Implicit Cooperative Caching based on Information Popularity for Vehicular Networks

Yuhong Li
State Key Laboratory of Networking and Switching Technology
Beijing University of Posts and Telecommunications, Beijing, China
The Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai, China
hoyli@bupt.edu.cn

Ji Wang
State Key Laboratory of Networking and Switching Technology
Beijing University of Posts and Telecommunications
Beijing, China
wj741238436@bupt.edu.cn

Anders Lindgren
RISE SICS, Sweden
Luleå University of Technology
Sweden
anders.lindgren@ri.se

Xiang Su
Centre for Ubiquitous Computing
University of Oulu
Finland
xiang.su@oulu.fi

Jukka Riekki
Centre for Ubiquitous Computing
University of Oulu
Finland
jukka.riekki@oulu.fi

ABSTRACT

Information-centric networking (ICN) technology is becoming a popular research topic in vehicular networks due to the connectionless and lightweight characteristics of this networking paradigm. Caching plays an essential role in information-centric networks, but current caching techniques for ICN are not ideal for the dynamic and wireless vehicular networks. This paper presents a caching approach for ICN-based vehicular networks that takes into account both the dynamicity of vehicular networks and the popularity of the information being distributed. We introduce an interval metric for selective caching. With this metric and estimates of information popularity and vehicle density, cooperative caching can be realized without exchanging cache management information among the vehicular nodes. Simulation results show that the proposed approach can increase the storage space utilization and has low data response time for vehicular networks.

CCS CONCEPTS

Networks →**Network types** →**Ad hoc networks** →Mobile ad hoc networks • **Networks** →**Network services** →In-network processing

KEYWORDS

Caching, vehicular networks, information-centric networking (ICN), information popularity, vehicle density

1 INTRODUCTION

Intelligent transport and safe and comfortable driving are important goals for the vehicular industry and society at large. In order to realize these goals, the behaviours of vehicles and the corresponding people need to be coordinated. Accordingly, large amounts of information need to be exchanged among vehicles, people in the vehicles, and the environment. Information-centric networking (ICN) concentrates on exchanging information objects without much consideration from where the information objects are obtained [1][2]. By identifying information objects instead of hosts in the networks, ICN separates the information from its locations and therefore does not need to address the mobility management, multicasting and other related issues. Hence, ICN can be expected to deal well with the highly dynamic topology and non-uniform distribution of information faced by vehicular networks. Several ICN based solutions have recently been proposed for vehicular networks [3][4][5].

In ICN, data is requested and retrieved by name. The Named Data Networking (NDN) [6] architecture provides a clear example of this idea as it is based on two types of messages: Interest and Data. An information consumer requests an information object by sending an Interest message with the name of the object in the packet. Any node hearing the request and having the data can issue a response with a Data message. The consumer can therefore obtain the information by knowing only the object's name. With no clearly defined caching strategy, in NDN every node on the data delivery path will cache the data.

Caching plays an essential role in information-centric networks [7]. Through caching the information in the network nodes on the return path to the requesters, the information can be gradually distributed to the edge of the networks, that is, closer to information users. Accordingly, caching can reduce the time required for users to obtain the information and reduce the network traffic. This may also reduce the load on the servers providing the information.

However, the caching strategies discussed for wired networks may cause problems when used in vehicular networks due to the temporal and spatial constraints of the information and the highly dynamic topologies of vehicular networks. Few caching strategies

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specific for vehicular networks have been discussed so far. More efficient solutions are needed for vehicular networks.

In this paper, we concentrate on caching in ICN-based vehicular networks and propose a new caching approach. The proposed approach considers the characteristics of vehicular networks and the information to be distributed. By introducing the interval metric and distinguishing the types of information, cooperative caching among nodes can be realized without exchanging extra management information among them. The rest of the paper is organized as follows. First, the related work is discussed and challenges for caching strategies in vehicular networks are summarized. Following this, in Section 3, we propose an interval-based caching approach for ICN-based vehicular networks. The implementation and validation of the proposed approach are described in Section 4, and conclusions are drawn in Section 5.

