Edge Caching to Deliver Mobile Content in Vehicular Ad Hoc Networks

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Abstract. Vehicular ad hoc networks (VANETs), which can provide drivers with convenience and entertainment services, have attracted attentions from both academia and industry. In the VANETs, caching contents at the edge of road-side units (RSUs) can facilitate the timely content delivery to driving-through vehicles when requested. However, as both the scale of network and the number of content keep increasing, due to the limited cache capacity, how to selectively keep the replicas in the cache in VANETs becomes a challenging issue. In this paper, to resolve the above issue, we firstly make an analysis on the edge caching based on content access, vehicle velocity and road traffic. Then, we propose a cost model to decide whether and where to obtain the caching replica of content when the moving vehicle requests for it. In addition, we prove the efficiency of our proposed scheme with intensive simulation experiments.

Keywords: Vehicular ad hoc networks · Dynamic content · Caching

1 Introduction

Vehicular ad hoc networks (VANETs) [1–3] have become a promising filed as diverse multimedia communication services can be provided for drivers during driving. Currently, both the inter-vehicle content delivery and roadside-to-vehicle content delivery have already been applied to daily life with a great deal of market potential [4–10]. In VANETs, road-side units (RSUs) and on-board units (OBUs) are two important elements for content delivery. RSUs are a group of fixed peers, which are placed along the side of roads to provide moving vehicles with wireless communications within their coverage areas. OBUs are moving vehicles with wireless equipments, by which the OBUs may request content during moving. With OBUs and RSUs, VANETs can be formed where each vehicle can communicate with other vehicles and can also access backbone networks through RSUs.

Compared with RSUs, OBUs always have limited storage capacity and unstable connection. Therefore it becomes necessary to store several replicas of the original content on the edge of a group of RSUs. When an OBU requests for content, if the replica of this content is available in the cache of its connecting RSU, the requested content can be provided directly from the RSU to this moving vehicle directly. Otherwise, the OBU needs to contact other OBUs or other

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far RSUs connected by wired network to fetch the content, resulting in an extra user delay.

However, due to the limited caching capacity of RSU, with the increasing scale of various content delivered in the VANETs, it is impossible to keep caching the replicas of all content in RSUs. When the cache of an RSU exceeds its capacity limit, some replica must be removed to make room for the newly coming content. Then, when a future request from an OBU rises for this removed replica, as it is not available in its connecting RSU, the OBU will wait for more time to get it from other sites. Therefore, how to determine the replicas to be cached in the RSUs becomes a new challenge.

Vehicular content caching is different from the conventional caching [11,12]. On one hand, as the content requester in VCNs is a moving vehicle, the requested content needs to be delivered to a moving peer, instead of a static content requester in the conventional caching scenario. On the other hand, when a moving vehicle needs to get a content, there may be multiple options including getting content from other moving vehicles or from the connected RSU, while the conventional caching is just to fetch the requested content from its server. Therefore, in this paper an edge caching scheme is studied by fully exploring the features of vehicles and utilizing both the infrastructure and infrastructureless vehicle-to-vehicle communication modes.

The remainder of the paper is organized as follows. Section 2 reviews the related work. Section 3 presents the system model. Section 4 presents the analysis of caching for vehicular content request and delivery. Section 5 evaluates the performance of the proposal using extensive simulations and Sect. 6 closes the paper with concluding remarks.

2 Related Work

There are multiple works on VANETs. A swarming protocol for ad hoc wireless network is proposed in [13] by using a gossip mechanism and a piece-selection strategy, where the content can be delivered and shared in a peer-to-peer pattern among vehicles. Cabernet [14] is developed to deliver vehicular contents among moving peers using WiFi access points during the time of driving. [15] develops a content search mechanism (i.e., find out the location where the particular content is stored) based on the analysis of social cluster relations. To search for the desired content, the query can be efficiently sent out by considering the parameters such as bandwidth and lifetime. [16] presents an information sharing method which can maximize the spread of information queries among vehicles, and reduce the useless queries and duplicated replies at the same time.

