Mobility Support in Vehicular Named-Data Networking

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Abstract. *In this thesis, Vehicular Named-Data Networking (VNDN) refers to the use of the Named-Data Networking communication model over Vehicular Ad-hoc Networks. With the aim of addressing the problems caused by mobility to efficiently support VNDN communications in highly mobile traffic scenarios, various contributions were proposed in the scope of this thesis. These contributions include a routing protocol, able to address VNDN problems such as broadcast storms and message redundancy, as well as solutions to enable content advertisements and for addressing the problems caused by reverse path partitioning, network partitioning, and source mobility. Finally, all the proposed solutions are integrated into a single framework called MobiVNDN. The evaluation results show that the proposed solutions are efficient and scalable, providing high VNDN application performance even in complex traffic scenarios.*

1. Introduction

In the context of intelligent transportation systems (ITSs) vehicular ad-hoc networks (VANETs) [Da Cunha et al. 2014], are envisioned to provide more secure, pleasant, and efficient transportation infrastructures.

VANETs enable communications among vehicles as well as between vehicles and the existing communication infrastructure and were primarily conceived with the focus on applications related to road safety and traffic efficiency. However, the robustness of vehicles regarding energy, processing power, and storage capacities enables the deployment over VANETs of infotainment applications such as video streaming, gaming on the go, and social applications (e.g., chats) that usually demand very high packet delivery ratios and low latency simultaneously. In such cases, the performance of existing communication technologies such as the IP communication model, which is point-to-point and host-based, is significantly affected by inherent VANET characteristics including highly dynamic topologies, and short and intermittent connectivity among vehicles [Da Cunha et al. 2014].

Broadcast has been adopted as an alternative to IP for content dissemination over VANETs [Da Cunha et al. 2014]. However, when the content objects to be disseminated are large (e.g., video dissemination applications) or if they are of interest for a reduced number of vehicles, broadcast imposes significant and unnecessary overhead in the wireless communication medium, increasing the probability of message collisions and decreasing application performance. In this context, Named Data Networking (NDN) [Jacobson et al. 2010] emerges as an efficient way to support general purpose VANET communications. NDN presents a communication model based on the exchange of Interest/Data messages and decentralized in-network caching and addresses issues introduced by some VANET routing protocols that depend on neighborhood information. Such information is not stable in highly mobile scenarios and requires a continuous exchange of beacons. On the other hand, NDN retrieves content objects using content names directly from the closest content source. In this way NDN also reduces content delivery delay [Anastasiades et al. 2016], it increases the number of content sources, and it decouples content objects from the original producers, increasing content availability within the network.

Despite the advantages of deploying NDN over VANETs (i.e., Vehicular Named-Data Networking (VNDN)), there are still several problems that must be addressed to support VNDN communications efficiently [Duarte et al. 2017c][Soua et al. 2017]. For instance, NDN Data messages travel through the reverse path with respect to the corresponding Interest messages and the reverse paths can break due to high mobility. On the other hand, receiver and source mobility, as well as network partitions can also significantly affect VNDN communication performance.

This thesis provides efficient solutions to each of the main VNDN problems that we identified and integrates all the proposed solutions into a single framework, named as MobiVNDN.

In the remaining of this paper, Section 2 briefly analyzes the related work, Section 3 summarizes the main contributions of this thesis and Section 4 overviews the relevant publications. Finally, Section 5 concludes this paper and indicates possible directions for future research.

2. Related Work

In this Section we highlight two of the most important works on VNDN available in the literature.

In V-NDN [Grassi et al. 2014] the authors propose an architecture that modifies some of the NDN functional requirements in order to accommodate to VANETs. All messages are broadcast and to facilitate fast data dissemination, vehicles cache received content regardless of whether it was requested or not.

CCVN [Amadeo et al. 2013] enhances the CCN/NDN architecture to provide a content retrieval and distribution framework for vehicular applications, which is compliant with the WAVE architecture. It addresses the broadcast storm and message redundancy problems. The Forwarding Information Base (FIB) table is suppressed and Interest/Data messages are exchanged through broadcast.