2 CACHING AND ICN-BASED VEHICULAR NETWORKS

2.1 Problems of Caching in Information-centric Networks

In the early work, “on-path” caching of all data [6][8] is used. In other words, every network node caches all the data passing through it and there is no “cooperation” among the nodes to decide what data should be cached and where. Consequently, the same information is cached redundantly in nearby network nodes. Moreover, caching new information may cause the replacement of old information due to limited storage space in each node. The result is that some cached data may be replaced before subsequent requests for that data is needed from the cache. A data object can be cached everywhere in neighbouring nodes for a certain time and then disappear from all nodes. Hence, the limited storage space of the network nodes is not used efficiently. Moreover, with most of the current ICN schemes, only the “on-path” caches are checked when there is a request, although the requested data may be cached in the nearby nodes. In this way, network caching has not been well used.

The above mentioned problems have led to the emergence of cooperative caching strategies [9]. The main purpose of these strategies is to reduce redundant caching among neighbouring nodes and increase the efficiency of the storage usage without increasing the response time of data retrieval too much. A node can ask its close neighbours for an information object quickly and then decide whether to cache the object or not. When making the decision, the node can consider if and how many copies of the object have been cached in its immediate neighbourhood. Thus, to a certain extent, redundant caching can be avoided. In addition, a node may already know in advance where a certain object is cached when there is a request. In this way, cached objects can be used efficiently and the transmission distance of the objects can be minimized.

Despite these advantages, there are some problems associated with cooperative caching. First, it is difficult to determine the extent of cooperation; in other words, to determine the groups of network nodes that should cooperate with each other. It is not easy to find a unified strategy in the whole network to determine how many nodes should belong to a cooperating group or how big the cooperative extent should be. The dynamic nature of vehicular network topologies introduce additional challenges. Some networking overhead may be caused by cache management messages among the nodes. The second problem is that most caching strategies concentrate only on reducing redundant caching and do not consider the popularity of the information objects. As a result, a copy of a seldom requested information object may be cached in several nodes, at a high price of communication. Although caching based on popularity has been proposed [10], vehicular networks were not discussed.

2.2 Challenges for Caching in Vehicular Networks

The large amount of continuously generated data place high demands on the size of the cache in each vehicle. If too many objects are cached, the overhead for searching and replacing cached information objects also decreases overall system performance. Thus, caching and the policies used to determine what and where to cache are important issues in ICN-based vehicular networks. Moreover, the highly dynamic topology of vehicular networks, the non-uniform distribution of vehicles, and the heterogeneous types of information in the networks also pose challenges for caching.

First, the topology of vehicular networks changes frequently when vehicles run at different speeds and in different areas such as motorways and city streets, requiring flexible caching mechanisms, which can adapt to the frequent changes of topology with variable vehicle densities. This makes normal cooperative caching with interactive messages for caching management infeasible.

Secondly, different categories of information have different temporal and spatial constraints. For example, an accident notification needs to be cached by vehicles within a two kilometre radius and for only about 30 minutes. On the other hand, a photograph of a landscape may be cached for days but is of interest only within a range of several hundred metres. Therefore, different caching strategies should be applied to different categories of information in vehicular networks.

The highly dynamic topology and non-uniform distribution of networking nodes challenge cooperative caching strategies in vehicular networks. On the one hand, the cooperating group may change too quickly and, as a result, the caching information from the neighbours may be not reliable, causing the cooperation to fail even though the overhead for the cooperation has been paid. On the other hand, the density of vehicles in different areas makes it difficult to determine the extent of the cooperation groups. Thus, a non-cooperative caching (i.e., without special message exchanges among nodes for caching) is necessary in vehicular networks.

In order to overcome the disadvantages of non-cooperative caching, while achieving the advantages of cooperative caching, we propose an interval based selective caching approach for vehicular networks. The proposed method does not cache information objects in every node, but only at calculated intervals along the path. The caching interval depends on the distribution of vehicles and the category of information.