Mobile content dissemination is studied with variable sensitivity levels and lengths of delay in an opportunistic RSU-aided network [17], where the storage of RSU is analyzed with different sizes allocated by a heuristic algorithm. A design of distributed content services in peer-to-peer based vehicular networks is presented [18]. The proposed scheme can improve users' satisfaction and achieve fairness through opportunistic transmissions and the media-aware content distribution. [19] propose to explore the parked vehicles to help with vehicular content distribution. [20] develops a coalitional graph game for modeling the cooperation where OBUs can be organized into coalitions to coordinate transmissions autonomously. It allows different OBUs to exchange and complement content when some content is lost during delivery.

In the least recently used (LRU), the content which is the least recently accessed by users would be removed from the cache, when the near-capacity cache needs to accommodate the newly coming content. In the least frequently used (LFU), the content which is the least frequently accessed would be removed. The main problem of LRU is that the caching is determined only by the interval between two requests, where the characteristics of content are not well considered, while in LFU, content which was frequently accessed in a past period may remain in the cache for a long time even it has lost its popularity and has not been requested by the user recently.

3 System Model

Each RSU r_i $(i = 1, \ldots, I)$ is placed in different locations of the network. Within the coverage area of r_i, there are several roads and the j-th $(j = 1, \ldots, J)$ road in r_i's coverage area is denoted by $l_{i,j}$. Let $c_{i,j}$ denote the length of road $l_{i,j}$, and let $u_{i,j}$ denote the number of lanes of road $l_{i,j}$. For road $l_{i,j}$, there could be multiple moving vehicles where $o_{i,j,k}$ denotes the k-th moving vehicle on road $l_{i,j}$. For the vehicles moving on road $l_{i,j}$, the velocity of vehicle $o_{i,j,k}$ is denoted by $v_{i,j,k}$. The velocity of different vehicles is divided into N discrete levels by ls_n $(n = 1, \ldots, N)$,

$$ls_n \in [\min(v_{i,j,k}), \max(v_{i,j,k})]. \tag{1}$$

The arrival rate of moving vehicles at each level of velocity is defined by ra_n $(n = 1, \ldots, N)$, where

$$RA = \sum_{n=1}^{N} ra_n. \tag{2}$$

According to [21], the occurrence probability of each velocity level is obtained by p_{ra_n} $(n = 1, \ldots, N)$, where

$$p_{ra_n} = \frac{ra_n}{RA}. \tag{3}$$

For communications between moving vehicle $o_{i,j,k}$ and its connected RSU r_i, the coverage area of r_i is divided into several zones according to the transmission rate of vehicles to the RSU. As indicated in [22] and the references therein, with different distances to RSUs, vehicles would suffer from different channel impairments and transmit at different data rate. In zone u $(u = 1, \ldots, U)$, the transmission rate $bw^u_{r_i,o_{i,j,k}}$ between moving vehicle $o_{i,j,k}$ and its connected RSU r_i is determined by the zone model, in which different mobility zone within the coverage area of RSU has different transmission rate.

The arrival of content requests from moving vehicles follows a Poison process. Let $\lambda_{i,j,k}$ denote vehicle $o_{i,j,k}$'s request rate. Let Q denote the total number of content which can be requested. For the q-th $(q = 1, \ldots, Q)$ content, its data size is defined by s_q. The original content is stored in the content server which is connected to RSUs by wire connections. The RSUs can only store replicas of certain content due to a limited caching capacity. Considering that some content may be requested more frequently than others, content in VANETs is modeled to have different popularity. The popularity of content follows a Zipf distribution [12]. The probability that content q is requested is given by

$$p_q = \frac{\left[\sum_{q=1}^{Q} \frac{1}{e_q^{\tau}}\right]^{-1}}{e_q^{\tau}}, \tag{4}$$

where τ is the parameter of the Zipf distribution, and the ranking of request times of content q is denoted by e_q.

