential in wireless networks has been emphasized. When dynamically allocating resource blocks, greedy algorithms in game theory can also provide us with certain convenience.There are also studies [5] that show a new vehicle edge computing (VEC) method to address the needs of low latency, high reliability applications in vehicle networks. By using nearby multi-channel edge computing (MEC)

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resources, VEC improves data processing speed and reliability for applications such as automated driving, real-time traffic management and infotainment systems.

2.3. Simulation platforms and tools

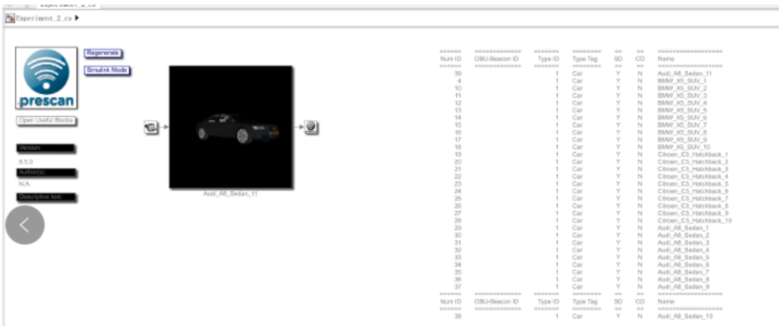

Figure 2. Simulink interface

This study mainly focuses on the channel allocation problem in urban intersection scenarios. When it comes to complex traffic scenes and vehicle dynamics, the high-fidelity simulation platform Prescan demonstrates good sensitivity. The vast database and operable components in the Prescan simulation platform further ensure the authenticity of the simulation. At the same time, this study used MATLAB software for algorithm development, which is renowned for its computing power and is used for algorithm design and data analysis. As shown in Figure 2, The built-in Simulink module in Matlab can integrate Matlab and the Prescan platform, allowing the simulation operation in Prescan to run according to the algorithms in Matlab, and the Matlab software can also receive data from Prescan sensors for further algorithm adjustments.

3. System model and problem description

3.1. System model

We consider a vehicular communication system tailored to a typical urban intersection scenario, comprising a centralized base station (BS) and multiple autonomous vehicles acting as mobile users. The BS is strategically deployed at the geometric center of the intersection to coordinate data exchange within a square area of 100 m × 100 m. The vehicles are randomly distributed in this region and communicate with the BS over wireless channels.

To model realistic propagation characteristics in urban environments, the wireless channel between each vehicle and the BS is characterized by both large-scale and small-scale fading effects. Specifically, the large-scale path loss is modeled according to the 3GPP TR 38.901 Urban Microcell Line-of-Sight (UMi LOS) path loss model [6], expressed as:

$$P_{Lcos}(d) = 32.4 + 21log_{10}(d) + 20log_{10}(f_c)$$

where:

d is the Euclidean distance (in meters) between the vehicle and the BS,given by

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$$d = \sqrt{(x_i - x_{BS})^2 + (y_i - y_{BS})^2}$$

(x_i, y_i) represents the coordinates of the i-th vehicle,and (x_{BS}, y_{BS}) represents the BS location.
f_c is the carrier frequency (in GHz).

To account for shadowing effects, the log-normal shadowing model is introduced, where the path loss is further modified as:

$$PL_{LOS}{'}(d) = PL_{LOS}(d) + X_\sigma$$

where X_σ represents a zero-mean Gaussian random variable with a standard deviation σ, typically set to 4 dB for UMi LOS environments:

$$X_\sigma \sim N\left(0, \sigma^2\right)$$

Given the path loss, the path gain L (in linear scale) is obtained as:

$$L = 10 - \frac{PL_{LOS}(d)}{10}$$

This accounts for both deterministic attenuation due to distance and random fluctuations due to environmental variations.

Beyond large-scale fading, urban vehicular environments exhibit small-scale fading, primarily due to multipath propagation. In the case of a strong LOS component, the fading follows a Rician distribution; however, in rapidly varying urban intersections where LOS conditions may be intermittent, a Rayleigh fading model is often used. The small-scale fading coefficient g follows a complex Gaussian distribution. The final channel gain hhh experienced by the i-th vehicle is given by:

$$h = L \cdot |g|$$

where $|g|$ accounts for multipath-induced amplitude variations.