3 IMPLICIT COOPERATIVE CACHING AMONG VEHICLES

From a data dissemination point of view, the main objective of caching is to store the information close to end users so that the information can be accessed as quickly as possible when requested. This requires the information to be cached as widely as possible. However, if all the nodes have copies of the same objects, storage is wasted. Therefore, our basic idea is first to measure how often an information object is requested, i.e., the popularity of the information object. The information objects that may frequently be requested by users should be cached more widely than those not needed by most users, so that most of the information requests can be satisfied quickly without wasting too much transmission bandwidth. Secondly, we measure the density of the vehicles on the road. The denser the vehicles in a certain area, the smaller fraction of nodes need to cache the same object, since it is relatively quick and easy for the nodes very close to each other to exchange different information objects, and more information can be stored in the network as a whole. Thirdly, we realize the effect of cooperative caching without introducing much overhead through extra control messages. For this reason, caching instructions are delivered in the data packets instead of being exchanged separately. In the following sections, we first describe how to measure the popularity of information objects in vehicular networks and the density of vehicles, taking into account the temporal and spatial constraint of information objects and the dynamic topology of vehicular networks. Then we introduce the concept of interval and describe the caching approach based on intervals.

3.1 Information Popularity

In practice, the more often an information object is requested, the more worthy the object is to be cached. However, information often has temporal constraints too so that frequent requests in the past do not necessarily mean that it will be requested very often in the future. Therefore, we define an attenuation function of time *t*, namely

$$af(t,m) = \frac{1}{2} \times \left(\frac{1}{2}\right)^{e^{-\gamma_m t}} \qquad (1)$$

Here γ_m is a damping parameter dependent on the category of information *m*, and decided by the nature of the information.

Thus, the popularity of an information object with category *m* at node *i*, time *t* is:

$$pop_i(t,m) = \sum_{d=t_0}^{t} \left(w_m \times af(d,m)\right) \qquad (2)$$

d is the time when a request for the information object with category *m* is received, t_0 is the time when the first request of the object arrived at node *i*. w_m is a weight decided by type *m*. It reflects the popular nature of the information. Thus, the popularity of an information object at a node depicts the number of requests on the information in the past, and is attenuated over time.

3.2 Vehicle Density

The number of vehicles in a certain area greatly affects packet forwarding in the vehicular network. Obviously, the denser the vehicles are, the smaller the fraction of nodes that need to cache the same information objects, since the cached objects can be found quickly among the near neighbours and sent to the requester through fewer hops. We define the normalized density ρ of vehicular traffic around a vehicular node *i* as follows.

$$\rho = log_{10}\left[\frac{(n+1)\times 100}{L\times R}\right] \quad \text{when } 0<n< 0.1\times L \times R - 1$$
$$\rho = 1 \quad \text{when } n\geq 0.1\times L \times R - 1 \qquad (3)$$

Here *n* is the number of connections node *i* has with its neighbours, and *R* is the radio transmission range, *L* is the number of lanes on the street.

3.3 Caching at Intervals

We introduce the metric interval to calculate at which nodes a certain information object should be cached. It is a function of the popularity of the forwarded information object and the current density of vehicles around the forwarding node, namely *interval=f(pop,ρ)*. It can be defined in a flexible way depending on the amount of information in the network and the scale of the network. A node will use interval to determine if it should cache an object or not when forwarding the object, together with the parameter of distance between the requester and the node that owns or caches the requested information. We define *interval* for node *i*, information object with category *m* at time *t* as:

$$interval_i(t,m) = f(pop,\rho) = \lfloor s \times \rho \times 2^{-pop(t,m)} + 1 \rfloor$$
$$\rho \in （0,1）,\ pop(m\ ,\ t) \in （0,1） \qquad (4)$$

The value of *interval* is an integer, i.e. floor of *f* (*pop*,*ρ*); *s* is a weight parameter, which is used to adjust the scope of *interval*.

The principle of our approach is to add one “hop” field in the information request packet (i.e., Interest Packet), and two fields, “hop” and “interval”, in the response packet (i.e., Data Packet), after the “name” field in the two types of packets.

When a node receives an Interest Packet requesting an object, the node checks the Content Store (CS) and the Pending Interest Table (PIT), similar to the processing in NDN [6]. The biggest difference to NDN is the hop field recording the distance in hops from the information requester to the current node in the Interest Packet right after the “name” field. At the requester node, the hop field is inserted and its value is set to zero. When a node cannot satisfy the request from its own CS, it forwards the Interest Packet with the hop value incremented by one. Thus, when the requested object is found in the network, all the intermediate nodes know the number of hops to the node where the information object is cached.

When the Interest Packet reaches the server having the requested object or an intermediate node caching the object, one or more Data Packets will be created and sent. The value of the “hop” field in the Interest Packet will be assigned to the “hop” field in the Data Packet. Meantime, the request number of the same object will be accumulated and the value of the *interval* will be calculated and inserted in the “interval” field.