4 Caching Analysis for Content Distribution

When a given moving vehicle $o_{i,j,k}$ requests content q, if the replica of content q is available in its connected RSU r_i, the RSU r_i sends the replica of content q directly to the moving vehicle $o_{i,j,k}$. Otherwise, to obtain the requested content q there are two options for $o_{i,j,k}$. One is to contact other moving vehicles which have the replica of content q. The other is to let r_i contact other nearby RSUs for fetching the content. In this section, we give the analysis of both options.

For a given $o_{i,j,k}$, the number of moving vehicles that $o_{i,j,k}$ can connect is given by [21],

$$cv_{i,j,k} = \frac{1}{e^{-\sum_n \frac{ra_n}{ls_n} TR_{i,j,k}}}, \tag{5}$$

where $TR_{i,j,k}$ is the fixed transmission range of $o_{i,j,k}$. Define $o_{i,j,z}$ $(z = 1, \ldots, cv_{i,j,k})$ as the moving vehicles which $o_{i,j,k}$ is able to connect to within its fixed transmission range. We define the probability that a request arises from a given moving vehicle $o_{i,j,k}$ within the coverage of its connected RSU as $w_{i,j,k}$. Let t_i be the total number of requests for content where these requests are from all moving vehicles in the coverage area of r_i within a past watching period Δt. During the past watching period Δt, the number of requests from this moving vehicle can be obtained by

$$\sum_i \sum_j t_i \cdot w_{i,j,z}. \tag{6}$$

If there has been a request from $o_{i,j,z}$ for content q, as the vehicle keeps the content after obtaining it, $o_{i,j,z}$ can be a candidate to provide content q.

Define $rep_{z,q}$ as follows.

$$rep_{z,q} = \begin{cases} 1, & \sum_i \sum_j t_i \cdot w_{i,j,z} \cdot p_q \geq 1; \\ 0, & \sum_i \sum_j t_i \cdot w_{i,j,z} \cdot p_q < 1. \end{cases} \tag{7}$$

The transmission rate of $o_{i,j,z}$ is

$$bw_{o_{i,j,k},o_{i,j,z}} \cdot \log_2 \left(1 + \frac{po_{o_{i,j,k}}}{bw_{o_{i,j,k},o_{i,j,z}} \cdot N_0 + \sum_{i=1}^{cv_{i,j,k}} if_i} \right) \tag{8}$$

where $bw_{o_{i,j,k},o_{i,j,z}}$ denotes the bandwidth between $o_{i,j,k}$ and $o_{i,j,z}$. $po_{o_{i,j,k}}$ is the received signal power of $o_{i,j,k}$ while if_i is defined as the interference experienced at receiver from other transmitters. Thus, the delay to obtain content q from $o_{i,j,z}$ is

$$del_{o_{i,j,k},o_{i,j,z}} = \frac{s_q}{bw_{o_{i,j,k},o_{i,j,z}} \cdot \log_2 \left(1 + \frac{po_{o_{i,j,k}}}{bw_{o_{i,j,k},o_{i,j,z}} \cdot N_0 + \sum_{i=1}^{cv_{i,j,k}} if_i} \right)}. \tag{9}$$

If the above delay is smaller than the possible connection time $cd_{o_{i,j,k}}$ between $o_{i,j,z}$ and $o_{i,j,k}$, this moving vehicle can be a candidate for obtaining content.

$$con_{z,q} = \begin{cases} 1, & del_{o_{i,j,k},o_{i,j,z}} \leq cd_{o_{i,j,k}}; \\ 0, & del_{o_{i,j,k},o_{i,j,z}} > cd_{o_{i,j,k}}. \end{cases} \tag{10}$$

From [21], the possible connection time $cd_{o_{i,j,k}}$ between $o_{i,j,z}$ and $o_{i,j,k}$ can be obtained by

$$cd_{o_{i,j,k}} = \frac{1 - e^{-\sum_n \frac{ra_n}{ls_n} TR_{i,j,k}}}{\sum_n \frac{ra_n}{ls_n} \cdot e^{-\sum_n \frac{ra_n}{ls_n} TR_{i,j,k}}}. \tag{11}$$

