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Improving Traffic Information Retrieval in VANET with NDN

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***Abstract*—Traffic Information System (TIS) is a major application over vehicular networks. Decentralized TIS relies on vehicle-2-vehicle communications, and efficient traffic information dissemination is a major challenge. In this paper, we propose a preliminary design to support the traffic information retrieval in vehicular ad hoc networks (VANET). Our design adopts an information-centric communication model, and a probabilistic forwarding strategy based on names and geolocations. We implemented a prototype of our design and evaluated its performance in ndnSIM.**

***Index Terms*—vehicle-to-vehicle communication, Named Data Networking, Traffic Information System**

I. INTRODUCTION

Vehicular networking has been a hot research topic for the past decade. With emerging new wireless technologies, more in-car computational power, more and more exciting applications for vehicular context are proposed and developed. Traffic information system (TIS) is an important and representative form of application. TIS provides drivers with real-time information of the traffic ahead such as congestion or accident, helping the driver or in-car systems make driving-related decisions.

Traditional TIS uses traffic information center as the hub for traffic information propagation, which requires infrastructure and suffers from high delay, low data rate and reliability. Alternatively, later work utilizes vehicle-to-vehicle (V2V) communication to reduce the dependency on infrastructure and centralized servers. Specifically, Self-Organized TIS (SOTIS) [1] is a decentralized TIS design that entirely relies on V2V communication. In SOTIS, vehicles are both the source and sink of traffic information; the vehicles are equipped with wireless devices, and construct a typical vehicular ad hoc network (VANET) environment; the SOTIS design relies on efficient information dissemination in VANET.

Named-Data Networking (NDN) [2] is a proposed information-centric network architecture. NDN focuses on named data retrieval, instead of point-to-point packet delivery; the network identifies the immutable and named data directly, and data is "pulled" by explicit request for data (Interest), instead of "pushed" out to and exchanged between communication endpoints as in TCP/IP. Since NDN is not connection-based, the information-centric paradigm is more friendly to VANET; compared to IP-based solutions, NDN-based solutions do not require changes to the principles of the underlying network layer.

In this paper, we propose a preliminary design for retrieving traffic information in VANET with NDN. Our goal is to provide network layer support for decentralized TIS. The design aims to make use of the data-centric communication model to redefine forwarding in VANET. For VANET in TCP/IP context, one major issue is forwarding packets to a specific endpoint under high dynamics. The data-centric communication model of NDN gets rid of explicit locators such as IP address, and transforms the forwarding problem to forwarding Interest to potential data sources, i.e., forward Interest to where data may be found.

By enabling active caching of data on vehicles, we transform the problem of forwarding Interest to a specific vehicle to guiding Interests to an area where the probability of meeting the requested data is maximized. We take three measures to accomplish this goal. First, by application namespace design, we incorporate geolocation into data names, so that the name marks the location of the traffic information carried in the data; second, we make data available in the region close to the source of the traffic information by proactive data propagation and caching, effectively making a vehicle the data mule only for the traffic information nearby; third, we employ name-based collision avoidance measures to 1) serialize data transmission in a distributed manner with random timers, 2) reduce the number of transmissions by suppressing unnecessary transmissions, both based on the name of received packets. Finally, the proposed design is implemented and evaluated with ndnSIM [3].

II. BACKGROUND

A. VANET and Wireless Technology

In VANET, vehicles communicate with each other over wireless medium. The widely adopted Wi-Fi technology, which is based on IEEE 802.11 standard, does not provide adequate support for V2V communications; the issues include the

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inability to be in infrastructure mode and ad hoc mode at the same time, time consuming association and switching process, etc. [4]. IEEE 802.11p [5], or Wireless Access in Vehicular Environment (WAVE), emerges as an approved amendment to the IEEE 802.11 standard; it defines enhancements to 802.11 required to support Intelligent Transportation Systems (ITS) applications. 802.11p is designed for data exchange both between high-speed vehicles (V2V) and between the vehicles and the roadside infrastructure (V2I), so called V2X communication.

