# Low-Latency Transmission and Caching of High Definition Map at a Crossroad

Yue Gu(✉), Jie Liu, and Long Zhao

Wireless Signal Processing and Network (WSPN) Lab, Key Laboratory of Universal Wireless Communication, Ministry of Education, Beijing University of Posts and Telecommunications (BUPT), Beijing 100876, China
guyue0929@bupt.edu.cn

**Abstract.** High definition (HD) map attracts more and more attention of researchers and map operators in recent years and has become an indispensable part for autonomous or assistant driving. Different from existing navigation map, HD map has the features of high precision, large-volume data and real-time update. Therefore, the real-time HD map transmission to the vehicles becomes one main challenge in vehicular networks. This paper considers the scenario that a RSU at the crossroad caches and transmits HD maps to its covered vehicles in four directions. To reduce the average delay of HD map delivery, the transmission power allocation for vehicles and the cache allocation for HD maps of different road segments are optimized by leveraging the traffic density and vehicle positions. Simulation results indicate that the proposed scheme has lower latency than that of equal power allocation scheme based on real traffic data.

**Keywords:** Vehicle networks · High definition map · Cache · Delay

## 1 Introduction

High definition (HD) maps are lane-level maps within 10 cm precision and real-time updated maps. Usually, HD map can be divided into three layers, including static layer, dynamic layer and analysis layer [1]. Ordinary navigation map is about 1 kb per kilometer, while HD map data is much larger than that of the ordinary navigation map. Levinson and Thrun employed data compression technology to store 20,000 miles map data in 200 GB of memory, which is equivalent to 6 MB per kilometer [2]. Momenta claimed that they used a monocular camera to generate HD semantic maps, which could be compressed to 10 kb/km. TomTom's HD map named road DNA is founded with 25 kb/km in average [3]. In conclusion, the HD map has larger data per kilometer than the normal maps and needs to be updated in real time [4], therefore the on-board unit is not suitable for pre-caching the entire city map for driving. How to transmit HD maps to vehicles in a mobile environment timely and effectively becomes a challenge for automatic driving.

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In vehicular networks, V2I communications are helpful to take proactive management in order to avoid traffic jam or transmit entertainment contents [5]. Some schemes have been studied in the literature. An intelligent traffic management system based on V2I communications is proposed aiming to coordinate traffic in a limited urban area, including different driving scenarios [6, 7]. In [8], RSU transmits cycle information of traffic light to coming vehicles, then the vehicles can collaboratively optimize their speeds and other appropriate actions in order to pass crossroad within a shortest time. Caching based infrastructure is another research point, it usually focuses on minimizing the delay or resolving contents caching scheme with limited memory. Considering both RSU caches and vehicle caches in a single-directional highway scenario, the minimum latency has been studied in [9]. In vehicular content centric networks, based on the prediction results of mobile nodes' probability of reaching different hot areas according to their past trajectories, vehicles can be chosen as caching nodes which stay more time in a hot area and provide more services [10]. Considering the trajectory and dwell time of vehicles passing several RSUs on a single-directional road, the contents caching problem at the RSU has been studied based on aggregate statistics about the distribution of the dwell time under each cache nodes [11]. Moreover, the DDPG, a method of deep reinforcement learning, is also employed to find the proactive caching strategy of RSU on the road [12]. However, the features of transmission contents and the mobility of vehicles are less utilized in the aforementioned researches. This paper considers the requirement features of HD map and the mobility of vehicles in order to further reduce the latency of HD map transmission.

In this paper, we consider a scenario of vehicular networks at a crossroad. Located in the center of the crossroad, the RSU is in charge of caching and transmitting map sections of surrounding roads to the covered vehicles. The goal of this paper is to minimize the average delay of HD map delivery to the vehicles, where both the transmission delays and backhaul delays are primarily considered. Based on the mobility features of vehicles and requirement features of HD map, a transmission power allocation scheme and a caching allocation scheme are proposed, which can effectively reduce the transmission delay and the backhaul delay, respectively.

The rest of this paper is organized as follows. Section 2 introduces the system model and formulates the considered problem. The formulated problem is solved in Sect. 3, where the optimal power allocation and cache allocation schemes are proposed. Section 4 gives the simulation results and analysis. Section 5 concludes this paper in the end.

