Hybrid Caching Transmission Scheme for Delay-sensitive Service in Vehicular Networks

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Abstract. With the inspiring development of vehicular networks, caching popular contents in the network edge nodes could greatly enhance the quality of user experience. However, the highly dynamic movements of vehicles make it difficult to maintain stable wireless transmission links between vehicle-to-vehicle pairs or vehicle-to-road side units (RSUs) pairs, and then resulting in unbearable transmission delays or even transmission interruptions. In this paper, we proposed a predictive and hybrid caching transmission scheme for delay-sensitive services in vehicular networks. In order to select the most proper node for transmitting desired content from the nearby RSUs or vehicles, we evaluate the candidate nodes from the prediction on effective communication range and connection time based on the relative velocities and SINR threshold. Then the end-to-end delay for respective nodes is compared which includes two parts: waiting period and transmitting period. Waiting period is predicted based on the relative distance and relative velocities between two nodes at the starting position. Transmitting period is calculated from the transmission rate and effective communication range. The candidate node with the lowest delay is selected to transmit the desired content to the destination vehicle. Simulation results show that the proposed scheme could significantly reduce time delays in data transmission, especially when the requesting vehicle is far from the nearest RSU.

Keywords: Vehicular networks · Cached data distribution · Transmission delay

1 Introduction

The development of intelligent transportation systems (ITSs) has attracted increasing attention to the communication in vehicular networks. As more and more data needs to be exchanged within moving vehicles in various scenarios, the throughput and delay requirements have also been enhanced for users quality of

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services (QoSs). Then caching technology is introduced into vehicular networks to provide higher local throughput and lower end-to-end transmission delay. It has the potential to reduce vehicle data access times, improve the utilization of vehicular storage space, and reduce network bandwidth consumption [2,3]. There are still several open issues in the cached-based vehicular networks. How to provide efficient transmission for the delay-sensitive services for moving vehicles is an interesting and important problem that has attracted many researchers' attention.

Most of the existing research focus on pre-caching, data replacement, multi-hop relay and throughput maximization. But there is a practical constraint that has been ignored, which is the short connection time between the source and destination due to the mobility of vehicles. The connection time may be shorter than the time required to transmit the content, thus resulting in connection break. Even if there is no connection break, the time delay may be unbearable. In V2I communication, although a vehicle is within the communication range of a road side unit (RSU), the distance could be too long to establish a stable link. Thus the transmission rate or delay may be degraded or even cause user frustration and network congestion. In this paper, we investigate the problem of how to reduce data transmission delays in hybrid V2V and V2I scenarios by mobility prediction. We focus on the following issue: during V2I communication, a large distance between the vehicle and the nearest RSU could result in long delay in data transmission. In addition, if the connection time is not enough for content transmitting, there may be connection break.

Valuable research has already been conducted on the direction of where and how to efficiently cache content. Most of these have focused on where to cache, how to cache and cache replacement. For example, Ding et al. [4] proposed three algorithms to allocate files to RSUs to minimize the average transmission time delay. Ma et al. [5] proposed a caching placement policy which jointly considered caching at the vehicular and RSUs. The caching placement problem is modeled as an optimization problem to minimize the average latency while satisfying the QoE requirements of vehicles. Wei et al. [6] proposed a layered cooperative cache management to select neighbor nodes within broadcast range to cache proper contents to reduce retrieval time and prevent stalls of the video playback. Alotaibi et al. [7] proposed the Area Defer Transmission dissemination algorithm to enable each vehicle to independently decide whether to transmit considering heterogeneous transmission ranges and the amount of area that would be covered by potential new transmission. Deng et al. [8] proposed a Prior-Response-Incentive-Mechanism to stimulate vehicles to take part in cooperative downloading in VANETs-LTE heterogeneous networks.

In this paper, we propose a novel scheme to reduce transmission delays in hybrid V2I and V2V communications by evaluating the ability of the candidate nodes for maintaining a stable wireless link, based on the relative velocities and SINR threshold. Then we predict the waiting period and transmitting period of each nodes, using the relative distance and relative velocities between two nodes at the starting position, and the transmission rate and effective communication range. The waiting period together with the transmitting period composes the transmission delays. Finally we select the node which has the lowest delays to transmit the content. Simulation results show that the proposed hybrid caching transmission scheme achieves good performance.

