Universidade Estadual de Campinas
Instituto de Computação

João do Monte Gomes Duarte

Mobility Support in Vehicular Named-Data Networking

Suporte de Mobilidade em Redes Veiculares Centrados em Nome de Dados

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2018

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Supervisor/Orientador: Prof. Dr. Leandro Aparecido Villas e Prof. Dr. Torsten Braun

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Banca Examinadora:

- Prof. Dr. Leandro Aparecido Villas
  Instituto de Computação - UNICAMP
- Prof. Dr. Torsten Braun
  Instituto de Ciência da Computação - UNIBE
- Prof. Dr. Edmundo Roberto Mauro Madeira
  Instituto de Computação - UNICAMP
- Prof. Dr. Antonio Alfredo Ferreira Loureiro
  Departamento de Ciência da Computação - UFMG
- Prof. Dr. Eduardo Coelho Cerqueira
  Faculdade de Engenharia de Computação e Telecomunicações - UFPA
- Prof. Dr. Heitor Soares Ramos Filho
  Instituto de Computação - UFAL

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Resumo

Na presente tese, Vehicular Named-Data Networking (VNDN) refere-se ao uso do modelo de comunicação de Named-Data Networking (NDN) em Redes Ad Hoc Veiculares (VANETs). As VANETs tornam possíveis as comunicações veiculares e contribuem para o desenvolvimento de sistemas de transporte mais inteligentes, seguros, eficientes, e agradáveis.

NDN atribui nomes únicos a cada conteúdo disponivel na rede e não utiliza endereços IP. Com base em armazenamento em cache descentralizado NDN cria redundância de conteúdos na rede, o que é útil para otimizar a utilização dos recursos de rede e melhorar o tempo de resposta e disponibilidade de conteúdos. Desta forma, NDN melhora o desempenho de aplicações em VANETs quando comparado com outras técnicas de comunicação como IP, que se concentram em hosts em vez de conteúdos.

Esta tese de doutorado propõe soluções eficientes para mitigar os efeitos negativos nas comunicações veiculares que são introduzidos pela alta mobilidade dos veículos e pelas comunicações sem fio. Entre as contribuições, esta tese propôe uma nova arquitetura VNDN e um protocolo de roteamento geográfico para rotear mensagens entre as fontes de conteúdo e os solicitantes. O protocolo proposto ainda evita os efeitos de problemas bem conhecidos em VANETs, incluindo tempestades de broadcast, redundância de mensagens e ressincronização de transmissão. Esta tese também investiga os efeitos da mobilidade dos veículos solicitantes de conteúdo em VNDN e identifica o problema da Partição do Caminho Inverso (PCI). Para solucionar o problema de PCI se propõe o Conjunto Auxiliar de Encaminhamento (CAE). CAE determina a probabilidade de ocorrência de PCI e quando necessário elege um conjunto extra de veículos como candidatos para encaminhar mensagens em direção aos seus destinos, em oposição ao padrão NDN original, onde apenas os nós que encaminharam uma mensagem de interesse podem encaminhar a mensagem de dado correspondente. Esta tese investiga ainda os problemas causados pela mobilidade das fontes de conteúdo e partição de rede em VNDN. Para solucionar o problema da mobilidade das fontes de conteúdo se propõe o conceito de conteúdo flutuante (CF). Para resolver o problema das partições de rede, duas soluções diferentes foram propostas. Para os casos em que existe infra-estrutura, as solicitações de conteúdos podem ser delegadas ás Road-Side-Units (RSUs), enquanto que para os casos de inexistência de infra-estrutura o conceito de store-carry-forward (SCF) é aplicado. Como última contribuição, esta tese integra todas as soluções descritas anteriormente em uma estrutura que garante comunicações VNDN com alta performance tanto em rodovias como em regiões urbanas com densidades de veículos variáveis.

Os resultados das avaliações experimentais mostram que as soluções propostas são eficientes e escaláveis e garantem alto desempenho ás aplicações VNDN, mesmo em cenários complexos e altamente dinâmicos de tráfego de veiculos.