## 2 System Model and Problem Formulation

### 2.1 System Model

As shown in Fig. 1, we consider a scenario of vehicular networks, where the RSU with the storage capacity $C$ and $M$ antennas at the crossroad caches the HD maps of four directions and transmits them to $K$ single-antenna vehicles within its coverage. The available system bandwidth is $B$, the coverage radius is $L$ and the vehicles are uniformly distributed on the covered road segments.

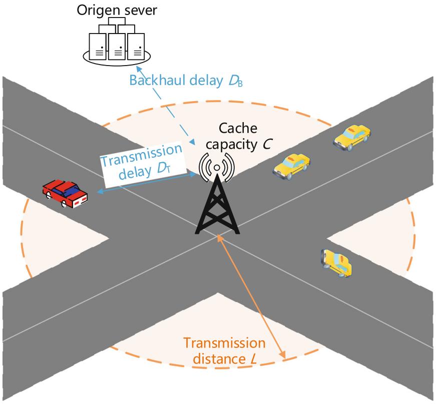

**Fig. 1.** HD map transmission scenario at the crossroad.

### Channel Model

The channel vector from the RSU to the $k$th vehicle can be obtained by the uplink pilot transmission and channel estimation, which can be expressed as

$$\mathbf{g}_k^{\mathrm{H}} = [g_{k1}, g_{k2}, \ldots, g_{kM}], \tag{1}$$

where $g_{ki} = \sqrt{\phi \xi_k d_k^{-\alpha}} h_{ki}$, $\phi$ is a constant related to antenna gain, shadow fading variable $\xi_k$ follows the log-normal distribution $10\log_{10}\xi_k \sim \mathbb{N}(0, \sigma_{\mathrm{SF}}^2)$, $d_k$ denotes the distance between the $k$th vehicle and the RSU, and $\alpha$ represents path loss exponent. Small-scale fading variables $h_{ki} \sim \mathbb{CN}(0, 1)(k = 1, 2, \cdots, K; i = 1, 2, \cdots, M)$.

### Transmission Model

When the number of antennas becomes large, matched filtering (MF) has been proved to be the asymptotically optimal precoder, therefore it is employed in this paper. The MF precoding vector of the $k$th vehicle is $\mathbf{w}_k = \mathbf{g}_k \big/ \|\mathbf{g}_k\| (k = 1, 2, \ldots, K)$. Denoting $s_k$ as transmitted modulation symbol of the $k$th vehicle with $\|s_k\| = 1$, then the received signal of the $i$th vehicle is given by

$$y_i = \sqrt{\frac{p_i}{M}} \mathbf{g}_i^{\mathrm{H}} \mathbf{w}_i s_i + \mathbf{g}_i^{\mathrm{H}} \sum_{k=1,\neq i}^{K} \sqrt{\frac{p_k}{M}} \mathbf{w}_k s_k + n_i, \tag{2}$$

where $\mathbf{p}/M = [p_1, p_2, \cdots, p_K] \big/ M$ denotes the power allocation vector, $n_i \sim \mathbb{CN}(0, N_0 B)$ is the complex white Gaussian noise (AWGN) at the $i$th vehicle with the noise power spectral density $N_0$.

Then, the signal-to-interference-plus-noise ratio of the $i$th vehicle can be written as

$$\gamma_i(p_i) = \frac{\frac{p_i}{M}\|\mathbf{g}_i\|^2}{N_0 B + \sum\limits_{k=1,\neq i}^{K} \frac{p_k}{M} \frac{\left|\mathbf{g}_i^{\mathrm{H}} \mathbf{g}_k\right|^2}{\|\mathbf{g}_k\|^2}}. \tag{3}$$

According to [13], the channel hardening and asymptotic orthogonality effects are valid for large $M$, i.e., $\mathbf{g}_i^{\mathrm{H}}\mathbf{g}_i \big/ M \to \phi\xi_i d_i^{-\alpha}$ and $\mathbf{g}_k^{\mathrm{H}}\mathbf{g}_i \big/ M \to 0 (i \neq k)$. Substituting them into (3) gives rise to

$$\gamma_i(p_i) = \frac{\phi\xi_i d_i^{-\alpha} p_i}{N_0 B}. \tag{4}$$

According to Shannon's formula, the transmit rate of the $i$th vehicle can be expressed as

$$R_i(p_i) = B \log_2\left[1 + \gamma_i(p_i)\right]. \tag{5}$$

### Caching Model and Delay Model

We assume that $m_x$ and $M_x (x \in \{\mathrm{n,s,e,w}\})$ denote the map data cached at the RSU and the road map data of the $x$ direction, therefore $\eta_x = m_x \big/ M_x (x \in \{\mathrm{n,s,e,w}\})$ represents the ratio of $x$-direction road data cached at the RSU. The total delay of HD map transmission mainly consists of downlink transmission delay and backhaul delay, while the processing delay and queuing delay are ignored in this paper.