For wireless transmission collision avoidance, 802.11p currently provides carrier sensing mechanisms, i.e., a node first checks if the the medium is busy before sending. Specifically, the enhanced distributed channel access (EDCA) is adopted by 802.11p as the MAC method. EDCA evolves from the basic distributed coordination function (DCF) from 802.11. EDCA uses CSMA with collision avoidance (CSMA/CA), which means that the node first listens to the channel until it is free for an AIFS (arbitration inter-frame space), at which point the node starts transmitting. If the channel becomes busy during the AIFS, the node must backoff. The negotiation-based RTS/CTS mechanisms adopted by Wi-Fi for collision avoidance is currently not adopted by 802.11p, because it introduces significant delay [6].

B. *Traffic Information System*

Traffic information system (TIS) is an important form of vehicular application. Typically, a TIS collects and processes current traffic data, then the data is disseminated to vehicles for the driver or in-car systems to use, typical usages include route advisory and optimizing cruise speed for emission control.

Traditional TIS is centralized and infrastructure-based. Centralized TIS faces many challenges including but not limited to: a large number of sensors needs to be deployed in order to monitor the traffic situation; the traffic information service is limited to streets where sensors are integrated; traffic information is distributed with a relatively high delay (typically in the range of 20-50 minutes); an extremely large investment for the communication infrastructure (sensors, central unit, wired and wireless connections) is necessary.

Alternatively, Wischhof et al. [1] proposed SOTIS, a decentralized TIS design. In SOTIS, each vehicle collects local traffic situation by sensing the nearby environment and receiving updates from other vehicles; each vehicle also analyzes the information locally and generates traffic information; no sensors, central units or communication infrastructures are needed. The deployment of a decentralized TIS such as SOTIS is much easier than a centralized TIS, and no service fee are required for end users to use a decentralized TIS.

C. *NDN Basics*

NDN features a stateful forwarding plane, which enables a pull-based communication model. Data (Data packets) is fetched by explicit requests (Interest packets), each forwarder maintains three main data structures to support the data retrieval process: Forwarding Information Base (FIB) contains the forwarding information for name prefixes; Pending Interest Table (PIT) keeps track of received and unsatisfied Interests, and guides Data back to the consumer in a hop-by-hop fashion; Content Store (CS) caches received Data packets to satisfy future Interests. Each time an Interest comes, the incoming network interface is recorded for the Interest in PIT, and the Interest is forwarded according to the information in FIB, eventually reaching the data producer; after receiving Data, the Data is forwarded through the incoming interface of the corresponding Interest, eventually being forwarded back to the consumer.

III. RELATED WORK

A. *VANET and NDN*

The connection-less communication model of NDN naturally fits the characteristics of VANET, especially for reducing the volume of data traffic and dealing with communication loops; various attempts have been made to solve the VANET communication problem using NDN semantics.

Wang et al. [7] targets rapid propagation of data in VANET. The design involves various mechanisms aimed at efficiently propagating data further away, where the data is of more potential value. We also incorporate location information into names, and mitigate transmission collisions with random timers; but instead of maximizing the propagation range of data, we aim to make data available within a specific region, and fetch data with multi-hop Interest forwarding, enhancing the scalability of the design.

Navigo [8], an extension to their prior work V-NDN [9], is a recent work that addresses the Interest forwarding problem in VANET. Navigo maps data names to geolocations through self-learning, and introduces *geo-face* for geolocation-based forwarding without routing protocols. Our work further explores the direction of multi-hop forwarding of Interests without routing, but focuses on a more specific fraction of application, namely traffic information sharing, while Navigo aims to provide general support for all kinds of applications, especially those for recreational purposes, e.g., music streaming; we assume that the data names incorporate geolocation information in them, and the semantics are understood by all vehicles[1], thus we eliminate the process of learning the mapping between data names and geolocations. Also, we explore the direction of active data pushing, as adopted by [7], in the hope of achieving significant delay reduction with reasonable extra network cost.

