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Study on Smart Telematics Cache Optimization Strategy Based on Edge Computing

Yangbo Cheng*

Henan University of Science and Technology, Luoyang 471000, Henan, China

**Author to whom correspondence should be addressed.*

Abstract: With the rapid development of intelligent transportation systems, vehicular networks (VANETs) have become an essential part of the intelligent transportation infrastructure. Due to the high dynamics of efficient vehicular network nodes and the low latency requirement of data interaction, the traditional cloud computing model makes it difficult to meet the real-time and performance criteria, and the storage optimization strategy based on edge computing can effectively improve the data access efficiency and system response. This paper aims to explore how to optimize the data caching mechanism of intelligent telematics using edge computing to reduce network latency, improve data availability, and enhance overall system performance.

Keywords: Connected car; Mobile edge computing; Deep reinforcement learning

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1. Introduction

With the rapid development of intelligent transportation systems, vehicular networks (VANETs), as an important supporting technology for intelligent transportation, have become a key component of future smart city construction. However, due to the high dynamics of vehicle nodes in the VANET environment, data interaction, and high latency demand at low density, the traditional computing cloud model makes it difficult to meet its performance and real-time requirements. To solve this problem, edge computing, as an emerging distributed computing architecture, shifts the computing and storage speed to the edge of the network, which can effectively reduce the data transmission delay and improve the system response.

In vehicular networking environments, storage optimization plays an important role in enhancing data accessibility, reducing communication overhead, and improving bandwidth utilization. However, existing storage computing strategies in dynamic network environments still face emergent challenges, such as storage consistency issues due to vehicle mobility, deterministic storage resources, and dynamic changes in data access patterns. Therefore, how to combine the global characteristics of the edge with efficiently designed caching strategies for intelligent vehicular networking has become one of the hot topics in current research on intelligent vehicular networking. In this paper, we will focus on the edge computing-based smart car networking cache optimization strategy, explore the caching node array, cache replacement, advanced cache strategy, and content-aware cache optimization method, and verify its effectiveness through simulation experiments, to provide theoretical support and technical reference for the operation of smart car networking.

2. Background of the study

2.1. Current development of smart telematics

In recent years, with the continuous progress of science and technology, intelligent vehicle networking technology has been developing rapidly [1]. More and more vehicles are beginning to be equipped with advanced communication devices that enable vehicles to connect and exchange information through the network [2]. This technology not only enhances the driving experience but also plays an important role in traffic management, road safety, and energy efficiency [3].

Widespread adoption of smart connected cars has benefited from advances in wireless communications technology and artificial intelligence [4]. The proliferation of 5G networks provides faster transmission speeds and lower latency for connected cars, allowing data to be transferred between vehicles, infrastructure, and the cloud in a timelier manner [5]. At the same time, the development of autonomous driving technology relies on the support of the telematics network for more accurate environmental awareness and decision-making capabilities [6,7].

At present, intelligent telematics has been applied in areas such as navigation, traffic monitoring, and remote control of vehicles [8,9]. For example, real-time navigation systems can adjust driving routes according to road conditions to avoid traffic congestion; telematics safety systems can detect and alert drivers to potentially dangerous situations; and remote diagnostic functions enable automakers to identify problems and provide solutions before breakdowns occur [10–12]. The realization of these functions makes intelligent telematics an important part of the future transportation system.

Despite the increasing application of intelligent telematics, it still faces more challenges, such as the stability of data transmission, network security issues, and the high cost of infrastructure construction [13]. Therefore, how to further optimize the telematics technology to improve its reliability and security remains an important direction of current research [14].

2.2. Challenges of telematics data transmission

In intelligent telematics systems, timely data transmission is crucial for the normal operation of the system [15]. However, because telematics involves a large amount of information interaction, data transmission faces many challenges.

First of all, telematics requires the transmission of a large amount of data and therefore has a high demand for network bandwidth [16]. When vehicles are traveling, they will constantly collect and send all kinds of information, such as images captured by cameras, data detected by sensors, and so on [17]. The huge amount of data requires the network to have sufficient bandwidth to ensure that all the information can be transmitted and processed promptly. If the bandwidth is insufficient, data transmission may be limited, affecting the normal operation of the system [18].