When a node receives a Data Packet, as shown in Figure 1, if the corresponding data has been requested and has not been delivered, the node will check the value of the *hop* and *interval* carried in the packet to determine whether it should forward and/or cache the data.

In this case the result of *hop* modulo *interval* (i.e., *hop* % *interval*) is used by the node to determine whether it should cache the data. This results in the information object only being cached every *interval* nodes along its path to the requester. The larger the *interval*, the fewer the nodes cache the data. Before forwarding the Data Packet to the next node, the *hop* field is decremented by one.

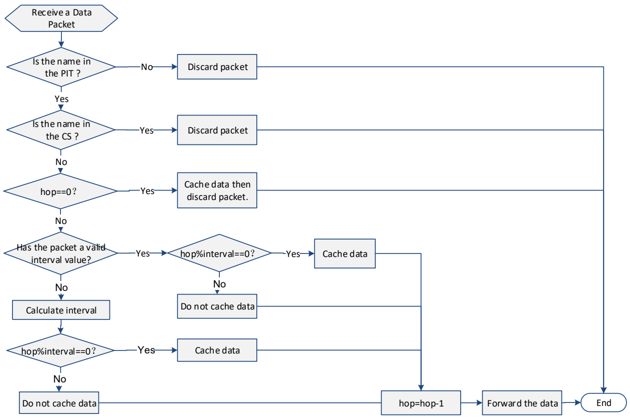


Figure 1: Caching based on interval when receiving data.

4 IMPLEMENTATION AND EVALUATION

4.1 Implementation

We have implemented the interval-based caching approach and integrated it as an independent module in the ONE simulator [11]. ONE is specifically designed for evaluating DTN [12] routing and application protocols, which typical vehicular networks run. We modified ONE and implemented the basic NDN and the proposed interval-based caching approach. We implemented a message generator that can send Interest and Data packets and the PIT and CS in the ONE environment. We use the broadcasting mechanism to disseminate the Interest Packets through the network, whereas the Data Packets are forwarded to the requestor along the same path that the corresponding Interest Packets traverse the network. In the simulation, we use the Shortest Path Map Based Movement mobility model that is included in the ONE simulator, using a map of downtown Helsinki to drive the movement of the vehicles.

Table 1 shows the values of the parameters used in the simulation.

Table 1: Parameters for simulation

Parameters	Value	Parameters	Value
Simulation time	18000 s	Wireless transmission range	200m
Area	4.5km* 3.4km	Transmission mode	broad-casting
Mobility velocity	8.3m/s-33.3m/s	Default cache size at nodes	50Mbytes
Data trans. Rate	250kbps	Data packet size	0.5M-1M bytes
Damping parameter	γ_m=1	Zipf distribution	k=0.5

4.2 Evaluation

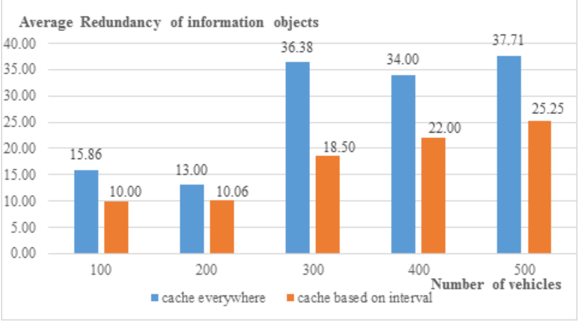
We have implemented the interval-based caching approach and integrated it as an independent module in the ONE simulator [11]. ONE is specifically designed for evaluating DTN [12] routing and application protocols, which typical vehicular networks run. We modified ONE and implemented the basic NDN and the proposed interval-based caching approach. We implemented a message generator that can send Interest and Data packets and also realized the PIT and CS in the ONE environment. We use the broadcasting mechanism to disseminate the Interest Packets through the network, whereas the Data Packets are forwarded to the requestor along the same path that the corresponding Interest Packets traverse the network. In the simulation, we use the Shortest Path Map Based Movement mobility model that is included in the ONE simulator, using a map of downtown Helsinki to drive the movement of the vehicles. In the evaluations, 500 different types of information objects (i.e., Data Packet) are used. An object request (i.e., Interest Packet) is sent from a node randomly at an interval of 1-5 seconds. The requested object follows Zipf distribution from the 500 different objects. In our simulation, we set the parameters k=0.5 for the Zipf distribution$P(r) = c/r^k$.