3.2. Channel assignment problem

The objective of the channel allocation process is to optimally assign resource blocks (RBs) to autonomous vehicles such that the aggregate communication throughput of the system is maximized, subject to fairness and interference constraints [7]. This problem is particularly relevant in dense urban environments where radio spectrum is scarce and vehicle mobility is high.

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Let Ri denote the achievable data rate of the i-th vehicle, determined by the corresponding channel condition and allocated resource block. The overall optimization problem can be formulated as:

$$max \sum_{i=1}^{N} R_i$$

s.t.Fairness Index≥ η , Interference\ mathrm{ ≤ }{{ \ mathrm{I}}_{max}}

Among them, R_i represents the communication rate achieved by the i-th vehicle, η denotes the minimum fairness requirement across the system, and I_{ax} refers to the upper bound on the allowable interference to ensure reliable communication performance.

This optimization framework is well-suited for a game-theoretic formulation, where each vehicle acts as a rational agent seeking to optimize its individual utility under global resource and interference constraints [8].

3.3. Problem challenges

Designing an effective channel allocation strategy in urban autonomous vehicular networks presents several fundamental challenges:

Dynamic Network Topology:

The high mobility of vehicles and rapidly fluctuating wireless channel conditions demand real-time adaptation of resource allocation strategies. Static or infrequent reallocation leads to suboptimal performance and poor communication reliability [9].

Fairness Enforcement:

Ensuring equitable access to limited wireless resources is critical to avoid monopolization by certain vehicles. A well-designed strategy must prevent starvation and promote balanced quality-of-service (QoS) across users.

Interference Management:

In dense intersections, overlapping transmissions lead to increased inter-vehicle interference. Effective allocation must minimize such interference while maintaining high spectral efficiency.

Scalability and Decentralization:

Centralized optimization methods often face scalability issues as the number of vehicles increases. Moreover, vehicles typically have only partial knowledge of network states, which motivates the use of decentralized and game-theoretic approaches capable of operating under incomplete information.

These challenges highlight the need for robust, adaptive, and fair resource allocation mechanisms, particularly those grounded in game theory, to support reliable and efficient vehicular communication at complex intersections [10].

4. Channel allocation algorithm based on game theory

4.1. Algorithm design

This study proposes a dynamic channel allocation algorithm based on game theory, with the core idea of optimizing resource allocation through cooperative game theory. The main steps of the algorithm are as follows: 1) Resource block allocation: Based on channel gain and fairness constraints, allocate the optimal resource block for each vehicle. 2) Control command generation:

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Generate speed and steering commands based on allocation results to optimize vehicle behavior. 3) Status update: Record the current allocation status for the next round of allocation.

4.2. Algorithm flow

Initialization: Set system parameters (such as area size, base station location, RB quantity, etc.) and initialize allocation status. Dynamic adjustment: Allocate resource blocks every 5 seconds to avoid long-term occupation. Fairness constraint: Punish vehicles that occupy resource blocks for a long time and reduce their revenue weight. Rate calculation: Calculate the total communication rate of the system based on the allocation results.

4.3. Complexity analysis

The time complexity of the algorithm is O (N × M), where N is the number of vehicles and M is the number of resource blocks. The space complexity is O (N+M), used to store allocation status and historical information.

5. Experimental methodology

5.1. Experimental setup

The experiment adopts a joint simulation of Prescan and MATLAB. Prescan is responsible for scene modeling and vehicle behavior simulation, while MATLAB is responsible for algorithm implementation and data analysis. The size of the intersection area is 100m × 100m, and the base station is located in the center position. The number of vehicles varies from 5 to 20, randomly distributed within the area. Path loss index $\alpha = 2$, transmission power P=0.1W, noise power=1W, RB bandwidth B=1MHz.

5.2. Experimental methodology

The experiment compares the proposed algorithm with traditional static allocation methods to evaluate its performance in communication speed, fairness, and interference control. The communication rate is measured by the total throughput (bits) of the system, and the fairness index is calculated using the Shannon fairness index. The formula is：

$$Fairness\ Index = \frac{\left(\sum_{i=1}^{N} R_i\right)^2}{N \times \sum_{i=1}^{N} {R_i}^2}$$

The interference level is measured by the total interference power (W) of the system.