Abstract

In this thesis, Vehicular Named-Data Networking (VNDN) refers to the use of the Named-Data Networking (NDN) communication model over Vehicular Ad-hoc Networks (VANETs). VANETs enable vehicular communications and support the deployment of more intelligent, secure, efficient, and pleasant transportation systems.

NDN focus on named content and does not use IP addresses. NDN relies on in-network and decentralized caching to provide content redundancy within networks, which is useful for optimizing network resource utilization and improve response time and content availability. In this way, NDN improves VANET application performance when compared to other communication techniques such as IP, which focus on hosts instead of content.

This Ph.D. thesis proposes efficient solutions to address the negative effects of communication conditions induced by high vehicle mobility and wireless communications on VNDN application performance. Among the contributions, this thesis first proposes a new VNDN architecture and a geographic routing protocol to route VNDN messages between content sources and requesters. The proposed routing protocol also addresses the effects of well-known VANET problems such as broadcast storms, message redundancy and transmission resynchronization. Then, this thesis investigates the effects of content receiver/requester mobility in VNDN, and identifies the problem of Reverse Path Partitioning (RPP). To address RPP this thesis introduces Auxiliary Forwarding Set (AFS). AFS determines the RPP probability and when required chooses and extra set of eligible vehicles as candidates to forward message towards their destinations, as opposite to standard NDN where only the nodes that forwarded an Interest message forward the corresponding Data message. This thesis also investigates the problems caused by content source mobility and network partitions in VNDN. To address the content source mobility problem, this thesis applies the concept of Floating Content (FC). To address the network partition problem this thesis proposes two different solutions. For the cases where infrastructure support is available, content retrieval can be delegated to existing road-side units (RSUs) while for the cases of no infrastructure support the concept of store-carry-forward (SCF) is applied. As the last contribution, this thesis integrates all the solutions described above in a framework that supports VNDN communications with high performance in both highway and urban scenarios with variable vehicle densities.

The evaluation results show that the solutions proposed in this thesis are efficient and scalable providing high VNDN application performance even in complex and highly mobile traffic scenarios.

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Chapter 1

Introduction

This Chapter presents the motivations that lead to the choice of the research topic for this doctoral program, it highlights the main objective and describes the organization of this thesis.

1.1 Motivation

According to demographic data provided by the United Nations (UN), the world has been experiencing a tremendous population growth during the last decades. For instance, the world population has grown from 2.6 billions of individuals in 1950 to 7.5 billion in 2017 and forecasts point to a world population of 9.5 billions of individuals in 2050 [7]. This population growth has also been accompanied by a significant exodus of people from rural to urban areas and, more recently, by a refugee crisis from countries affected by wars. These factors have contributed to an unprecedented increase in urban population around the world [8], creating enormous challenges for the efficient management of cities in diverse fields. From the mobility point of view, Intelligent Transportation Systems (ITSs) are envisioned to provide more secure and efficient transportation infrastructures as well as making the time that drivers and passengers spend on roads more pleasant [9].

Vehicular Ad-hoc Networks (VANETs) are seen as key enablers for ITSs. VANETs rely on the processing capabilities and wireless communication of on-board units, which are currently being incorporated into vehicles by manufacturers, to provide a communication interface for vehicular communications.

VANET Applications

VANETs were primarily conceived to support applications related to road safety and traffic efficiency. Examples of these applications are information/warnings about traffic jams, accidents, unsafe road and weather conditions, location of facilities, shorter riding times, pollution, etc. However, unlike smartphones, smartwatches, and other types of mobile devices, vehicles are robust in terms of energy, processing power, and storage capacities. This fact enables the deployment over VANETs of infotainment applications such as video-streaming, gaming on the go and social applications (e.g., chats) that are more demanding in terms of resources. Infotainment related applications are strict regarding application performance, usually demanding very high content delivery ratios and low latency simultaneously.