We evaluate the interval-based caching approach according to the following metrics:

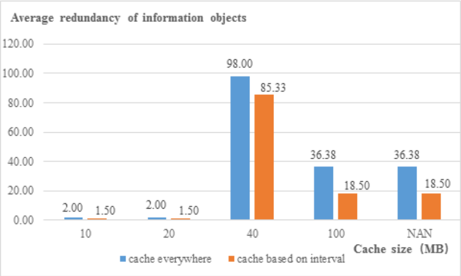
- Redundancy: the number of copies of an object that are cached in the network after a certain number of requests.
- Space Utilization Ratio: the proportion of used storage space to the total space of a node.
- Cache Hit Ratio: the probability to obtain a cache hit along the path from a request node to a node caching the requested information object.
- Response time and distance to the information: the latency required for a piece of requested information to be obtained and the distance (in hops) that the requested information is found from the requestor.

We test and analyse the influences on the above metrics from different network scales (i.e., the number of nodes) and cache sizes. We also study the influence of popularity and vehicular density on the interval value and the stability of the caching strategy based on intervals by our test results.

Figure 2 illustrates the average redundancy of information when there are different numbers of vehicles in the network (Figure 2(a)) and when the cache size of the vehicles are limited to different values (Figure 2(b), NAN means no limitation). From this figure, we can see that the average number of copies of data when using interval-based caching is less than that when the data are cached everywhere. This may decrease the ratio of space utilization at the nodes and more information objects can be cached in the networks.



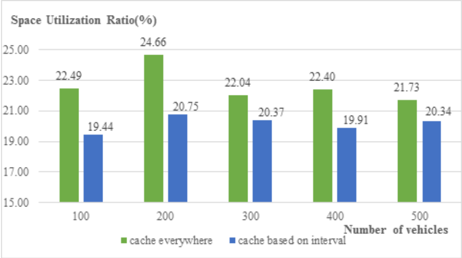
(a) Average redundancy vs. number of vehicles (cache=50M)



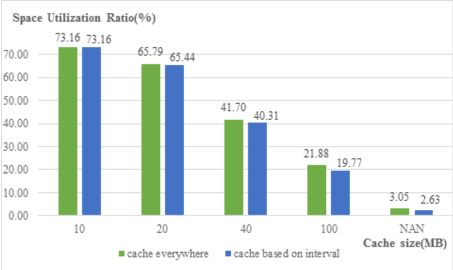
(b) Average redundancy vs. cache size of nodes (node no.=300)

Figure 2: Average redundancy of information

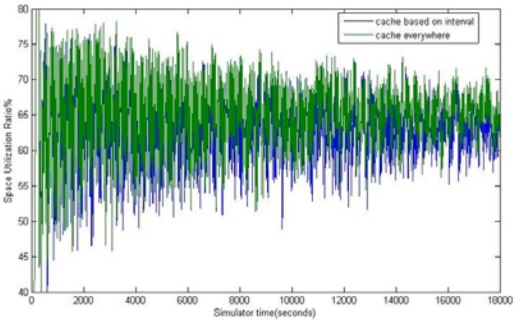
The average space utilization of the vehicle nodes is shown in Figure 3(a). Here we can see that the space utilization ratio of the nodes when interval-based caching is used is less than when information is cached everywhere. This is because information with lower popularity is cached in the network more sparsely. Moreover, the number of nodes in a fixed area affects also the density of vehicles, which contributes to the space utilization ratio.



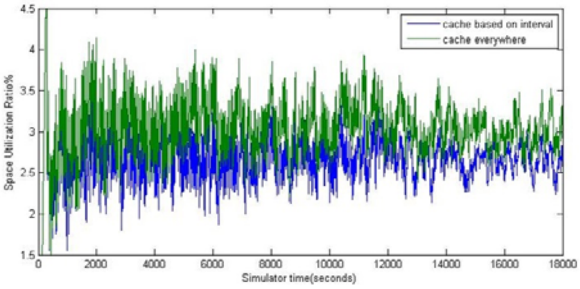
(a) Average space utilization vs. number of vehicles



(b) Average space utilization vs. cache size when node number = 300.