*Transmission Delay*

Supposing that $m$ bit data of HD map is requested by each vehicle at each time, the transmission delay of the $k$th vehicle can be expressed as

$$d_{\mathrm{T}k}(p_k) = \frac{m}{R_k(p_k)}, \tag{6}$$

and the total transmission delay of all vehicles is given by

$$D_{\mathrm{T}}(\mathbf{p}) = \sum_{k=1}^{K} \frac{m}{R_k(p_k)}. \tag{7}$$

*Backhaul Delay*

If the requested map data was not cached at the RSU, the RSU should request it from the data center, which generates the backhaul delay and it can be expressed as

$$d_{\mathrm{B}k} = \frac{m}{R'}, \tag{8}$$

where $R'$ represents the transmit rate from the data center to the RSU.

As the path planning of automatic driving has been determined in advance, the RSU knows the number of vehicles requesting the map of $x$-direction, denoted by $n_x$ and $\sum_{x \in \{\mathrm{n,s,w,e}\}} n_x = K$. Then, the total backhaul delay of all vehicles can be written as

$$D_{\mathrm{B}}(\boldsymbol{\eta}) = \sum_{x \in \{\mathrm{n,s,w,e}\}} n_x (1 - \eta_x) \frac{m}{R'}, \tag{9}$$

where $\boldsymbol{\eta} = [\eta_{\mathrm{n}}, \eta_{\mathrm{s}}, \eta_{\mathrm{e}}, \eta_{\mathrm{w}}]$ and $\eta_x$ is equivalent to the probability that the RSU has stored the requested map segments.

*Average Delay*

Based on the transmission delay in (7) and backhaul delay in (9), the average delay of each vehicle is given by

$$D(\boldsymbol{\eta}, \mathbf{p}) = \frac{1}{K} D_{\mathrm{B}}(\boldsymbol{\eta}) + \frac{1}{K} D_{\mathrm{T}}(\mathbf{p}) = \frac{1}{K} \sum_{k=1}^{K} \frac{m}{R_k(p_k)} + \frac{1}{K} \sum_{x \in \{\mathrm{n,s,w,e}\}} n_x (1 - \eta_x) \frac{m}{R'}. \tag{10}$$

### 2.2 Problem Formulation

Assuming that the total transmit power of the RSU is $P/M$, the objective of this paper is to minimize the average delay of each vehicle, while satisfying the constraints of the total transmit power and RSU storage capacity, i.e., the problem can be formulated by

$$\begin{aligned} &\min_{\mathbf{p}, \boldsymbol{\eta}} \{D(\boldsymbol{\eta}, \mathbf{p})\} \\ \text{s.t. } &\sum_{k=1}^{K} p_k \le P, \\ &\sum_{x \in \{\mathrm{n,s,e,w}\}} \eta_x M_x \le C, \\ &0 \le \eta_x \le 1, \quad x \in \{\mathrm{n,s,e,w}\}. \end{aligned} \tag{11}$$

## 3 Caching and Transmission Schemes of HD Map

The average delay expression (10) can be divided into two independent parts. One part is the backhaul delay influenced by storage capacity and the traffic flow on each road, which can be reduced by optimizing the cache allocation at the RSU. Another part is the transmission delay, which can be minimized by power allocation at the RSU. Therefore, problem (11) can be divided into caching allocation problem and power allocation problem, i.e.,

$$\begin{aligned} &\min_{\boldsymbol{\eta}} \{D_{\mathrm{B}}(\boldsymbol{\eta})\} \\ \text{s.t. } &\sum_{x \in \{\mathrm{n,s,e,w}\}} \eta_x M_x \le C, \\ &0 \le \eta_x \le 1, \quad x \in \{\mathrm{n,s,e,w}\}, \end{aligned} \tag{12}$$

and

$$\begin{aligned} &\min_{\mathbf{p}} \{D_{\mathrm{T}}(\mathbf{p})\} \\ \text{s.t. } &\sum_{k=1}^{K} p_k \le P. \end{aligned} \tag{13}$$

The problems (12) and (13) will be solved respectively in the following subsections.