IP Networks Over Vehicular Ad-hoc Networks

The performance of the traditional IP point-to-point and host-based communication model is significantly affected in VANET scenarios. For instance, VANET characteristics such as highly dynamic topologies, and short and intermittent connectivity among vehicles makes it difficult to maintain up to date IP routing tables as it requires a continuous exchange of messages between vehicles to update domain name services, network masks, default gateways, neighbor lists and other specific IP features [9]. High levels of message exchanging in the limited wireless communication medium leads to excessive message collisions and decreases application performance in cases of a significant number of applications running simultaneously. Besides, IP assigns network addresses (i.e., IDs) to hosts according to their topological network location. Consequently, the IDs of mobile nodes change as nodes move to new physical locations, requiring frequent changes in the IDs of vehicles in VANETs and disturbing communication between vehicles. In fact, the IP communication model was conceived with the focus on static network topologies and with the objective of sharing resources between a reduced number of reliable, robust and known end systems. The IP communication model also was designed assuming that a conversation occurs between two hosts, one wishing to access a given resource and the other providing access to the resource. As opposite, nowadays computer networks are primarily used for content distribution between nodes [10]. According to Cisco, the Internet content traffic will continue increasing at a high rate during the following years, and it will reach 1.4 zettabytes per year during 2017 [11]. This paradigm shift in computer networks, in the era of the Internet of Things (IoT), and the high mobility of nodes bring a set of new and challenging tasks for the future Internet that is unlikely to be solved under the IP assumptions. For the case of VANETs, at the data link layer, new wireless communication technologies such as the IEEE802.11p [12][13] have been developed with the focus on vehicular communications. At the network and transport layers, new solutions are still being proposed as alternatives to IP.

Broadcast Communication Over Vehicular Ad-hoc Networks

In traditional VANET applications, such as traffic warning applications, the sizes of exchanged content objects are usually small and of interest to all vehicles in a certain geographical region. In such cases, the broadcast communication approach used in several VANET protocols [14][15][16] can be used without significantly affecting the available communication bandwidth. However, when the content objects to be disseminated are large sized (e.g., video dissemination applications) or of interest for a reduced number of vehicles (e.g., a VoIP call) the broadcast communication approach imposes large and unnecessary overhead in the wireless communication medium, increasing the probability of message collisions and decreasing application performance. Therefore, the broadcast communication approach is useful only for specific types of applications and lack the ability to support general purpose cases.

Named-Data Networking Over Vehicular Ad-hoc Networks

To efficiently support content distribution in the network layer, new network architectures have been proposed. Named-Data Networking (NDN) [3] described in Chapter 2, which is an evolution of Content-Centric Networking (CCN), is one of the most prominent among the recently proposed Information Centric Network (ICN) architectures. Other examples of existing ICN architectures or NetInf [17], DONA [18], and PSIRP [19].

NDN presents a communication model based on the exchange of Interest/Data messages and decentralized in-network caching and applies three main data structures. The content store (CS) is used for caching incoming content objects, the pending interest table (PIT) to keep track of forwarded Interest messages and the forwarding information base (FIB) to store outgoing interfaces to forward Interest messages. A node wishing to receive a specific content object (i.e., content requester) sends an Interest message specifying the name of the requested content. In response, a node having a cached copy of the requested content object (i.e., content source), when receiving the Interest message sends a Data message containing the specified content towards the content requester. Besides not having to deal with the IP requirements mentioned above, NDN also eliminates the use of IP addresses, it decouples content from producers and retrieves content using names directly from the closest content source. The closest content source can be either the original content producer or any node caching a valid copy of the requested content object. In this way NDN reduces content delivery delay [20], it increases the number of available content sources consequently increasing content delivery probability and making content available after the original content producers have disconnected from the network, and allows content objects to be produced by request through the use of Interest messages. Concerning security, NDN secures each piece of content individually (e.g., using digital signatures). Therefore, NDN avoids dealing with the security issues of unreliable communication channels. On the other hand, NDN only routes Data messages in response to Interest messages, decreasing in this way the overhead generated by the broadcast communication approach in the shared wireless communication medium, which contributes to increase the number of applications that can run simultaneously.