CarSpeak [10] addresses the problem of localized information sharing among autonomous vehicles in a content-centric way. The data generated by in-car or roadside sensors are organized into a structured tree and broadcasted to one-hop neighbors. CarSpeak adopts a distributed protocol to coordinate the usage of wireless medium across nearby vehicles. Our work complements CarSpeak in the sense that the propagated information is derived from sensory data and are more valuable

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[1] Situations related to partial coverage is covered in future work.

to vehicles further away, thus the two can work together to further optimize autonomous driving.

B. Data Spot

Yu et al. [11] coined the term data spot to refer to a data-centric way to address producer mobility in NDN. Instead of directing Interest towards the producer, data spot directs Interest to an area where the requested data may be found. Data spot provides a geo-aware method to help Interests meet Data, and usually does not require running routing protocols. Data spot especially fits ad hoc environments where routing protocols is more expensive and less efficient.

Data spot supports the applications where "data is associated with a specific geographical region and can be generated by any mobile producer 'on the spot"'. Examples include: DMND [12] facilitates the collection of diagnosis information for a specific car model in a specific area, which is a common need for car manufacturers; V-NDN [9] supports road traffic applications that generate road condition reports for the current location. TIS also falls into this category, because the data about the traffic information at a certain location can be generated by any of the vehicles (the mobile producer) recently within the region (the "spot"). If a vehicle leaves the region, it stops receiving Interests for the data bound with the region, while other vehicles in the region will continue to serve as the producer for the data.

IV. THE DESIGN

In this section, we propose our systematic design for data retrieval in VANET under NDN semantics.

Our design serves SOTIS-like applications, which means each vehicle may generate traffic information for nearby regions based on sensor data. Thus, each vehicle is a potential data producer, and the data it produces is bound to a specific nearby region.

To bind data to geographic regions, we adopt a namespace design to incorporate geolocation information into data names, denoting a specific road segment (§ IV-A). To fetch traffic information data of a region, Interests are forwarded towards the source region, i.e., the data spot, or the *source*, of the traffic information to be fetched according to names; Interests are first forwarded towards the region, and then propagated in all directions within the region with a probabilistic approach (§ IV-D). To mitigate packet losses caused by the vehicle mobility, and reduce the data retrieval delay, we make data available within the vicinities of the source by actively pushing data out within nearby region (§ IV-C). To mitigate wireless transmission collisions, we adopt random waiting timers for transmissions (§ IV-E). To cope with intermittent connectivity, we utilize the mobility of vehicles to extend the propagation range of Interests by making each forwarder rebroadcast sent packets multiple times (§ IV-F).

We make the following assumptions with the vehicles: each vehicle is equipped with 1) a wireless device, 2) a GPS, a 3) digital street map, 4) sensors, and 5) traffic information analysis unit [1]. Each vehicle should be equipped with an SOTIS-like system, which means it picks up and analyzes readings of the sensors and generates traffic information at any arbitrary pattern.

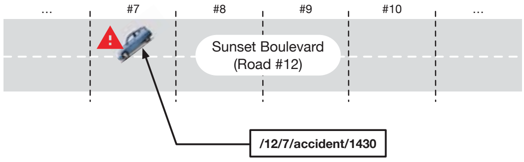

Fig. 1. Namespace design

A. Namespace design

A piece of traffic information is bound to a specific region, i.e., the source. Since traffic information is always about a segment of a road or the surroundings, the source can be easily represented by a road segment. In this section, we sketch a simple namespace design to incorporate road segment information into data names[2].