### 3.1 Optimal Cache Allocation Scheme

The objective function in problem (12) can be transformed into

$$D_{\mathrm{B}}(\boldsymbol{\eta}) = -\frac{m}{R'}\left(\frac{n_{\mathrm{n}}}{M_{\mathrm{n}}}\eta_{\mathrm{n}}M_{\mathrm{n}} + \frac{n_{\mathrm{s}}}{M_{\mathrm{s}}}\eta_{\mathrm{s}}M_{\mathrm{s}} + \frac{n_{\mathrm{e}}}{M_{\mathrm{e}}}\eta_{\mathrm{e}}M_{\mathrm{e}} + \frac{n_{\mathrm{w}}}{M_{\mathrm{w}}}\eta_{\mathrm{w}}M_{\mathrm{w}}\right) + \frac{mK}{R'}, \tag{14}$$

and problem (12) can be rewritten as

$$\max\left(\frac{n_{\mathrm{n}}}{M_{\mathrm{n}}}\eta_{\mathrm{n}}M_{\mathrm{n}} + \frac{n_{\mathrm{s}}}{M_{\mathrm{s}}}\eta_{\mathrm{s}}M_{\mathrm{s}} + \frac{n_{\mathrm{e}}}{M_{\mathrm{e}}}\eta_{\mathrm{e}}M_{\mathrm{e}} + \frac{n_{\mathrm{w}}}{M_{\mathrm{w}}}\eta_{\mathrm{w}}M_{\mathrm{w}}\right), \tag{15}$$

$$\text{s.t.}\quad \eta_1 M_1 + \eta_2 M_2 + \eta_3 M_3 + \eta_4 M_4 - C = 0. \tag{16}$$

Based on (15) and (16), it is easy to know that more cache capacity of RSU should be allocated for the map with larger $n_x \big/ M_x$. Therefore, we obtain Algorithm 1 to allocate $\eta_x$ in order to minimize the backhaul delay.

**Algorithm 1** Optimal Caching Allocation Algorithm

```
Step 1: Initialize $C$, $M_x$, $n_x$, $x \in \{\mathrm{n,s,w,e}\}$.
Step 2: Calculate $n_x/M_x$, sort them in descending order.
Step 3: Denote $n_1/M_1 \ge n_2/M_2 \ge n_3/M_3 \ge n_4/M_4$ as the order, then
    For $i$=1:4
        If $C - M_i \ge 0$, then $\eta_i = 1, C = C - M_i$;
        Else $C - M_i < 0$, then $\eta_i = C/M_i$, $C = 0$, break.
    End.
```

### 3.2 Optimal Power Allocation Scheme

*Proposition 1:* With the fixed number of vehicles $K$, the minimum transmission delay is given by

$$D_{\mathrm{T}} = \frac{m}{B}\sum_{k=1}^{K}\log_2^{-1}\left[1 + \frac{\phi\xi_k q_k(\lambda)}{N_0 B}\right], \tag{17}$$

where

$$q_k(\lambda) = \frac{N_0 B}{\phi\xi_k}\left\{\exp\left[2\mathrm{W}_0\left(\frac{1}{2}\sqrt{\frac{m\phi\xi_k \ln 2}{N_0 B^2 \lambda d_k^{-\alpha}}}\right)\right] - 1\right\}, \tag{18}$$

and $\mathrm{W}_0(\cdot) : \left[-\mathrm{e}^{-1}, +\infty\right) \to [-1, +\infty)$ is the first real branch of the Lambert W function satisfying $\mathrm{W}_0(x)e^{\mathrm{W}_0(x)} = x$. And $\lambda$ is the Lagrange multiplier, which can be calculated by a bi-section algorithm.

*Proof.* Let $q_k = d_k^{-\alpha} p_k$, the transmit rate of the $k$th vehicle can be rewritten into $R_k(q_k) = B\ln\big(1 + \phi\xi_k q_k \big/ N_0 B\big)\big/\ln 2$ and the total power constraint in problem (13) becomes $\sum_{k=1}^{K} q_k d_k^{\alpha} \le P$. Then, the objective is to allocate $q_k$ in order to minimize the average transmission delay.