(c) Variation of average space utilization with time when cache size =10M, node number=300.

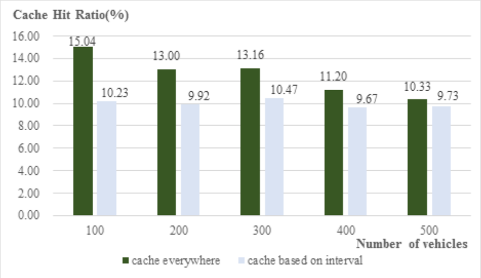


(d) Variation of average space utilization when cache size =1000M (i.e., no limitation), node number=300.

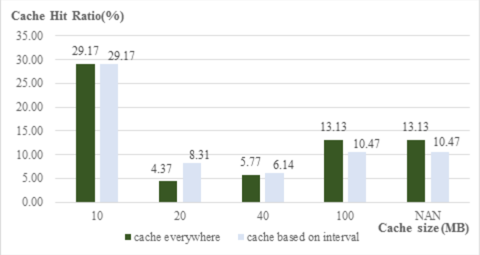
Figure 3：Average space utilization ratio in the network

Figure 3(b) shows the space utilization ratio when cache size is limited. LRU (Least Recently Used) algorithm is used to manage the cache at each node for the caching everywhere strategy, while a "lowest popularity first" cache replacement strategy is used for interval-based caching. Figure 3(c) and 3(d) illustrate the variation of the cache occupancy ratio with the time. Here we can see that the interval-based caching strategy always has better cache utilization than caching everywhere.

Figure 4 shows the cache hit ratio of caching based on interval and caching everywhere. Here we can see that when interval-based caching is used, the hit ratio decreases slightly. This is because the objects not often visited are cached more sparsely in the network in order to increase the efficiency of storage. In particular, when the cache size is limited, as shown in Figure 5(b), the cache hit ratio did not decrease with our method.



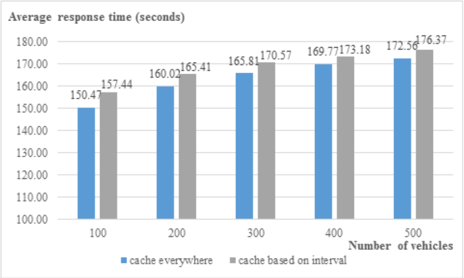
(a) Cache hit ratio vs. number of nodes in the network



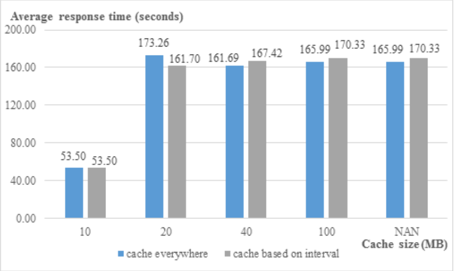
(b) Cache hit ratio vs. cache size of nodes

Figure 4: Average cache hit ratio in the network

We also compared response latency, that is, the time from sending a request to receiving the first packet of the requested data. As shown in Figure 5, our interval-based caching approach did not introduce much additional delay for information in the network, in particular for smaller cache sizes.



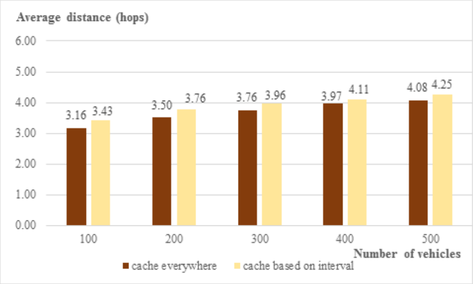
(a) Average response time vs. number of nodes in the network



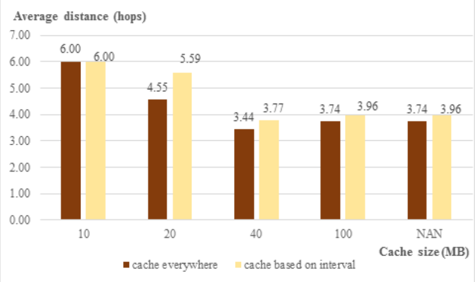
(b) Average response time vs. cache size of nodes

Figure 5: Average response time for obtaining information

Figure 6 shows the average distance (in hops) an Interest Packet travels in the network. From this figure, we can see that using the interval-based caching the average distances for finding information in the network do not increase much.