Considering the reasons stated above, Vehicular Named-Data Networking (VNDN) [21][22][23], which stands for the employment of the NDN communication model over VANETs, holds the potential to overcome the weaknesses of the IP networking model and the broadcast communication approach. Therefore, VNDN can provide high application performance and enable the deployment of general purpose applications in VANETs. In summary, VNDN can support both specific and general purpose applications with several advantages including improved delay and content availability, support for on-demand content (i.e., nonexistent content can be produced when requested), and decreased overhead in the wireless communication medium, .

Despite the advantages of VNDN, to allow its deployment in real communication scenarios, a set of challenges that arise due to the high mobility of vehicles and the unreliability of the wireless communication medium shall be addressed [24]. These challenges include problems related to receiver/requester mobility [25], source mobility [26], variable network densities and network partitions [27], message redundancy and broadcast storms [25], and transmission resynchronization [2]. Existing works on VNDN [22][28] do not focus on addressing the effects of high mobility and wireless communications and lack the ability to provide high application performance in VANET scenarios. In this context, this thesis recognizes the need for a new general purpose VNDN framework, designed with focus on highly mobile VANETs.

1.2 Objectives and Contributions

The general objective of this thesis is to study the negative effects caused by high mobility and wireless communications in VNDN and propose a framework to simultaneously address each identified problem and provide high application performance.

To achieve the general objective, this thesis has the following specific objectives:

1. Propose efficient mechanisms to route Interest and Data messages towards mobile content sources and content requesters respectively, and advertise newly produced content objects to potential consumers.
2. Propose efficient ways to prevent the occurrence of well-known VANET problems such as broadcast storms, message redundancy and transmission resynchronization;
3. Propose efficient solutions to support both content source and content requester/receiver mobility in VNDN;
4. Address the negative effects of network partitions in VNDN communications;
5. Integrate the proposed solutions in the final framework to efficiently support VNDN communications in highly mobile urban and highway scenarios.

According to the general objective presented above, the major contribution of this thesis is a distributed framework that simultaneously addresses the negative effects of mobility and the unreliability of the wireless communication medium and supports VNDN communication with high performance in highly mobile VANET scenarios.

According to the specific objectives introduced above, this thesis presents the following contributions:

1.2.1 Message Routing in Vehicular-Named Data Networking

To accomplish the main objective stated above a mechanism for message exchanging between vehicles is required. In this context, as the first contribution, this thesis proposed a multi-hop routing mechanism for Interest and Data messages. This routing mechanism is designed with the goal of enabling content requesters to retrieve content objects from distant locations. Besides, this routing mechanism avoids unnecessary usage of the limited and shared wireless communication medium and prevent the occurrence of the broadcast storm, message redundancy, and transmission resynchronization problems.

As explained in detail in Chapter 3, in multi-hop scenarios this proposed routing mechanism minimizes the number of intermediate vehicles that forward Interest and Data messages and reduces the number of message collisions. Consequently, it avoids the broadcast storm problem, by selecting as message forwarders only the vehicles that allow more progress towards the message destination, among all vehicles that receive a message. The decision of whether to forward a received message is taken locally by each vehicle through the use of a delay/timer approach, set in a way that 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. In this way, this mechanism does not require the exchange of state information between neighbor vehicles to find the best message forwarders. Therefore, this routing mechanism is multi-hop, receiver-based and beacon-less. Similar to NDN, vehicles use the information stored in their PITs 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.

To prevent transmission resynchronizations, this routing mechanism is aware of channel switchings in the wireless access in vehicular environments (WAVE) standard, which is used for communications. When calculating the delay for forwarding Interest messages, vehicles take into account the WAVE channel switching time, and when required they add extra delays to prevent close vehicles from simultaneously transmitting messages into the wireless communication medium.

To identify message redundancies, vehicles extract from received Interest messages the localizations of the vehicles from whom they received the Interest message. In this way, if a vehicle receives multiples copies of the same Interest message, it can distinguish a message that has been transmitted by a neighbor vehicle located closer to the message destination from a redundant message transmitted by another vehicle farther away from the message destination.