In [Ahmed et al. 2016] the authors propose a new mechanism to address the broadcast storm problem in VNDN called CODIE. The primary objective is to decrease the number of Data messages forwarded by intermediate vehicles, while keeping similar performance regarding Interest messages satisfied, compared to the case where the proposed mechanism is not applied.

The three works mentioned above present substantial contributions for the deployment of VNDN. The broadcast storm and message redundancy problems are addressed. However, in highly mobile scenarios the performances of V-NDN and CCVN are significantly affected by source and receiver mobility, as well as by other problems such as network partitions. Therefore, we recognized the need for a new framework able to mitigate the negative impacts of mobility and the unreliability of the wireless communication medium to support VNDN communication with high performance in highly mobile and complex traffic scenarios.

3. Main Contributions

This Section summarizes the main contributions of this thesis.

3.1. Message Routing in Vehicular-Named Data Networking

As the first contributions this thesis proposed a multi-hop routing mechanism for Interest and Data messages [Duarte et al. 2017a] enabling content requesters to retrieve content objects from distant locations. The proposed routing mechanism is also beacon-less [Heissenbüttel et al. 2004] and receiver-based [Duarte et al. 2017a].

To avoid the broadcast storm problem in multi-hop scenarios, the proposed routing mechanism minimizes the number of intermediate vehicles that forward Interest and Data messages by selecting as message forwarders only the vehicles that allow more progress towards the message destination. This is done through the use of a delay/timer approach set in a way that intermediate vehicles closer to the destination of the message calculate lower timer delays and the transmission by a vehicle inhibits the remaining neighbors from forwarding the same message. Similar to NDN, vehicles use the information stored in their Pending Interest Tables (PIT) to decide whether to forward received Data messages and any vehicle that possesses a content object or that can produce it, can act as a content source for that particular content object and provide it to content requesters through Data messages. This routing mechanism is aware of channel switchings in the wireless access in vehicular environments (WAVE) standard to prevent transmission resynchronizations [Donato et al. 2015]. To identify message redundancies, vehicles extract from received Interest messages the locations of the vehicles from whom they received the Interest message.

3.2. Content Advertisement

As the second contribution this thesis proposed a content advertisement mechanism [Duarte et al. 2019] specifically focused on VNDNs. Advertisement messages are used by content sources to advertise available content objects to potential content requesters supporting them in filling their FIBs. The proposed content advertisement mechanism extends the concept of sweet spots introduced in DRIVE [Villas et al. 2014]. A sweet spot is defined as a sub-area, in which messages sent by vehicles have a higher probability of reaching a larger number of vehicles. Thus, vehicles within sweet spots are selected with higher probability to forward Advertisement messages. The idea is to maximize message dissemination within the network with low overhead in the wireless communication medium and short delays.

After receiving a new Advertisement message, each vehicle add the name and the location information of the content object being advertised to its FIB (list of available content objects). With this information, vehicles know about existing content objects and can decide whether to request them at any time by sending Interest messages.

3.3. Reverse Path Partitioning

As the third contribution, this thesis addresses the effects of the VNDN reverse path partitioning (RPP) problem that we have identified [Duarte et al. 2017a]. RPP is defined as a disruption in the communication link between two consecutive Data message forwarders preventing them from communicating with each other and from delivering the Data message to subsequent vehicles, degrading VNDN application performance even in connected scenarios.

In a VNDN scenario very often vehicles travel at different speeds making inter-vehicle distances very dynamic. Considering this, during the time required for an Interest message to reach a content source and the corresponding Data message to travel back to the original content requester, one or more of the Data message forwarders (i.e., the vehicles that forwarded the corresponding Interest message) might get out of the transmission range of the subsequent Data message forwarder. In such a case, an RPP occurs. On the other hand, other factors can also lead to the occurrence of RPP. For instance, vehicles can be equipped with communication devices of different reach, antennas located in higher vehicles might provide better lines of sight consequently extending the communication reach, and the transmission range of a vehicle can suffer temporary attenuations due to obstacles or other conditions of the wireless communication medium.