The rest of this paper is organized as follows, In Sect. 2, we provide the system model we use. In Sect. 3, we present the proposed scheme. In Sect. 4, The Simulation scenarios and results are presented. The conclusions are stated in Sect. 5.

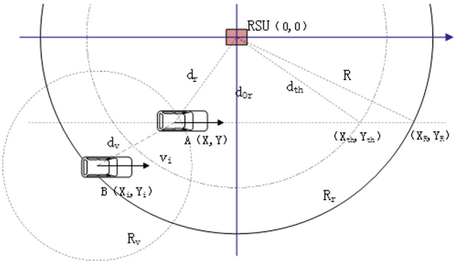

Fig. 1. Relative positions and distance between nodes

2 System Model

2.1 Vehicle Mobility Model

The communication scenario we consider in this paper is shown in Fig. 1. We focused on a one-way street which has road side units (RSUs) deployed in an urban setting. The traffic is assumed to flow freely, and the vehicle arrival process follows a Poisson distribution [9]. We further assumed no congestion, that arrival processes are independent and that the vehicle speed follows uniform distribution [10].

For V2I communication scenario let $(0, 0)$ be the location of the RSU, let (x, y) be the location of vehicle A which sends a request for specific content, and let (x_i, y_i) be the location of vehicle B which has the requested content cached and is within communication range of A. Where the communication range of the RSU is R_r then the point (x_r, y_r),where vehicle A would lose connection with RSU can be calculated as:

$$(x_r, y_r) = (\sqrt{R^2 - y^2}, y) \tag{1}$$

For V2V communication scenario, where the communication range of a vehicle is R_v, consider the relative motion between A and B, then let the relative velocity of B to A be $v_B = v_i - v$, and relative location be $(x_B, y_B) = (x_i - x, y_i - y)$. Here we only consider the horizontal distance of A and B, because the two vehicles are assumed to be moving on the same road. The minimum distance of two vehicle is set at 1 meter.

Assuming that the velocity of a vehicle stays the same during the data distribution process, then the horizontal location of a vehicle also follows uniform distribution. The probability distribution is given by:

$$y = \begin{cases} 1/(x_{t+\varDelta t} - x_t), & \varDelta t \geq 0 \\ 0, \quad \varDelta t < 0 \end{cases} \tag{2}$$

2.2 Communication Channel Model

We considered both V2V and V2I communications over Rayleigh fading channel. Let $\varUpsilon_{u,v}$ denote the SINR at node v when node u transmits data, let N_0, B, P_t, $I_{u,v}$ $d_{u,v}$, α denote the power spectral density of additive Gaussian white noise, the channel bandwidth, the transmit power of node u, the inter-cell interference, the distance between node u and node v, and the path loss exponent. Then the SINR is given by:

$$\varUpsilon_{u,v} = \frac{P_t \cdot d_{u,v}^{-\alpha}}{N_0 \cdot B + I_{u,v}} \tag{3}$$

3 Proposed Scheme

3.1 Overview of the Scheme

Data transmission rates are inversely proportional to the distance between RSUs and vehicles, meaning that vehicles far from the RSU may suffer longer delays when transmitting content. As the relative velocity between two vehicles moving in the same direction on the same road is relatively low, any two such vehicles are likely to stay close to each other over a short period of time. The data transmission rate in this case is therefore relatively high, and the vehicles are able to establish a connection which is able to transmit data with a short time delay. In the proposed scheme, when vehicle A requests content, it could get the content from either the RSU or from another nearby vehicle B, which has the requested content cached. We first determine if a candidate node is capable of successfully transmitting the content based on the relative velocities and SINR threshold. Then predict the time delays using the relative distance and relative velocities between two nodes at the starting position and the transmission rate and effective communication range. Finally, we compared the time delays in each case, allowing for a selection of the node that has lower delay as the transmission node.