The problem (13) can be solved by Lagrange multiplier method. Denoting $\mathbf{q} = [q_1, q_2, \cdots, q_K]^{\mathrm{T}}$, the Lagrange function of problem (13) can be written as

$$L(\mathbf{q}, \lambda) = D_{\mathrm{T}}(\mathbf{p}) + \lambda\left(\sum_{k=1}^{K} p_k - P\right) = \frac{m\ln 2}{B}\sum_{k=1}^{K}\ln^{-1}\left(1 + \frac{\phi\xi_k q_k}{N_0 B}\right) + \lambda\left(\sum_{k=1}^{K} q_k d_k^{\alpha} - P\right). \tag{19}$$

According to KKT conditions, we have

$$\frac{\partial L(\mathbf{q}, \lambda)}{\partial q_k} = \frac{-m\phi\xi_k\ln 2}{N_0 B^2\left(1 + \frac{\phi\xi_k q_k}{N_0 B}\right)\ln^2\left(1 + \frac{\phi\xi_k q_k}{N_0 B}\right)} + \lambda d_k^{\alpha} = 0, \tag{20}$$

and

$$\sum_{k=1}^{K} q_k d_k^{\alpha} - P = 0. \tag{21}$$

Solving (20) leads to

$$\left(1 + \frac{\phi\xi_k q_k}{N_0 B}\right)\ln^2\left(1 + \frac{\phi\xi_k q_k}{N_0 B}\right) = \frac{m\phi\xi_k\ln 2}{N_0 B^2 \lambda d_k^{\alpha}}. \tag{22}$$

Let $\Phi = m\phi\xi_k\ln 2\big/ N_0 B^2 d_k^{\alpha}$ and $\alpha = \ln\big(1 + \phi\xi_k q_k\big/ N_0 B\big)\big/ 2$, Eq. (22) can be transformed into

$$\alpha\exp(\alpha) = \frac{1}{2}\sqrt{\frac{\Phi}{\lambda}}. \tag{23}$$

Equation (23) is a transcendental equation with two roots, i.e., $\alpha_1 = \mathrm{W}_0\big(\sqrt{\Phi/\lambda}/2\big)$ and $\alpha_2 = \mathrm{W}_0\big(-\sqrt{\Phi/\lambda}/2\big)$. Because $\alpha > 0$ based on (23), then we can obtain $\alpha = \alpha_1 = \mathrm{W}_0\big(\sqrt{\Phi/\lambda}/2\big)$, and $q_k(\lambda)$ can be written as

$$q_k(\lambda) = \frac{N_0 B}{\phi\xi_k}\left\{\exp\left[2\mathrm{W}_0\left(\frac{1}{2}\sqrt{\frac{m\phi\xi_k\ln 2}{N_0 B^2 \lambda d_k^{\alpha}}}\right)\right] - 1\right\}. \tag{24}$$

In order to determine $\lambda$, we substitute (24) into (21) and have

$$\sum_{k=1}^{K} \frac{N_0 B}{\phi \xi_k} \left[ \exp\left( 2\mathrm{W}_0 \left( \frac{1}{2} \sqrt{\frac{m\phi\xi_k \ln 2}{N_0 B^2 \lambda d_k^{\alpha}}} \right) \right) - 1 \right] d_k^{\alpha} - P = 0. \tag{25}$$

Defining

$$f(\lambda) = \sum_{k=1}^{K} \frac{N_0 B}{\phi \xi_k} \left[ \exp\left( 2\mathrm{W}_0 \left( \frac{1}{2} \sqrt{\frac{m\phi\xi_k \ln 2}{N_0 B^2 \lambda d_k^{\alpha}}} \right) \right) - 1 \right] d_k^{\alpha} - P, \tag{26}$$

Function $f(\lambda)$ is a monotonically decreasing function with respect to $\lambda$. When $\lambda \to 0$, $f(\lambda)$ tends to infinity; while $f(\lambda)$ is less than 0 when $\lambda \to +\infty$. Therefore, equation $f(\lambda) = 0$ has a unique solution and can be obtained by bi-section method, which is given in Algorithm 2. □

The complexity of Algorithm 2 can be approximated by $\left\lceil \log_2 \left[ (\lambda_{\mathrm{U}} - \lambda_{\mathrm{L}}) / \varepsilon \right] \right\rceil$, where $\lceil \ \rceil$denotes rounding up to an integer.