Then, we can calculate the average delay to obtain content q from other vehicles by

$$\frac{1}{cv'_{i,j,k}} \sum_{z=1}^{cv_{i,j,k}} rep_{z,q} \cdot con_{z,q} \cdot del_{o_{i,j,k},o_{i,j,z}}, \tag{12}$$

where $cv'_{i,j,k}$ is the total number of $o_{i,j,z}$ which satisfies both $con_{z,q} = 1$ and $rep_{z,q} = 1$.

If the moving vehicle $o_{i,j,k}$ obtains the requested content q from other fixed RSUs, when its connected RSU r_i does not have the replica of content q, r_i needs to fetch this content from a nearby wired connected RSU r_m

$(m = 1, \ldots, M \ \& \ m \neq i)$ which has the replica of content q. And, after obtaining content q, r_i sends content q to the moving vehicle $o_{i,j,k}$.

For a given r_m, the delay to obtain content q from it to r_i can be obtained by

$$del_{r_i,r_m} = \frac{s_q}{bw_{r_i,r_m}} \cdot d_{r_i,r_m}, \tag{13}$$

where the shortest distance (hop count) away from r_m to r_i is defined by d_{r_i,r_m}, and the average bandwidth (per hop) during the path from r_m to r_i is denoted by bw_{r_i,r_m}.

Based on the zone model [22], the delay during the delivery from r_i to $o_{i,j,k}$ within the u-th zone becomes

$$del^u_{r_i,o_{i,j,k}} = \frac{s^u_q}{bw^u_{r_i,o_{i,j,k}}}. \tag{14}$$

If $\sum_{\varepsilon=1}^{u+1} s^\varepsilon_q > s_q$, we can know that all of the bytes of content q can be transmitted from r_i to $o_{i,j,k}$ and we have

$$del^{u+1}_{r_i,o_{i,j,k}} = \frac{s_q - \sum_{\varepsilon=1}^{u} s^\varepsilon_q}{bw^{u+1}_{r_i,o_{i,j,k}}}. \tag{15}$$

Thus, the total delay to transmit content q from r_i to $o_{i,j,k}$ is

$$\sum_{\varepsilon=1}^{u+1} del^\varepsilon_{r_i,o_{i,j,k}}. \tag{16}$$

In addition, the total delay when r_i fetches a replica of content q from r_m and then sends to $o_{i,j,k}$ can be obtained by

$$del_{r_i,r_m} + \sum_{\varepsilon=1}^{u+1} del^\varepsilon_{r_i,o_{i,j,k}}. \tag{17}$$

If RSU r_m has a replica of the requested content q and this replica can be delivered to the moving vehicle $o_{i,j,k}$ within the connection time between this moving vehicle and its connected RSU r_i, RSU r_m can be a candidate for content delivery. Define $con_{k,q,i,j,m}$ and $rep_{m,q}$ to show the candidate for providing the replica of content q as follows.

$$con_{k,q,i,j,m} = \begin{cases} 1, & del_{r_i,r_m} + \sum_{\varepsilon=1}^{u+1} del^\varepsilon_{r_i,o_{i,j,k}} \leq g_{r_i,o_{i,j,k}}; \\ 0, & del_{r_i,r_m} + \sum_{\varepsilon=1}^{u+1} del^\varepsilon_{r_i,o_{i,j,k}} > g_{r_i,o_{i,j,k}}. \end{cases} \tag{18}$$

$$rep_{m,q} = \begin{cases} 1, & cp_{m,q} \geq 1; \\ 0, & cp_{m,q} < 1. \end{cases} \tag{19}$$

In the above equations, if $con_{k,q,i,j,m} = 1$ and $rep_{m,q} = 1$, RSU r_m is determined as a candidate for content delivery.