3.2 Effective Connection Time

To ensure successful transmission, a receiver would only begin to receive data when the SINR is greater than a specific threshold $\varPsi$ [10]. Using Eq. 3, the maximum distance between two nodes for maintaining a link is given by:

$$d_{th} = \sqrt[\alpha]{\frac{P_t}{\varPsi \cdot N_0 \cdot B + I_{u,v}}} \tag{4}$$

Then the range of horizontal location for A to successfully receive content from RSU is $[-x_{th}, x_{th}]$, where $x_{th} = \sqrt{d_{th}^2 - y^2}$. And the range of relative distance between A and B to successfully transfer content is $[-d_{th}, d_{th}]$.

For V2I communication, the maximum effective connection time T_r depends on the location (x, y) of A when it sends the request for content. Let this location also be the observation start point. We distinguished between communication range (where communication between vehicle and RSU is possible, but where the SINR may be not big enough to ensure a stable link) and effective communication range (where communication between vehicle A and RSU is possible over a stable connection). Therefore, when the location of A is within communication range $[-x_r, x_r]$ of the RSU but out of the effective communication range$[-x_{th}, x_{th}]$, as soon as A moves into $[-x_{th}, x_{th}]$, it is able to form an effective connection with the RSU. When A is within the range $[-x_{th}, x_{th}]$, the connection is established immediately and will be maintained to the point x_{th}. Then T_r is given by:

$$T_r = \begin{cases} \frac{x_{th}-x}{v}, & -x_{th} \leq x \leq x_{th} \\ \frac{2x_{th}}{v}, & -x_{th} \leq -x_r \leq -x_{th} \\ 0, & otherwise \end{cases} \tag{5}$$

For V2V communication, the maximum effective connection time T_v depends on both the relative distance d_{0v} and velocity of B to A. The relative velocity of B to A is positive when B is moving faster than A, hence the relative distance threshold should also be positive. Similarly, when B moves slower than A, the relative distance threshold should be negative. Therefore T_v is given by:

$$T_v = \begin{cases} \frac{-d_{th}-d_0v}{v_B-v_A}, & v_B - v_A < 0 \\ \frac{d_{th}-d_0v}{v_B-v_A}, & v_B - v_A \geq 0 \end{cases} \tag{6}$$

Let R_b be the minimum data transmission rate, and assume it equals channel bandwidth [11]. Let q be the size of requested content. Then the maximum time delay T_m that A requires in order to receive the content is given by:

$$T_m = \frac{q}{R_b} \tag{7}$$

3.3 Transmission Delays Prediction

In order to calculate the data transmission rate, we first need to know the transmission location range according to the starting location (x, y) of A, velocity v and the maximum time delay R_b. In V2I scenario, the transmission location range is given by:

$$[x, x_w] = [x, x + v \cdot T_m] \tag{8}$$

In the V2V scenario, using the relative starting distance d_{0v} between B and A, the relative velocity of B to A, and the maximum time delay T_m ,the relative transmission distance range is given by:

$$[d_{0v}, d_w] = [d_{0v}, d_{0v} + (v_B - v) \cdot T_m] \tag{9}$$

According to Shannon's capacity formula, the maximum transmission rate equals the instantaneous capacity of the channel. Let $R_{u,v}$ be the transmission rate from node u to node v:

$$R_{u,v} = B \cdot \log_2 (1 + \Upsilon_{u,v}) \tag{10}$$

Where B is the bandwidth of the channel and $\Upsilon_{u,v}$ is the SINR. By combining Eqs. 3 and 10, the transmission rate is denoted by:

$$R_{u,v} = B \cdot \log_2 (1 + \frac{P_t \cdot d_{u,v}^{-\alpha}}{N_0 \cdot B + I_{u,v}}) \tag{11}$$

Let R_{avg} denote the average transmission rate, we have:

$$\begin{aligned} &R_{avg} = E[R_{u,v}] = \\ &\int_{d_0}^{d} f(d) \cdot B \cdot \log_2 (1 + \frac{P_t \cdot d^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd \end{aligned} \tag{12}$$

Where $f(d)$ is the probability distribution of the distance between two nodes. According to Eqs. 8 and 9, the average transmission rate from RSU to A is:

$$R_{avg} = \begin{cases} \frac{\int_0^{|x|} B \cdot \log_2 (1 + \frac{P_t \cdot (\sqrt{y^2+d^2})^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd}{x_w - x} + \\ \frac{\int_0^{|x_w|} B \cdot \log_2 (1 + \frac{P_t \cdot (\sqrt{y^2+d^2})^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd}{x_w - x} \\ , \quad x \cdot x_w < 0 \\ \frac{\int_{min(|x|,|x_w|)}^{max(|x|,|x_w|)} B \cdot \log_2 (1 + \frac{P_t \cdot (\sqrt{y^2+d^2})^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd}{x_w - x} \\ , \quad x \cdot x_w \geq 0 \end{cases} \tag{13}$$