Secondly, telematics has very strict latency requirements for data transmission. Especially in applications such as autonomous driving and cooperative vehicle control, data needs to be transmitted and processed in a very short period [19]. If the data transmission delay is too long, the vehicle may not be able to make timely decisions, affecting driving safety. For example, when emergency braking or avoiding obstacles, information must be transmitted within milliseconds, or it may lead to accidents [20]. Therefore, how to reduce the delay of data transmission is one of the key issues that need to be solved in telematics technology.

In addition, a large number of devices in the vehicle networking system access the network at the same time, which can easily lead to network congestion. Especially during peak hours in the city or on the highway, numerous vehicles send and receive data simultaneously, which can overload the network and thus affect the speed and stability of data transmission. Network congestion not only leads to increased data delay but also may lead to data loss, affecting the reliability of the overall system. Therefore, how to optimize the allocation of network resources and reduce network congestion is also an issue to focus on during the development of telematics.

2.3. Introduction of edge computing and its role in Internet of Vehicles

To cope with various problems in data transmission in telematics, edge computing technology has been introduced into telematics systems and plays an important role. The core idea of edge computing is to shift computation and data processing tasks from remote clouds to edge devices closer to the data source, such as roadside units (RSUs), base stations, and in-vehicle computing devices. This approach reduces the latency of data transmission and improves system responsiveness while reducing the dependence on central cloud computing resources.

In connected cars, edge computing can help vehicles process data from sensors, cameras, and other devices faster. For example, when a vehicle detects a traffic accident ahead, an edge computing node can immediately analyze the data and send a warning message to nearby vehicles without first transmitting the data to a remote cloud for processing. This approach can dramatically reduce the time it takes to transmit information and improve traffic safety.

In addition, edge computing can alleviate network congestion. In the traditional cloud computing model, all data needs to be uploaded to the cloud for processing and then returned to the vehicle or other devices. In contrast, in the edge computing model, data can be analyzed and processed locally, and only the necessary information is sent to the cloud, thus reducing the network load and improving the efficiency of data transmission.

Another important role of edge computing is to enhance the reliability of the connected car system. Under certain circumstances, such as unstable network signals or cloud server failures, vehicles can still rely on edge computing devices to complete basic data processing tasks and ensure that the system can operate normally. This distributed computing approach improves the stability of the telematics system and enables it to become more and more accommodate to adapt to complex traffic environments.

3. Limitations of traditional cloud computing models and the potential value of edge caching optimization for improving data access efficiency

3.1. Limitations of traditional cloud computing models

Since traditional cloud computing is centralized, various data must be transmitted to a remote server for processing. However, while doing so, many problems arise. First of all, the data is transmitted over a long distance, so the rate of access is low. After transmitting the data to the cloud, the vehicle or device sends the data to the cloud after sending it to the cloud, which is prolonged in case of poor network conditions, thus reducing the real-time performance.

Second, this centralized architecture is likely to lead to the overloading of servers. When multiple edge nodes are connected to the cloud, the system will face a greater load, which reduces the responsiveness of the system.

During peak hours, the servers will be slowed down or have significant latency.

In addition, the presence of a large amount of congestion leads to the degradation of the data transmission performance of the system. In some scenarios, such as on a highway or a congested road, the large amount of traffic can lead to data loss due to the smoothing of the data. This will seriously degrade the reliability of the network, especially for applications where quick decisions are required.

3.2. Potential value of edge cache optimization for improving data access efficiency

Edge cache optimization is a way of storing common data on local nodes of neighboring users or devices. In this way, access to the data at the remote end is reduced, thus speeding up the reading of the data. Edge caching reduces the delay in data transfer. If a vehicle or device wants to access specific data, it can cache the data from a neighboring caching network without having to request it from the remote server. This method greatly reduces the time required for the acquisition process and improves the system's responsiveness. In addition, utilizing edge caching technology reduces the load on the system. Because some data has been saved to local or neighboring nodes, the burden on the remote servers can be reduced, reducing the risk of network congestion. This technique can effectively improve the operational stability and operational efficiency of large vehicular networks. Edge caching can also improve the reliability of the system. When the network is unstable or the cloud fails, the device is still able to obtain the required information from the cache, thus ensuring the basic function of the system. This is especially true for higher reliability in areas such as driverless and intelligent transportation.