1.2.2 Content Receiver Mobility

After proposing the routing mechanism for VNDN Interest and Data messages introduced in the previous subsection, this thesis focuses on improving the performance of VNDN applications. Considering this, the second contribution of this thesis proposes to increase content delivery probability by addressing the effects of the VNDN reverse path partitioning (RPP) problem that has been identified in this thesis. RPP often prevents Data forwarder vehicles from communicating with each other, preventing Data messages from being delivered to content requesters, and degrading VNDN application performance even in connected scenarios.

In this thesis, a reverse path partitioning 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. In a VNDN scenario very often vehicles travel at different speeds making inter-vehicle distances very dynamic. In VNDN vehicles closer to a message destination (i.e., vehicles farther away from the previous sender/forwarder of the message) are selected as next forwarders for that Interest message, in order to allow more progress towards the message destination. Therefore, consecutive Interest message forwarders tend to be located distant from each other. When receiving and forwarding an Interest message, the distance between the current vehicle and the previous forwarder of the same Interest message can be up to the transmission range of the previous vehicle that forwarded the same Interest message. Considering this, often 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, even in the cases where the distance between consecutive Data message forwarders still unchanged, RPP can happen. The fact that vehicles can be equipped with communication devices of different reach and that antennas located in higher vehicles might provide better lines of sight, consequently extending the communication reach, can also allow one vehicle to deliver an Interest message for forwarding to a neighbor vehicle that is not able to communicate back with it. Furthermore, the transmission range of a vehicle can suffer temporary attenuations due to the conditions of the wireless communication medium. All these factors can lead to the occurrence of RPP. Since in NDN only the vehicles that forwarded an Interest message also forward the corresponding Data message, in case of RPP the content object is not delivered to the content requester. 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 and determines the probability of RPP occurrence between any two 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 any of the original Data forwarders, among the members of the AFS group that received the message, the one closer to it retransmits the Data message. The Data message is then received by the original forwarder and the reverse path is reconnected. Simulation results show that the proposed AFS solution is efficient and scalable to address the effects of RPP, since it is able to provide high VNDN application performance without excessive load on the communication channel, regardless of receivers mobility and the number of content requests.

1.2.3 Network Partitions

The third contribution of this thesis addresses the problem of network partitions in VNDN.

This thesis defines 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 differ from RPP since an RPP occurs when a vehicle forwarding a Data message is not able to communicate with the subsequent Data message forwarder vehicle (i.e., it might be able to communicate with other vehicles) whereas network partitions occur when vehicles sending/forwarding Interest messages are unable to communicate with any other subsequent vehicle. Network partitions can significantly degrade VNDN application performance leading to low ISR and high delays. Network partitions might temporary occur in VNDN scenarios with high vehicle densities due to signal attenuations caused by obstacles and other disturbances in the wireless communication medium. However, network partitions are more frequent and harmful in sparse VNDN scenarios where the density of vehicles is low, and often vehicles get out of the transmission range of each other for significant periods of time.

To address the network partitions problem, this thesis proposes two different solutions. The first proposed solution targets scenarios with infrastructure support and applies the idea of VNDN agent delegation. The VNDN agent delegation communication approach inspires on the concept of agent delegation previously proposed by members of our CDS research group at the University of Bern [20]. The main idea is that in sparse networks when nodes are unable to connect to content sources to request content objects, content requests can be delegated to other nodes that due to their trajectories will be able to communicate with a content source and again with the content requester in the future to deliver the requested content object. Since the agent delegation approach was designed for scenarios with low mobility, as opposed to this thesis that focuses on VNDNs with high vehicle mobility, a new communication model for the agents was required. In this sense, a new VNDN communication mechanism specifically designed for road side units (RSUs) was developed and deployed in RSUs along roads. In case of network partitions, content retrieval is delegated to these VNDN enabled RSUs. Since the VNDN RSUs form a network of static and connected nodes, they are immune to the problems of mobility, and as shown in the simulation results the VNDN agent delegation approach can efficiently retrieve requested content objects from distant locations with short delays and provide high application performance.