A road segment is identified by a tuple $\{id_r, id_s\}$; id_r is the ID of a road, and id_s is the ID of a road segment that the location of the source falls into, as shown in Figure 1 . The tuple in encoded as the first two components of data name, and rest of the name consists other application-specific information such as the type, and generation time of the traffic information. As shown in Figure 1, the data that contains the information of a traffic accident spotted in segment #7 of road #12, at 2:30 PM[3] is named $/12/7/accident/1430$.

Note that for this naming scheme to work, the vehicles must meet several assumptions, including: equipped with a GPS, has knowledge of the roads and the segmentation. These requirements are automatically met if the vehicle is equipped with a navigation system, which is pretty common these days.

B. Forwarder Tagging

In our design, each transmitted packet will carry the geolocation information of the last hop as hop-by-hop link-layer information, which is also widely adopted by various related works [7], [8], [13], [14]. We refer to such information as *geo-tag*; before a forwarder broadcasts a packet, the forwarder adds or updates the geo-tag in the packet to the current position of the forwarder. We refer to the process as *packet tagging*. After receiving a tagged packet, the forwarder learns about the geolocation of the last hop forwarder, and makes forwarding decisions accordingly.

C. Data Pushing

For NDN in infrastructure network, if a forwarder receives data that do not match any PIT entry, the data is regarded as *unsolicited data* and will be dropped. In our design, the unsolicited data is cached and forwarded, or "pushed" further

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[2] The namespace design is proposed only for demonstration, more details on naming details is irrelevant to the overall design, thus not discussed further.

[3] Traffic information has a relatively short lifespan, thus time is encoded into the name at minute level.

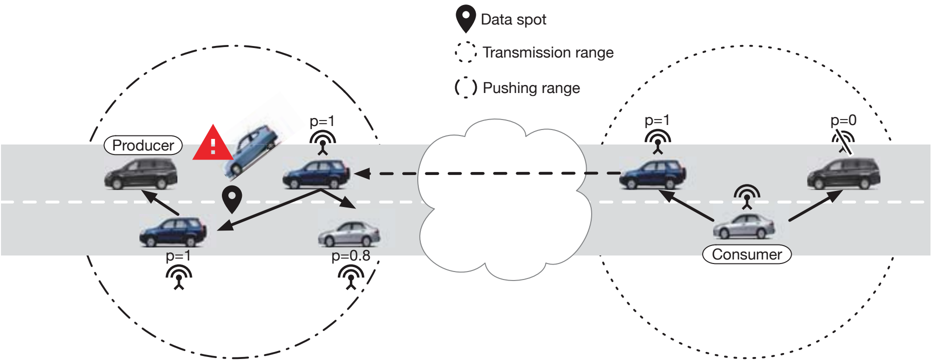

Fig. 2. Interest forwarding

to enhance the availability of the data in the highly dynamic vehicular network environment.

Data pushing is a controlled active data propagation process. Upon receiving an unsolicited Data packet that has not been cached[4], the forwarder learns the geographical coordinates of the source from the name by mapping the road segment information to a digital road map, and calculates the current distance to the source d[5]; the forwarder will broadcast this Data packet with the probability of $p = \frac{D}{D+d}$, where D is a parameter that controls the range of pushing, namely *pushing range*; the bigger D is, the more likely a forwarder further away from the source will broadcast the data. Note that Data pushing also makes each car a potential data mule for both solicited and unsolicited data, fully utilizing the in-car data storage capabilities.

D. Interest Forwarding

In this section we introduce how Interests are forwarded according to geolocations. A forwarder outside of the pushing range will only forward Interests from a last hop that is further away from the source, as shown in the right half of Figure 2, so that the Interest is forwarded towards the source. A forwarder inside the pushing range takes a probabilistic approach, as shown in the left half of Figure 2: a forwarder V will forward, i.e., broadcast the Interest at probability $p = (\frac{min(d_t,d)}{d})^3$, where d_t is the distance between the last hop forwarder and the source, and d is the distance between V and the source; in other words, if the last hop is further away from the source, V will always forward the Interest; if the last hop is nearer to the source, V may still forward the Interest, but the probability rapidly drops the nearer the last hop is to the source; such a probabilistic approach takes the data availability within the pushing range into account, allowing Interests to fetch data from nearer caches, reducing the data retrieval delay.