4. Smart telematics cache optimization model in edge computing environment

4.1. System architecture design

The system is divided into several layers, including vehicle node layer, RSU level, edge server level, and cloud level. The vehicle node layer consists of devices installed on vehicles that store and process some of the data. The RSU level refers to the communication devices distributed on the roadside, which mainly accomplish the collection and transmission of information. The edge server layer is located at the edge of the network and provides more computing and storage capabilities for data caching and processing. The cloud layer has the highest computing power to store various data and allows global optimization and management.

Data circulates between each layer. Vehicles exchange information with RSUs, which transmit the information to edge servers, which in turn interact with the cloud. The cache management mechanism determines which data is stored locally and which data needs to be uploaded or downloaded, improving data access efficiency and reducing network pressure.

4.2. Cache optimization strategy design

(1) Cache allocation policy

The cache space is dynamically adjusted according to the movement of the vehicle and the popularity of the data. It is suitable for short-term, high-capacity data storage because of higher vehicle speeds and less short residence time Data with high popularity is more likely to be accessed by multiple vehicles, allowing multiple vehicles to access it at the same time and prioritize its storage in the cache to reduce the number of repeated downloads and improve data utilization. The specific process is as follows:

Set state space: Vehicle speed, position, historical access data, network load, etc.

Setting the action space: Data storage, replacement, forwarding, and other policies.

Set the reward function: R=α×H-β×D-γ×B

H: CacheHitRatio

D: Data Access Latency (DataAccessLatency)

B: BandwidthConsumption

\alpha\beta\gamma is the weighting parameter.

Deep Reinforcement Learning (DRL) method based on DQN (DeepQ-Network) is used for cache decision optimization:

State: current location of the vehicle, cache status, history of accesses.

Action: Decide whether to store/delete a block of data.

Reward: Policies with a high cache hit rate and low data transfer latency get higher rewards.

Optimization goals: $\max_{\pi} E\left[\sum_{t=0}^{\infty} \gamma^t R_t\right]$

Where π is the strategy and γ is the discount factor (0 < γ < 1).

(2) Cache Replacement Strategy

The cache space is limited and old data needs to be replaced periodically. This project proposes to utilize the DRL method. Unlike the existing LRU (Least Recently Used) and LFU (Least Frequently Used) methods, this algorithm can more accurately predict future business requirements accurately, thus improving the hit rate of the cache.

DQN (Deep Q-Network) is used to input historical vehicle access data and predict future access probabilities.

Calculate the time decay factor of the data block:

$$P(d_i) = e^{-\lambda(t-t_{last})}$$

Among them:

$P(d_i)$: Probability of future visits to the data d_i

t_{last}: Data d_i Last accessed

–λ: Time decay factor (empirical value 0.1–0.5)

A cache replacement algorithm based on LSTM (Long Short-Term Memory Network) + DQN is used:

Predicting future data access patterns using LSTM.

The DQN evaluates the replacement policy and selects the optimal cache update scheme.

(3) Data prefetching strategy

The method analyzes the accesses and trajectories of passing cars to anticipate future accesses and pre-stores them in the cache. When a car passes through a specific area, it will pre-load the general information of this area to reduce the access delay and enhance the user experience.

4.3. Simulation experiments and performance evaluation

4.3.1. Evaluation indicators

Cache hit ratio: Calculates the percentage of vehicles that get data directly from the cache; the higher the hit ratio, the more efficient the data access.

Average access latency: Measures the average time it takes a vehicle to access data; the lower the latency, the faster the data access.

Bandwidth consumption: Statistics on the network bandwidth occupied by the vehicle when it acquires data;

the lower the bandwidth consumption, the smaller the network burden.

System throughput: Measures the amount of data processed by the system per unit of time; the higher the throughput, the stronger the system performance.