To address the effects of RPP, this thesis proposes the concept of Auxiliary Forwarding Set (AFS). AFS takes as inputs the distance and speeds of vehicles, as well as the maximum transmission range and the maximum expected content delivery delay to determine the probability of RPP occurrence between consecutive Interest message forwarders. Whenever the probability of RPP between two vehicles is detected, AFS selects an extra set of vehicles as candidates to also forward the Data message, as opposite to NDN where only the vehicles that forwarded the corresponding Interest message can forward the Data message. This extra set of vehicles form an AFS group, and in case the Data message is not received by an original Data message forwarder, the vehicle in the AFS group that is closer to it retransmits the Data message. The original forwarder then receives the Data message, and the reverse path is reconnected.

3.4. Network Partitions

The fourth contribution of this thesis addresses the problem of network partitions in VNDN [Duarte et al. 2017b].

We define the network partition problem as the case where a vehicle wishing to send or forward and Interest message towards a content source is unable to do so because it is currently not connected to any vehicle closer to the destination of the Interest message. Network partitions are more frequent and harmful in sparse VNDN scenarios where the density of vehicles is low. However, this problem might also occur in VNDN scenarios with high vehicle densities due to signal attenuations caused by obstacles and other disturbances in the wireless communication medium.

To address the problem of network partitions, this thesis proposes two different solutions based on the availability of infrastructure. The first solution is VNDN agent delegation and the second one is called VNDN store-carry-forward (VNDN-SCF). The VNDN agent delegation approach, which is inspired on agent delegation [Anastasiades et al. 2016], targets scenarios with infrastructure support. The main idea is that when nodes are unable to connect to content sources to request content objects, content requests can be delegated to other nodes that are able to communicate with a content source and again with the content requester in the future to deliver the requested content object. A VNDN communication mechanism specifically designed for road side units (RSUs) was developed. In the case of network partition occurrence, content retrieval is delegated to these VNDN enabled RSUs. Since the VNDN RSUs form a network of static and connected nodes, they can efficiently retrieve requested content objects from distant locations with short delays and provide high application performance.

For scenarios without infrastructure support VNDN-SCF is applied. In VNDN-SCF a vehicle after sending or forwarding an Interest or a Data message keeps overhearing the wireless communication channel to perceive whether the message is received and forwarded by subsequent neighbor vehicles. When a message is not forwarded by any neighbor vehicle, the current vehicle buffers the message and keeps periodically retransmitting it until a communication link is available and the message is delivered to another vehicle.

3.5. Content Source Mobility

The fifth contribution of this thesis targets the problem of content source mobility [Duarte et al. 2018].

In VNDN if a vehicle is interested in receiving a content object, it can request it by sending an Interest message with the content name towards the location where the content object was advertised. However, the probability of Interest messages reaching the content producer decreases proportionally as the content producer vehicle moves. For the case of popular content objects, several content requests might be satisfied by third party vehicles through cached copies. In the case of unpopular content objects, the probability of finding a copy of the content object in the caches of neighbor vehicles is low. To solve this problem this thesis applies the concept of floating content [Duarte et al. 2017c][Soua et al. 2017]. Whenever a node moves away from the location where it advertised a content object, it replicates the content object to the remaining nodes in that particular region. In this way, the content object may be available on a set of nodes and floats over time within the same region and it still available after the node that initially generated it left. The content region called anchor zone (AZ) is defined by a center (i.e., the geographic location where the content object was produced) and a radius. When receiving a replica of a content object, vehicles check whether they are within the AZ for that particular content object. In such a case, they cache the content and become content sources for that specific content object. When leaving the AZ they also replicate the content to the other vehicles within the AZ and delete the content object.

3.6. Mobility Support for Vehicular Named-Data Networking

As the last contribution, this thesis proposed MobiVNDN [Duarte et al. 2019], a distributed framework designed to enhance VNDN communications and improve application performance in both highway and urban traffic scenarios, regardless of the degree of mobility and network node density.

The MobiVNDN framework integrates all the solutions described in the previous contributions. Summarizing, MobiVNDN simultaneously supports the routing of Advertisement, Interest, and Data Messages, it prevents the broadcast storm, message redundancy, and transmission resynchronization problems, and it addresses the effects of reverse path partitioning, content source mobility, and network partitions.