E. Transmission Waiting and Suppression

In VANET, packets are broadcasted to all vehicles within transmission range, and the forwarding process, i.e., multi-hop broadcasting, may cause *broadcast storm*; also, as mentioned in [7], if multiple nearby vehicles receive an Interest that can be satisfied from cache at approximately the same time, when they send Data back, the transmissions will very likely collide and fail; while the medium becomes busy, preventing others from sending, no packet is successfully sent out.

Wisitpongphan et al. [14] suggest mitigating the broadcast storm issue by waiting before transmission and suppress transmissions according to the overheard packets during the waiting period; in the same spirit, we employ the following name-based mechanisms to mitigate the broadcast storm issue, and space out nearby transmissions.

For each packet to be broadcasted, the sender first performs *random waitng*; a random waiting period is picked between 0 and T_w; during the waiting period, the sender conducts *transmission suppression* depending on overheard packets. If an Interest is awaiting transmission, the transmission may be cancelled by a received Interest or Data with the same name; in the former case, the transmission is cancelled if the Interest comes from a forwarder *closer* to the source, in the latter case, the Interest is satisfied and does not need to be sent out. If a Data is awaiting transmission, the transmission will be cancelled by a received Data with the same name if the Data comes from a forwarder *further* away from the source.

F. Packet Retransmission

VANET suffers from short link durations and rapidly changing topology [15], and the wireless medium adopted by VANET provides no acknowledgement for sent packets. However, as suggested by [9], overheard packets can serve as implicit acknowledgements. Thus we make each vehicle retransmit sent packets multiple times until it receives an implicit acknowledgement, i.e., the same packet.

Specifically, for each sent packet, the forwarder will broadcast it for up to n times at the interval of T_r. The retransmission for the packet will cease when the upper limit is reached or when the scheduled transmission is suppressed, as described in IV-E. T_r should be significantly bigger than the waiting timer to allow time for nearby vehicles to transmit the packet, preventing unnecessary retransmissions.

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[4] Which implies the Data has not been received before, or at least no for a while, assuming the cache is big enough to hold recently received Data.

[5] Currently, the distance is the straight line distance between the two coordinates, refer to [8] for a method that considers the road shape.

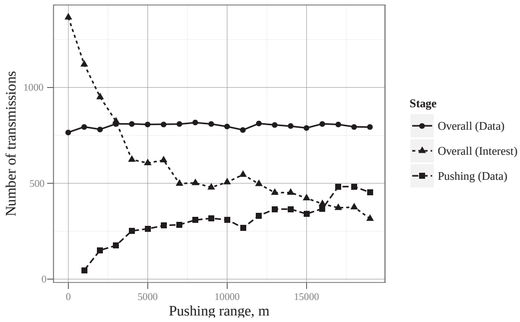

Fig. 3. Number of packets transmitted vs. pushing range

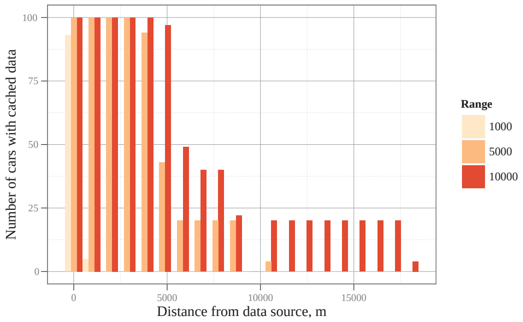

Fig. 4. Number of vehicles with cached data at different distances from the source vs. pushing range

V. Evaluation

We implemented the design as a prototype in ndnSIM, and evaluated its performance in terms of user experience and network cost. The source code can be found at [16].