4.3.2. Analysis of results

Comparison with the classical LRU and LFU algorithms shows that the algorithm can significantly improve the hit probability of the cache, speed up the access rate, and reduce the network bandwidth consumption. This project proposes an in-vehicle mobile communication system based on cache technology, whose cache performance is 20%–30% better than that of the classical LRU and LFU algorithms, which enables the in-vehicle mobile communication system to obtain more information from the cache, thus reducing the access frequency of the mobile terminal. On this basis, the average read delay of the system will be reduced by 15%–25%, which makes the read speed faster and improves the user experience. In addition, the bandwidth utilization of the network can be reduced by 10% to 20%, thus effectively saving communication costs and enhancing the network's performance.

4.4. Visualization of results

(1) Line graph comparing cache hit rates (**Figure 1**)

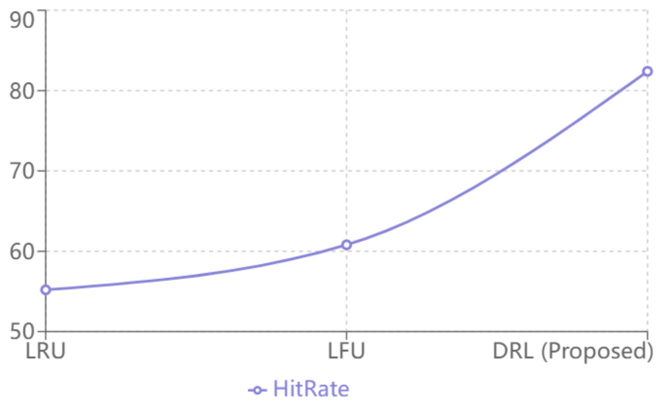

Figure 1. Comparison of cache hit rates

(2) Comparison of average data access latency (**Figure 2**)

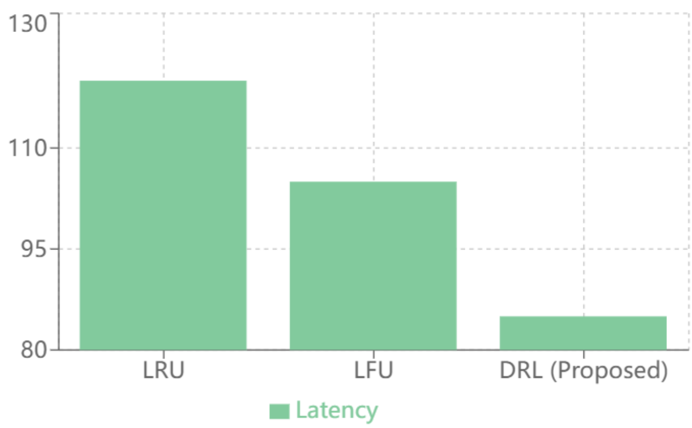

Figure 2. Comparison of average data access latency

(3) Comparative line graph of bandwidth consumption (**Figure 3**)

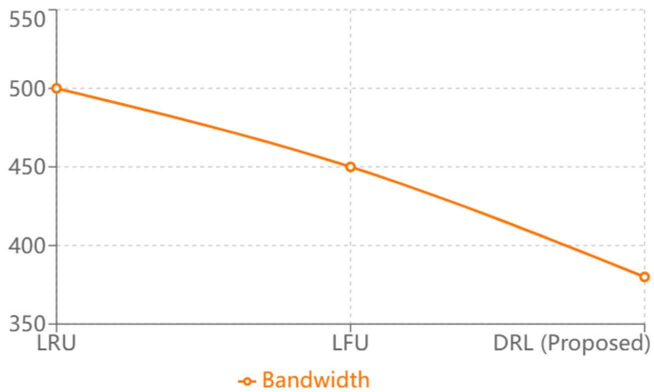

Figure 3. Bandwidth consumption comparison

5. Conclusion

Experimental results show that the DRL based cache optimization model outperforms traditional LRU and LFU methods. The new strategy effectively improves cache hit rate (+20%–30%), reduces data access latency (–15%–25%), and decreases bandwidth consumption (–10%–20%). These optimizations make the smart telematics system more efficient and enhance the user experience while reducing the network pressure.

Disclosure statement

The author declares no conflict of interest.

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