In the following we quickly compare the MobiVNDN performance with respect to VNDN (i.e., the plain adaptation of NDN to VANETs) and the message routing mechanism proposed in V-NDN [Grassi et al. 2014] (i.e., a framework focused on NDN over VANETs from the literature).

The performance metrics applied are Interest Satisfaction Ratio (i.e., ISR - the average percentage of content objects received in response to content requests) and Delay per Interest Satisfied (i.e., Delay - the average time difference between sending an Interest message and receiving the corresponding Data message by a content requester).

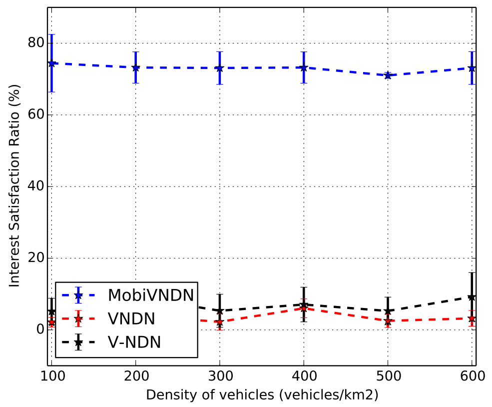

Figure 1. ISR - Urban Scenario

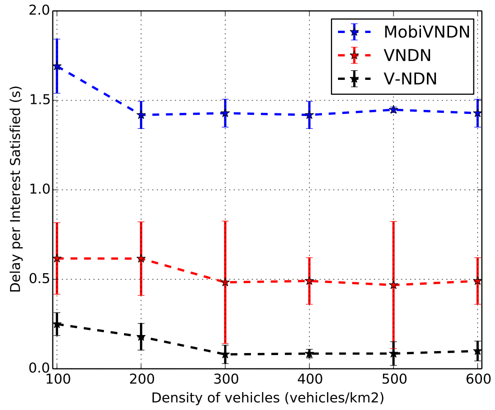

Figure 2. Delay - Urban Scenario

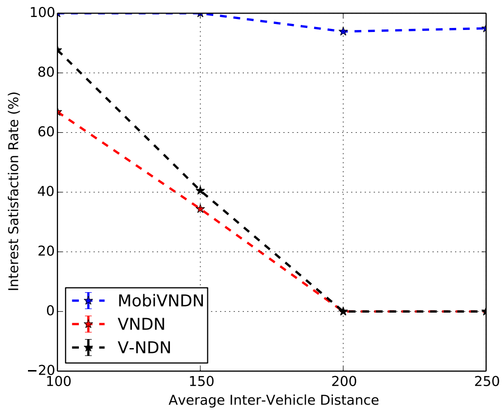

Figure 3. ISR - Highway Scenario

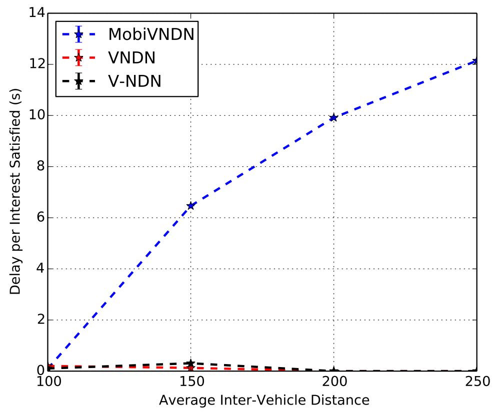

Figure 4. Delay - Highway Scenario

Evaluations were conducted in urban as well as in highway traffic scenarios. As it can be seen in Figures 1,2,3, and 4 MobiVNDN significantly outperforms the other solutions regarding Interest Satisfaction Ratio and the Delay in MobiVNDN is either lower or equal than the Delay in VNDN and V-NDN. Figures 5 and 6 also show that MobiVNDN is scalable as it maintains high performance regardless of the number of concurrent applications. For detailed explanation please refer to the MobiVNDN paper [Duarte et al. 2019] or the thesis.