A. Simulation Setup

We simulate the data retrieval process in a highway with vehicles traveling in one direction. 100 vehicles are placed along a straight line, the distance between two adjacent vehicles is randomly chosen between 50 and 100 meters; the vehicles travel at the same fixed speed of 60 miles per hour. For the wireless medium, we use the NS3 802.11p implementation; the transmission power is set to 5 dbm (3.16 mW), and antenna gain is set to 1; for receivers, the minimal energy level is set to -96.0 dbm; Nakagami propagation process is used to simulate signal losses; with these settings, packet delivery ratio is about 90% for receivers 50 meters away from a transmitter. For retransmission parameters, n is set to 6, and D_i is set to 200.

B. The impact of Data pushing

In this section, we investigate the impact of different pushing ranges on the number of overall transmissions and data propagation.

For a specific piece of Data, its propagation first happens during the active pushing process, i.e., the pushing stage. Generally, the further data is pushed out to, the more Data packets are transmitted in the pushing stage, meanwhile, the number of Interests and Data packets transmitted to retrieve the data should decrease because the data is available nearer to the consumer. Thus, we measured the total number of Interest and Data packets transmitted in the network under different push range settings in the pushing stage and for the overall data retrieval process. Figure 3 shows that although more Data packets are transmitted in the pushing stage for broader pushing range, the number of packets transmitted to complete the data retrieval doesn't fluctuate much. This is because the propagation range of consumer's Interest shrinks if the Data is fetched from a nearer vehicle, and less vehicles need to forward the Interest towards the source, and forward Data back towards the consumer.

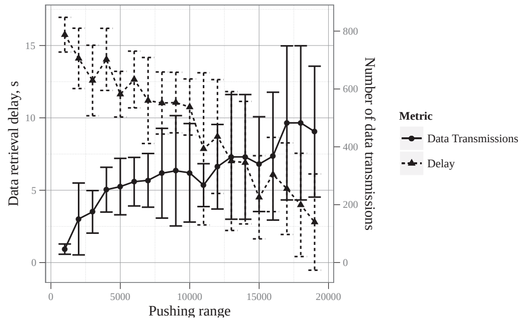

Fig. 5. Data retrieval delay and Data transmissions vs. pushing range. The delay drops rapidly as pushing range increases, and slows down at 5000 meters. Meanwhile, the number of Data transmissions in pushing stage rises with pushing range, with increasing slope.

To further investigate what happens in the pushing stage, and how it is affected by the pushing range, we count the number of vehicles that has the data in cache after pushing stage at different distances from the source. Figure 4 shows that the pushing range significantly impacts the distribution of vehicles with cached Data, demonstrating the effectiveness of different pushing range settings.

C. Data retrieval

In this section, we show results observed from the data retrieval process. A consumer and a producer is placed at each end of the highway, the producer first pushes a Data packet out, and after 60 seconds, the consumer sends an Interest out to retrieve the data. For these results, the transmission waiting time T_w is set to 2 ms, and we try different pushing ranges, setting D from 100 to 1000 meters. We run 50 simulations with different random number generators for each pushing range setting.

Figure 5 shows the end-to-end data retrieval delay and the number of transmissions for Data packets in the corresponding pushing stage under different pushing ranges. The results show that the delay is significantly reduced when data is actively pushed out. This is because the pushed Data is cached by vehicles nearer to the consumer, and the consumer's Interest can fetch Data back sooner. The difference is also magnified by the packet losses, which are common in VANET environment. Meanwhile, with pushing range set larger, the number of cars

TABLE I
COMPARISON WITH TWO CONCEPTUAL SCHEMES

Name	Delay	Delay.SD	Transmissions	Transmissions.SD
Pure-P	2.53	0.32	793	32.79
Hybrid	11.64	1.58	807	31.55
Pure-IF	16.97	0.69	766	107.05

that actively pushes Data out also increases, which means more bandwidth is consumed by the Data packet.