And the average transmission rate from B to A is given by:

$$R_{avg} = \begin{cases} \frac{\int_1^{|d_w|} B \cdot \log_2 (1 + \frac{P_t \cdot d^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd}{|d_w - d_{0v}|} + \\ \frac{\int_1^{|d_{0v}|} B \cdot \log_2 (1 + \frac{P_t \cdot d^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd}{|d_w - d_{0v}|} \\ , \quad d_w \cdot d_{0v} < 0 \\ \frac{\int_{min(|d_{0v}|,|d_w|)}^{max(|d_{0v}|,|d_w|)} B \cdot \log_2 (1 + \frac{P_t \cdot d^{-\alpha}}{N_0 \cdot B + I_{u,v}})\, dd}{|d_w - d_{0v}|} \\ , \quad d_w \cdot d_{0v} \geq 0 \end{cases} \tag{14}$$

Let Q be the size of requested content, and let D_r, D_v be the average time delay incurred when A receives content from RSU and from B. When the starting location of A is out of the effective communication range $[-x_{th}, x_{th}]$, A must wait until it gets into this range. This waiting time is denoted as:

$$T_w = \frac{-x_{th} - x}{v} \tag{15}$$

Then D_r, D_v are given by:

$$D_r = \begin{cases} \frac{Q}{R_{avg}}, & -x_{th} \leq x \leq x_{th} \\ T_w + \frac{Q}{R_{avg}}, & -x_{th} \leq -x_r \leq -x_{th} \end{cases} \tag{16}$$

$$D_v = \frac{Q}{R_{avg}} \tag{17}$$

3.4 Node Selection Algorithm

The algorithm to select the transmission node with the lowest time delay follows the following steps:

Step1: give both RSU and vehicle B flags which start as zero. Calculate the distance threshold between A and RSU and between A and B. Get the achievable effective connection time by comparing the distance threshold to the maximum time delay needed to receive content q. If achievable effective connection time between A and node U is larger than maximum time delay, the value of U's flag becomes 1.

Step 2: node U is capable of content transmission only if node U's flag is 1. If the flag of a node is zero, set the time delay as infinite. Calculate the transmission rates from RSU and B according to the predicted distances, then calculate the time delays for both the RSU and B according to the predicted location of A.

Step 3: compare the transmission time delays for transmission from RSU and B, and choose the node which has shortest delay to be the transmitter for content q.

4 Simulation Results and Discussions

In this section, we present the simulation results of the proposed scheme. The simulation setup and detailed experimental results are as follows:

4.1 Simulation Setup

We conducted the simulation using MATLAB. The simulation parameters are shown in Table 1. In order to analyse the performance of our scheme, we set the location range of vehicle A as $[-x_r, x_r]$, and the velocity of each vehicle randomly between 10m/s and 20m/s. Our model assumed traffic was going in one direction, as vehicles moving at two opposite direction would have lower connection times. We simulated connection time, average transmission rate, average transmission delay and reduction in transmission delay to examine the effectiveness of our scheme and how it performs under different levels of transmission power.

4.2 Simulation Results

Average Transmission Delay Figure 2 shows the average delay incurred when vehicle A receives content q from: (1) only the RSU; (2) only a vehicle nearby. The time delay incurred when content is received from the RSU is related to the location of A. When A is far from RSU (outside of the effective communication range), the time delay is relatively high. As A moves closer to RSU, the time delay decreases. By contrast, the average time delay incurred when A receives content from another vehicle is stable over the observation area. Our results show that after adopting our scheme, when A is far from the RSU it receives content from a nearby vehicle, and when it is close to the RSU it receives content from the RSU. This ensures that the time delay is minimized throughout the observation area.