**Algorithm 2** Bi-Section Algorithm for Minimum Transmission Delay.

```
Step 1: Initialize $\lambda_{\mathrm{L}}$ and $\lambda_{\mathrm{U}}$ with $f(\lambda_{\mathrm{L}}) > 0$ and $f(\lambda_{\mathrm{U}}) < 0$, toleration error $\varepsilon > 0$.
Step 2: Let $\lambda = (\lambda_{\mathrm{L}} + \lambda_{\mathrm{U}})/2$ and calculate $f(\lambda)$.
        If $|f(\lambda)| > \varepsilon$, go to step 3;
        Else go to step 4.
Step 3: If $f(\lambda) > 0$, then $\lambda_{\mathrm{L}} = \lambda$;
        Else $f(\lambda) < 0$, then $\lambda_{\mathrm{U}} = \lambda$.
        Go to step 2.
Step 4: Substituting $\lambda$ into (24) results in $q_k$ and therefore we obtain the minimum delay $D_{\mathrm{T}}$ using (17).
```

# 4 Simulation and Analysis

In this section, the backhaul delay and transmission delay of the proposed scheme are first evaluated with respect to different system parameters in contrast to the equal cache or power allocation scheme. Then, the average delay of HD map delivery for each vehicle is given based on real traffic data in Beijing.

## 4.1 Simulation Setup

In the simulation, the distance from the $k$th vehicle to the RSU, $d_k$, follows uniform distribution within the RSU's coverage, i.e., $[10, L]$ m. The other default parameters are listed in Table 1.

**Table 1.** Simulation parameters.

| Parameters | Values | Parameters | Values |
|---|---|---|---|
| $L$ | 300 m | $R'$ | 10 Mbps |
| Number of vehicles $K$ | 100 | Bandwidth $B$ | 500 kHz |
| $\sigma_{\mathrm{SF}}$ | 8 dB | Total transmit power $P$ | 25 dBm |
| $\alpha$ | 3 | Constant $\phi$ | 0.001 |
| $N_0$ | −174 dBm/Hz | $C$ | 100 kb |
| $M_x$, $x \in$ {n,s,w,e} | 50 kb | Map segment size $m$ | 1 kb |
| Free flow speed $v_{\mathrm{F}}$ | 50 m/s | Jamming density $\rho_{\mathrm{J}}$ | 1 vehicle/m |

## 4.2 Backhaul Delay

The backhaul delay is mainly affected by the total number of vehicles and cache. An equal cache allocation scheme is used for comparison, where the cache is equally divided into four parts to store maps of four directions, respectively.

Figure 2 shows the backhaul delay of 20 vehicles distributed in four directions. The horizontal axis denotes the number of vehicles in the north-direction road while the other vehicles are equally distributed in other three roads. Table 2 enumerates the numbers of vehicles in four-direction roads. From Fig. 2, the backhaul delay of the proposed scheme first increases and then decreases with the number of vehicles increases in the north-direction road, because the vehicle numbers of four directions first tends to the same and then the number of north-direction dominates the total number; meanwhile the RSU first tends to equally allocate the cache capacity and then prefers to cache the north-direction map. Moreover, the total backhaul delay of the proposed scheme is lower than that of the equal cache allocation scheme.

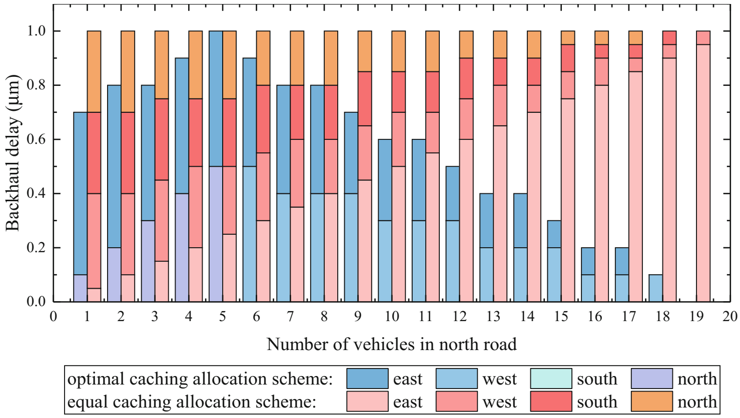

**Fig. 2.** Backhaul delay of four directions at the crossroad.

**Table 2.** Enumeration of vehicle distribution in four direction

| Horizontal axis | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| North | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| South | 7 | 6 | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 |
| West | 6 | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 |
| East | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 3 |
| **Horizontal axis** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| North | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| South | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 0 |
| West | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 |
| East | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 | 0 |