Then, we can obtain the average delay to obtain content q from RSU r_m after the moving vehicle $o_{i,j,k}$ sending the request to RSU r_i by

$$\frac{1}{M'} \sum_{m=1}^{M} rep_{m,q} \cdot con_{k,q,i,j,m} \cdot (del_{r_i,r_m} + \sum_{\varepsilon=1}^{u+1} del^{\varepsilon}_{r_i,o_{i,j,k}}), \tag{20}$$

where M' is the number of r_m which satisfies both $con_{k,q,i,j,m} = 1$ and $rep_{m,q} = 1$.

If the following inequality holds,

$$\frac{1}{cv'_{i,j,k}} \sum_{z=1}^{cv_{i,j,k}} rep_{z,q} \cdot con_{z,q} \cdot del_{o_{i,j,k},o_{i,j,z}} < \frac{1}{M'} \sum_{m=1}^{M} rep_{m,q} \cdot con_{k,q,i,j,m} \cdot (del_{r_i,r_m} + \sum_{\varepsilon=1}^{u+1} del^{\varepsilon}_{r_i,o_{i,j,k}}), \tag{21}$$

content q is delivered from moving vehicles. Otherwise, content q is provided by the replica on the edge of RSUs.

5 Simulation Results

Using the scenario in [23], simulation involves 100 vehicles moving on a linear highway, where the velocities of vehicles are uniformly distributed in the range [70 km/h, 130 km/h]. The communication range of a vehicle is 300 m. Each content is divided into 100 pieces of equal size which is 2 MBytes. A content is downloaded successfully when all the pieces are collected. The probability that a content is requested follows the Zipf distribution where contents have different popularity. Here, the parameter of Zipf distribution is set to be 0.8 [12]. The cache size of RSUs is 0.15, i.e. 15% of the total content can be cached in an RSU (due to limited cache capacity) [21]. The transmission rate between moving vehicles and fixed RSUs is determined based on the zone model [22].

Figure 1 shows the relative delay compared with the delay to fetch the requested content by using the Random scheme, where the total number of requests is varied from 1000 to 9000. It can be seen that the proposed algorithm can achieve the lowest relative delay. The reason is as follows: in our proposal, the edge caching among several RSUs is analyzed, where the RSUs can also provide the requested content. Therefore, different from other conventional algorithms, when the vehicle requests for the replica of the content, the caching replicas on the edge of RSUs may provide this content cooperatively with other vehicles based on the constraints of transmission time. Then, the requested content need not to be fetched from its content server so that the delay can be reduced.

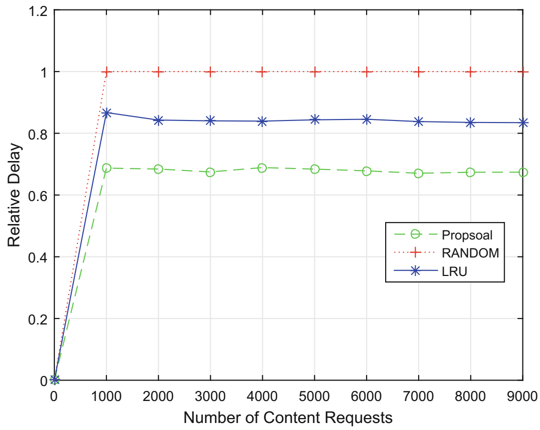

Fig. 1. Relative delay of different algorithms when the number of content requests is increased.

6 Conclusion

In this paper, a cooperative scheme for edge caching has been proposed for VANETs to provide multimedia content delivery services. Based on the properties of vehicle velocity, road traffic and content popularity, the edge caching has been analyzed. Besides, a cost model has been proposed to compare the cost to fetch the requested content from a moving vehicle or other RSUs. Furthermore, simulation results clearly demonstrated the performance improvement with the proposed algorithm. There are several works to be done as further researches. Security issue related to the replicas of cache will be considered.

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