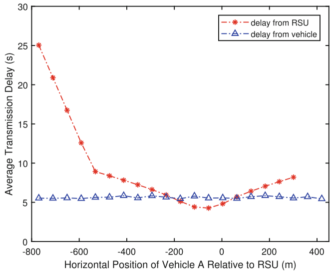

Fig. 2. Delay of a getting content from RSU and from vehicles on different position

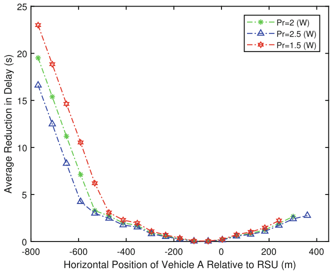

Fig. 3. Relationship between vehicle position, average delay reduction and RSU transmission power

Average Reduction in Transmission Delay Figure 3 shows the average reduction in transmission delay. When A is outside of effective communication range of the RSU, there are relatively long delays in receiving content from the RSU. As A moves closer to the RSU and into effective communication range, the average transmission delay falls due to increases in the transmission rate between A and RSU. This indicates that the greatest reductions in transmission delay from adoption of our scheme are likely to occur when vehicle A is outside the effective communication range. These results also indicate that when the RSU is using lower levels of transmission power, adoption of our scheme could result in greater reductions in transmission delay.

Average Transmission Rate Figure 4 shows the average transmission rate in both V2V communication and V2I communication. In V2V communication, the random nature of inter-vehicle distance implies that the average transmission rate is mainly a function of the transmission power of the vehicles involved. In our experiment, as vehicle A and vehicle B are assumed to have the same

Table 1. Simulation parameters

Parameter	Value
RSU coverage range R_r(m)	800
Communication range of vehicle R_v (m)	250
RSU transmission power P_r (W)	2
Vehicle transmission power P_v (mw)	100
Vehicle speed v (m/s)	[10, 20]
Channel bandwidth B_w (MHz)	10
Path loss exponent α	3
Packet length Q (mB)	100
SNR threshold Ψ	400
Inter-Cell Interference (dBm)	–75
Addictive Gaussian Noise (dBm)	–105

level of transmission power, the transmission rate fluctuates around $1.5 * 10^8 b/s$. In V2I communication, the fixed transmission power of the RSU implies that the average transmission rate depends on the distance between A and RSU. As shown in Fig. 4, the transmission rate is highest when A is at the nearest point to the RSU, and as A gets farther away from RSU the transmission rate falls.

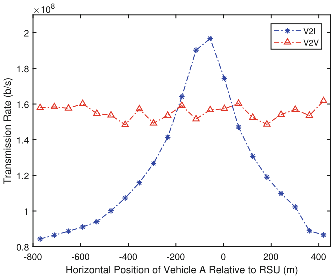

Fig. 4. Transmission rate in V2V and V2I communications on different position

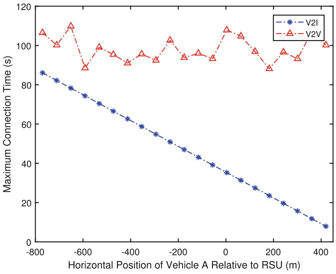

Fig. 5. Maximum effective connection time in V2V and V2I communications on different position

Maximum Connection Time Figure 5 shows the average transmission rate in both V2V communication and V2I communication. In V2V communication, the relative velocity between vehicles on the same road over a short period of time can be assumed not to change substantially, with the result that the distance between the two vehicles also remains relatively stable. The maximum connection time therefore fluctuates around 90s. In V2I communication, the maximum connection time between RSU and A depends on two factors: first, it depends on the distance from A to the point x_{th} where A loses contact with RSU. Second, it depends on the velocity of A. As the velocity of A is assumed to remain the same over the observation period, as A gets closer to x_{th} the maximum connection time falls.

5 Conclusion

In this paper, we proposed a predictive and hybrid caching transmission scheme to reduce time delays in transmitting content within vehicular networks. The scheme first decides the reliability of the connections between the requesting vehicle and an RSU and between the requesting vehicle and any vehicle nearby which has the requested content cached. Then compares the predicted time delay needed to receive the content from the RSU and the nearby vehicle. Finally, this information is used to choose the node which has the shortest time delay to be the transmitter. Simulation results show that our scheme could substantially reduce data transmission time delays.

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