We also compare our solution (hybrid) with two conceptual schemes: pure pushing (pure-P), and pure Interest forwarding (pure-IF). The former takes the approach similar to [7], where Data is actively pushed out to as far as possible; the latter takes the approach similar to [8], where no data is pushed out, and Interests are forwarded according to geolocations. Our approach is somewhere in the middle, and we wish to find out whether we can reach a sweet spot by setting a reasonable pushing range, reducing delay and mitigating the redundant transmissions. For the comparison, we set the pushing range to 5000 meters, which is where the dropping rate of delay begins to decrease. Table I shows the average delay and network cost for the three schemes. As expected, for the delay, our solution stands in the middle, offering adequate performance. However, the total number of overall data transmissions is roughly the same for all three schemes, implying the advantage of uncontrolled data pushing. We argue that 1) not all data are useful, i.e., will be retrieved by vehicles far away, so pushing data as far as possible may be a waste of valuable wireless bandwidth; 2) the data retrieval process can be further tuned to reduce the number of transmissions, so that an optimal pushing range can be picked, and we will briefly cover the topic in VI-A.

VI. DISCUSSION

The effectiveness of the proposed design is subject to various factors, which we briefly discuss here to pave the way for future work.

A. Tuning the data retrieval process

In the current design, even if the transmission of an Interest packet is suppressed, a PIT entry is still created for the Interest because the suppression happens at link layer, which normally does not impact PIT operations. However, this means after receiving the corresponding Data, the vehicle will always try to broadcast it because the Data is solicited. Considering the observation made by [8], that the PIT is resilient against VANET dynamics, we can prevent the creation of a PIT entry if an Interest is suppressed, and let only those vehicles that actually sent Interest out relay Data back to the consumer. We expect this to reduce the traffic volume for the data retrieval process, and will go on to explore this direction in our future work.

B. Two-way traffic

For two-way traffic, vehicles coming from the other direction may serve as more efficient data mules for traffic information. Which also helps dealing with intermittent connectivity issue. Note that two-way traffic does not harm the performance of the proposed design, but will boost the performance with simple adjustments.

C. Data availability degradation

With time passing, and existing data mule leaving the area, some data may no longer be available near the source. However, we make three observations: 1) the traffic information is real-time information, which means it has a relatively short lifespan; 2) the data is cached along its way back to the consumer, these cars become new data sources that may satisfy the requests before they are forwarded to the source region; 3) traffic information keeps generating, actually, to avoid fetching stale information, a freshness period may be added to Data packets to allow later Interests be forwarded to the source to fetch newly generated data.

A particular case is at major highway exits, the data availability may go through significant drop due to a non-trivial portion of the cars exiting the highway. However, a major exit should also see bigger traffic, which means that cars keep coming into the region to replace the exited data mules.

D. Calculating distance

Our design relies heavily on comparing the distance to the source with that of the last hop. However, the mobility of vehicles are restricted by the shape of the road, thus the calculation of distance should take more factors into consideration, instead of directly computing the direct distance between two points. [8] covers the topic in details, and addresses the problem in complex urban areas. We start by evaluating the highway traffic, thus simplifies the distance calculation. In our future work, the topic will be expanded and investigated.

VII. CONCLUSION

In this paper, we proposes a simple but effective design for a specific application scenario: distributed TIS in pure VANET. The design employs the NDN semantics, and is based on a namespace design that incorporates geolocation information into data names. Instead of trying to retrieve data from a specific vehicle, our design enhances the successful rate of data retrieval by making data available within a region. We adopt adaptive Interest forwarding to forward Interests in a geo-aware way: first the Interest is guided to the vicinity of the source of the data, then is forwarded in all directions to meet the nearest vehicle with the data cached, speeding up the data retrieval process. The evaluation results show that our design offers adequate performance for the application scenario of distributed TIS, and by reasonably increasing the pushing range, the data retrieval delay can be further reduced without extra network cost. In our future work, we will refine the preliminary design and conduct further evaluations.