## 4.3 Transmission Delay

Figure 3 shows the error, upper bound and lower bound of $f(\lambda)$ in each iteration in order to verify the convergence of the bi-section algorithm with the initialization values $\lambda_L = 10^{-7}$ and $\lambda_U = 10^{-5}$. We can see that the upper bound decreases and the lower bound increases with the increasing number of iterations. Both bounds and the error tend to zero, which validates the convergence of the proposed bi-section algorithm.

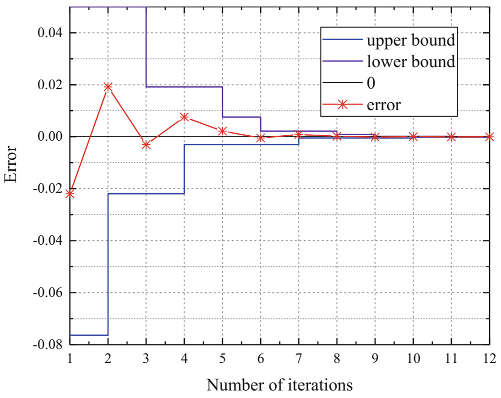

**Fig. 3.** Error v.s. the number of iterations in bi-section algorithm.

Figure 4 or 5 shows the relationship between the average transmission delay and the system bandwidth or total transmit power. With the same bandwidth, the average transmission delay of the optimal power allocation is lower than that of equal power allocation in Fig. 4; with the same transmission power, the average transmission delay of the optimal power allocation performs better than the equal power allocation in Fig. 5. Therefore, both Figs. 4 and 5 validate the proposed power allocation algorithm. Besides, the delay gap between the optimal power allocation and equal power allocation decreases with the increasing total transmit power.

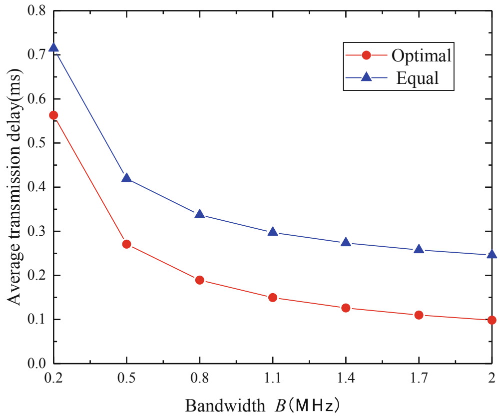

**Fig. 4.** Average transmission delay v.s. bandwidth.

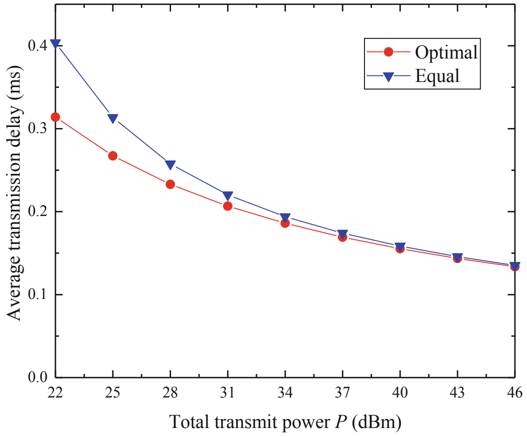

**Fig. 5.** Average transmission delay v.s. total transmission power.

### 4.4 Average Delay Based on Real Traffic Data

Next, the real traffic data of one day is employed to simulate the change of content requirements at the RSU. The origin data contains the vehicle speed samples on the Jianguomen Bridge in Beijing on October 2018. In order to obtain the traffic numbers of four-direction roads, the following relationship between average vehicle speed and traffic density is employed [14]

$$\bar{v} = v_{\mathrm{F}}(1 - \rho/\rho_{\mathrm{J}}), \tag{27}$$

where the constant $v_F$ is the free flow speed and the constant $\rho_J$ denotes the jamming density. Then, the traffic density and the numbers of vehicles on the four-direction roads can be calculated. Table 3 lists the calculated numbers of vehicles of 24 h in four-direction roads.