(a) Average distance vs. number of nodes



(b) Average distance vs. cache size of nodes

Figure 6: Average distance to obtain information objects in the network

Figure 7 illustrates the general relationship among the value of interval, popularity and density. Here we can see that most of the intervals are less than 6. When the density is close to 1, the interval can reach 6.

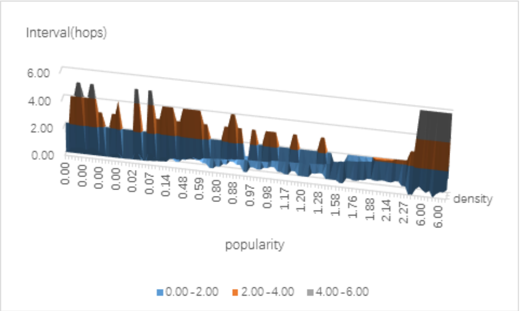


Figure 7: Relationship among interval, popularity and density

5 CONCLUSIONS

In this paper, we propose a new method for caching data in ICN-based vehicular networks. The characteristics of the information and its popularity are considered when making caching decisions. In addition, the distribution density of the vehicles is also taken into account. Simulation results show that our methods reduces the caching frequency of information and this way reduces the caching redundancy and saves storage space in the network. This saving hardly affects the average response time for obtaining information from the network. Our future work is to perform a more thorough analysis and evaluation of the characteristics of information and further consider the dynamicity of network topology on caching.

REFERENCES

[1] Jacobson,V., Smetters, D. K. and et al, “Networking Named Information”, in Proc. of 5th International Conference on Emerging Networking Experiments and Technologies, Dec. 2009

[2] Ahlgren, B., Dannewitz, C. and et al, “A Survey of Information-centric Networking”, IEEE Communications Magazine, July 2012.

[3] Grassi, G., Pesavento, D., Pau, G., Vuyyuru, R., Wakikawa, R. and Zhang, L., “VANET via Named Data Networking”, INFOCOM Workshop on Name Oriented Mobility (NOM), Toronto, Canada, April-May 2014.

[4] Leal, M., Röckl, M., Kloiber, B. and et al, “Information-centric Opportunistic Data Dissemination in Vehicular Ad-hoc Networks”, in Proc. of 13th International IEEE Annual Conference on Intelligent Transportation Systems, Madeira Island, Portugal, Sept. 19-22, 2010.

[5] Grassi, G., Pesavento, D., Pau, G., Zhang, L., Fdida, S., “Navigo: Interest Forwarding by Geolocations in Vehicular Named Data Networking”, in Proc. of IEEE World of Wireless Mobile and Multimedia Networks (WoWMoM), Boston, USA, June 2015.

[6] Zhang, L. , Afanasyev, A., Burke, J., Jacobson, V. and et al, “Named Data Networking”, ACM SIGCOMM Computer Communication Review (CCR), July 2014.

[7] Psaras, R., Clegg, G., Landa, R., Chai, W. K. and Pavlou, G. ,“Modelling and Evaluation of CCN-caching Trees”, in Proc. of IFIP Networking, Valencia, Spain, May 2011.

[8] Perino, D. and Varvello, M., “A reality check for content centric networking”, in Proc. of ACM SIGCOMM ICN Workshop, Toronto, Canada, Aug. 2011.

[9] Wang, J. M., Zhang, J., and Bensaou, B., “Intra-AS cooperative caching for content-centric networks”, in Proc. of ACM SIGCOMM ICN workshop, Hongkong, China, Aug. 2013.

[10] Bernardini, C., Silverston, T., and Festory, O., “MPC: Popularity-based Caching Strategy for Content Centric Networks”, in Proc. of 2013 IEEE International Conference on Communications (ICC 2013), Budapest, Hungary, June, 2013.

[11] Keränen, A., Ott, J., and Kärkkäinen, T., “The ONE simulator for DTN protocol evaluation,” in Proceedings of the 2nd international conference on simulation tools and techniques, 2009. 10.ONE simulator,

[12] DTN, “Delay Tolerant Networking Research Group”; http://www.dtnrg.org