REFERENCES

[1] L. Wischoff, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "Sotis-a self-organizing traffic information system," in *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual*, vol. 4. Ieee, 2003, pp. 2442–2446.

[2] L. Zhang, A. Afanasyev, J. Burke, V. Jacobson, P. Crowley, C. Papadopoulos, L. Wang, B. Zhang *et al.*, "Named data networking," *ACM SIGCOMM Computer Communication Review*, vol. 44, no. 3, pp. 66–73, 2014.

[3] S. Mastorakis, A. Afanasyev, and L. Zhang, "On the evolution of ndnsim: An open-source simulator for ndn experimentation," *ACM SIGCOMM Computer Communication Review*, vol. 47, no. 3, pp. 19–33, 2017.

[4] F. Hui and P. Mohapatra, "Experimental characterization of multi-hop communications in vehicular ad hoc network," in *Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks*. ACM, 2005, pp. 85–86.

[5] D. Jiang and L. Delgrossi, "Ieee 802.11 p: Towards an international standard for wireless access in vehicular environments," in *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*. IEEE, 2008, pp. 2036–2040.

[6] C. Campolo, A. Molinaro, C. Casetti, and C.-F. Chiasserini, "An 802.11-based mac protocol for reliable multicast in multihop networks," in *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*. IEEE, 2009, pp. 1–5.

[7] L. Wang, A. Afanasyev, R. Kuntz, R. Vuyyuru, R. Wakikawa, and L. Zhang, "Rapid traffic information dissemination using named data," in *Proceedings of the 1st ACM workshop on emerging name-oriented mobile networking design-architecture, algorithms, and applications*. ACM, 2012, pp. 7–12.

[8] G. Grassi, D. Pesavento, G. Pau, L. Zhang, and S. Fdida, "Navigo: Interest forwarding by geolocations in vehicular named data networking," in *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2015 IEEE 16th International Symposium on a*. IEEE, 2015, pp. 1–10.

[9] G. Grassi, D. Pesavento, G. Pau, R. Vuyyuru, R. Wakikawa, and L. Zhang, "Vanet via named data networking," in *Computer Communications Workshops (INFOCOM WKSHPS), 2014 IEEE Conference on*. IEEE, 2014, pp. 410–415.

[10] S. Kumar, L. Shi, N. Ahmed, S. Gil, D. Katabi, and D. Rus, "Carspeak: a content-centric network for autonomous driving," in *Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication*. ACM, 2012, pp. 259–270.

[11] Y. Zhang, A. Afanasyev, J. Burke, and L. Zhang, "A survey of mobility support in named data networking," in *Computer Communications Workshops (INFOCOM WKSHPS), 2016 IEEE Conference on*. IEEE, 2016, pp. 83–88.

[12] J. Wang, R. Wakikawa, and L. Zhang, "Dmnd: Collecting data from mobiles using named data," in *Vehicular networking conference (VNC), 2010 IEEE*. IEEE, 2010, pp. 49–56.

[13] H. Füßler, J. Widmer, M. Käsemann, M. Mauve, and H. Hartenstein, "Contention-based forwarding for mobile ad hoc networks," *Ad Hoc Networks*, vol. 1, no. 4, pp. 351–369, 2003.

[14] N. Wisitpongphan, O. K. Tonguz, J. S. Parikh, P. Mudalige, F. Bai, V. Sadekar *et al.*, "Broadcast storm mitigation techniques in vehicular ad hoc networks," *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 84–94, 2007.

[15] A. Rowstron and G. Pau, "Characteristics of a vehicular network," *University of California Los Angeles, Computer Science Department, Tech. Rep*, pp. 09–0017, 2009.

[16] "Simulation code in ndnsim," 2018. [Online]. Available: https://github.com/NDN-TIS