**Table 3.** The numbers of vehicles in four-direction roads.

| Time in one day (hour) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North | 80 | 95 | 72 | 72 | 57 | 76 | 141 | 148 | 137 | 131 | 126 | 116 |
| South | 45 | 30 | 15 | 26 | 4 | 11 | 53 | 95 | 92 | 95 | 90 | 81 |
| West | 101 | 92 | 75 | 56 | 44 | 64 | 51 | 88 | 110 | 103 | 105 | 106 |
| East | 117 | 139 | 121 | 111 | 105 | 99 | 109 | 102 | 114 | 111 | 111 | 114 |
| Time in one day (hour) | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| North | 106 | 111 | 120 | 130 | 136 | 143 | 145 | 117 | 99 | 107 | 83 | 83 |
| South | 72 | 71 | 83 | 84 | 84 | 112 | 120 | 116 | 107 | 85 | 67 | 56 |
| West | 107 | 106 | 107 | 94 | 100 | 119 | 135 | 117 | 105 | 98 | 108 | 83 |
| East | 101 | 113 | 109 | 105 | 108 | 125 | 121 | 122 | 132 | 113 | 103 | 112 |

Figure 6 shows the cache allocation change of one day with $M_n = M_w = 45$ kb and $M_e = M_s = 35$ kb. The vertical axis represents the cache proportions of four-direction roads, and the horizontal axis denotes the time of 24 h. It can be seen from Fig. 6, the caching proportions of four-direction maps are related to not only the numbers of vehicles on four directions but also the map sizes of four directions, i.e., $n_x \big/ M_x (x \in \{\text{e,s,w,n}\})$.

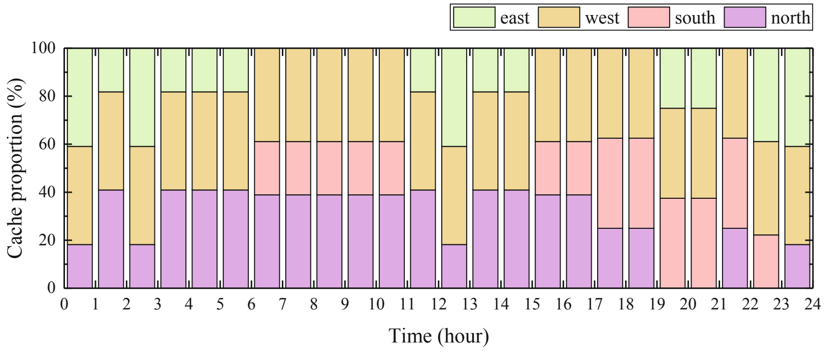

**Fig. 6.** Cache proportion at the RSU of one day based on real traffic data.

Figure 7 shows the average delay of each vehicle based on the numbers of vehicles in Table 3 and cache allocation in Fig. 6. The average delay of the proposed scheme is lower than that of the equal power and cache allocation scheme. Besides, we can observe that the average delay becomes smallest at 4:00 am and highest at around 6:00 pm, which is the evening rush hour in Beijing.

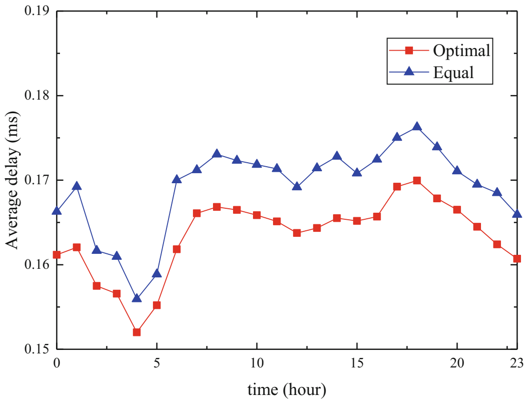

**Fig. 7.** Average delay of one day based on real traffic data.

## 5 Conclusion

This paper considered the problem of caching HD map at the RSU and transmitting it to vehicles at a crossroad. The objective of this paper is to minimize the average delay of HD map delivery for each vehicle with both the total transmit power and cache capacity constraints at the RSU. According to the vehicle mobility, we proposed the transmission power allocation and cache allocation scheme in order to minimize the average delay of HD map delivery. Simulation results indicate that the proposed power or cache allocation scheme can reduce the transmission or backhaul delay compared with the equal power/cache allocation scheme. Therefore, the average delay of the HD map delivery for each vehicle can be significantly reduced.

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