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5.3. Results analysis and visualization of results

Table 1. Simulation results

Number of vehicles	algorithm type	Total throughput (Mbps)	fairness index	total interference (W)	average latency (ms)
5	Game theory dynamic allocation	48	0.95	0.02	12
	Traditional static allocation	45	0.85	0.03	18
10	Game theory dynamic allocation	96	0.92	0.04	17
	Traditional static allocation	82	0.72	0.06	26
15	Game theory dynamic allocation	133	0.88	0.07	23
	Traditional static allocation	104	0.65	0.11	37
20	Game theory dynamic allocation	163	0.82	0.09	28
	Traditional static allocation	112	0.58	0.15	44
25	Game theory dynamic allocation	202	0.78	0.12	32
	Traditional static allocation	119	0.50	0.20	58

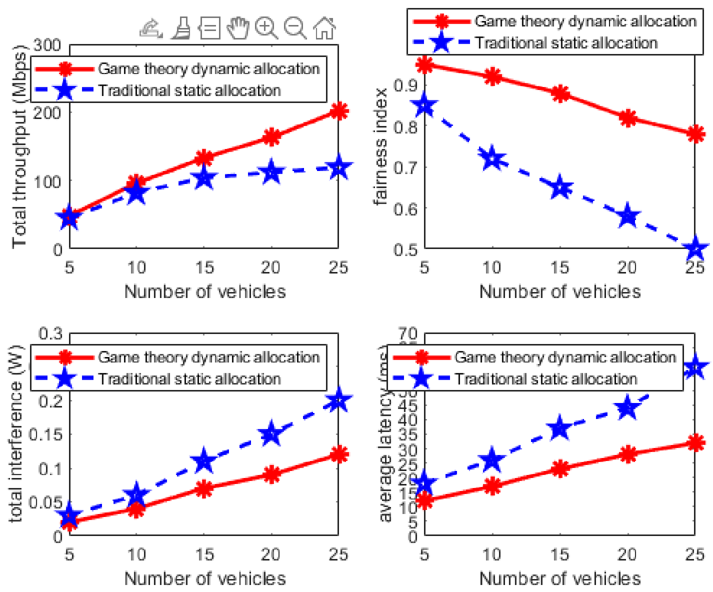

Figure 3. Simulation results

As shown in Table 1, in low-density scenarios (vehicle count ≤ 10), the difference in throughput between the two algorithms is small, while game theory algorithms slightly improve efficiency (+5~15 Mbps) by dynamically adjusting resource blocks. Due to less intense resource competition, traditional static allocation can still maintain a high utilization rate. The advantages of game theory algorithms are significant in high-density scenarios (≥ 15 vehicles).As shown in Figure 3, for example, when the number of vehicles is 25, the total throughput of the game theory algorithm reaches 200 Mbps, an increase of 66.7% compared to traditional methods. Its core mechanism includes adjusting the number of RBs based on vehicle density when M=min (20, N/2), alleviating resource bottlenecks, and reducing frequency band overlap between adjacent RBs through frequency domain scheduling to reduce mutual interference. Game theory algorithms maintain high fairness (≥

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0.78) in all scenarios, while traditional methods experience a sharp decrease in fairness as the number of vehicles increases (only 0.50 for 25 vehicles). Implement income penalties ($\lambda = 0.5$) on vehicles that occupy resources for a long time, force resource release, and redistribute RB every 5 seconds to avoid "resource monopoly". Meanwhile, game theory algorithms significantly reduce interference by optimizing frequency domain allocation. For example, in a scenario of 25 vehicles, the total interference is 0.12 W, which is 40% lower than traditional methods.

6. Conclusion

This study proposes a dynamic channel allocation algorithm for intersection scenarios based on game theory, and verifies it through joint simulation with Prescan MATLAB. The simulation results show that compared with traditional static allocation methods, the dynamic channel allocation method based on game theory has significant improvements. This algorithm performs well in throughput, fairness, and interference control, with the Shannon fairness index of the dynamic channel allocation algorithm consistently exceeding 0.78 in this simulation. And as the vehicle throughput increases, the signal transmission delay and total signal interference data of the dynamic channel allocation algorithm are also superior to traditional static allocation methods. To some extent, this research alleviates the problem of channel resource utilization of current urban auto drive system in busy times, and is expected to provide a feasible optimization scheme for intelligent vehicle communication system.

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