4. Publications

As results of this thesis, we had the following publications:

4.1. Journal Publications

- Joao M. Duarte, Torsten Braun, and Leandro A. Villas. "MobiVNDN: A distributed framework to support mobility in vehicular named-data networking." Ad Hoc Networks (2018).
- Joao M. Duarte, Eirini Kalogeiton, Ridha Soua, Gaetano Manzo, Maria Rita Palattella, Antonio Di Maio, Torsten Braun, Thomas Engel, Leandro A. Villas, and

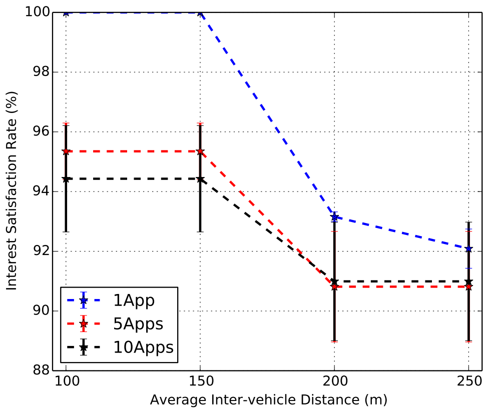

Figure 5. ISR - Multiple Applications

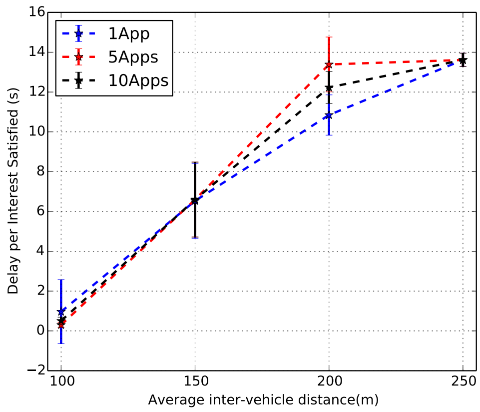

Figure 6. Delay - Multiple Applications

Gianluca A. Rizzo. ”A multi-pronged approach to adaptive and context aware content dissemination in VANETs.” Mobile Networks and Applications (2017): 1-13.

4.2. Conference and Workshop Publications

- Joao M. Duarte, Torsten Braun, and Leandro A. Villas. ”Receiver Mobility in Vehicular Named Data Networking.” In Proceedings of the SIGCOMM Workshop on Mobility in the Evolving Internet Architecture, pp. 43-48. ACM, 2017.
- Joao M. Duarte, Torsten Braun, and Leandro A. Villas. ”Source mobility in vehicular named-data networking: An overview.” Ad Hoc Networks. Springer, Cham, 2018. 83-93
- Joao M. Duarte, Torsten Braun, and Leandro A. Villas. ”Addressing the Effects of Low Vehicle Densities in Highly Mobile Vehicular Named-Data Networks.” In the 6th ACM MSWIM Symposium on Development and Analysis of Intelligent Vehicular Networks and Applications.
- Soua, Ridha, Eirini Kalogeiton, Gaetano Manzo, Joao M. Duarte, Maria Rita Palattella, Antonio Di Maio, Torsten Braun, Thomas Engel, Leandro A. Villas, and Gianluca A. Rizzo. ”SDN coordination for CCN and FC content dissemination in VANETs.” In Ad Hoc Networks, pp. 221-233. Springer International Publishing, 2017
- Donato, Erick, Guilherme Maia, Joao M. Duarte, Antonio AF Loureiro, Edmundo Madeira, and Leandro Villas. ”PResync: A method for preventing resynchronization in the IEEE 802.11 p standard.” In Computers and Communication (ISCC), 2015 IEEE Symposium on, pp. 457-462. IEEE, 2015.

5. Final Remarks

To accomplish the main objective of this thesis, a set of partial contributions were first proposed. At the end, all the partial contributions were integrated into the MobiVNDN framework to provide high VNDN application performance. The contributions of this thesis were published in international workshops, conferences, and journals. Future opportunities for extending the scope of this thesis include data structures management, content naming, and caching techniques.

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