Despite the efficiency of the VNDN agent delegation approach in retrieving content objects from distant locations, the high costs associated with the deployment and maintenance of networks of RUSs along roads represent a great obstacle for the deployment of RSU networks and currently, such networks are still scarce around the world. In this context, this thesis recognizes the need for an alternative solution to the problem of network partitions in VNDN scenarios without infrastructure support. For such cases, this thesis proposes the VNDN store carry forward mechanism (VNDN-SCF). The intuition behind VNDN-SCF is that 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. Vehicles use the messages forwarded by their neighbors as implicit acknowledgments of message delivery. When a vehicle sending or forwarding a message perceives that the message was not forwarded by any neighbor vehicle, it concludes that a network partition has occurred. In such a case, 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. Simulation results show that despite presenting higher message delivery delays and generating more traffic in the wireless communication medium compared to the VNDN agent delegation solution, the VNDN-SCF communication approach provides high ISRs even in highly partitioned VNDN scenarios where content delivery drops to zero in the cases where the VNDN-SCF is not used.

1.2.4 Content Source Mobility

The fourth contribution of this thesis proposes a solution to the problem of content source mobility. NDN assumes that content sources might advertise the content objects that they can provide, to inform the remaining nodes about available content objects within the network. In VNDN, a vehicle might send an Advertisement message informing the remaining vehicles that it can provide a specific content object at its current location. After understanding about the availability of a given content object, vehicles can decide whether they are interested or not in receiving such a content object. If a vehicle is interested in an existing content object it can request it, either immediately or after a certain time interval, by sending an Interest message with the content name towards the location announced in the Advertisement message. However, due to the high mobility of vehicles in VNDN, vehicles usually only stay for short time periods in particular locations. Considering this, the probability of Interest messages sent towards the location where a given content object was advertised reaching the vehicle that advertised the content object (i.e., the content producer) decreases proportionally with mobility and time as the content producer vehicle moves away from the location indicated in the Advertisement message. For the cases of popular content objects that might be requested by a large number of vehicles, several content requests might be satisfied by vehicles other than the content producer, if they previously requested the content object and have a cached copy of it. Nevertheless, in the case of unpopular content objects that are requested by few vehicles, the probability of finding a copy of the content object in the caches of neighbor vehicles is low, leading to a large number of unsatisfied content requests and significantly decreasing application performance.

Since the aim of this thesis is to provide a general purpose framework to support VNDN applications and provide high application performance, a solution to address the problem of content source mobility is presented. The proposed solution applies the concept of floating content (FC). FC is a communication scheme, which supports infrastructure-less distributed content sharing over a given geographic area (i.e., the anchor zone). Whenever a node possessing a content object moves out of the spatio-temporal limits of its anchor zone (AZ), it replicates the content object to the remaining nodes within the AZ and deletes it. In this way, the content object may be available on a set of nodes and moves over time within the AZ and after the node that initially generated the content left the AZ, the content object still available within the AZ. In this thesis the AZ is defined by a center (i.e., the geographic location where the content object was produced) and a radius (i.e., 200m coinciding with the maximum transmission range of vehicles). When receiving a replica of a content object (i.e., Data message of type R) vehicles check whether they are within the AZ for that particular content object. If that is the case, they cache the content and become content sources for that specific content objects. When leaving the AZ they also replicate the content to the other vehicles within the AZ and delete the content object. In this way, Interest messages sent towards the location where the content object was advertised can still be satisfied over the time regardless of the mobility of the original content producer, leading to improved application performance compared to the cases where the problem of source mobility is not handled.

Simulation results show that the proposed solution is scalable and efficient to mitigate the effects of content source mobility in VNDN and improve application performance.

1.2.5 Mobility Support for Vehicular Named-Data Networking

As the last contribution, this thesis proposed MobiVNDN, a distributed framework designed to enhance VNDN communications and improve application performance in both highway and urban scenarios. The MobiVNDN framework integrates all the solutions described in the previous contributions. Summarizing, MobiVNDN simultaneously prevents the occurrence broadcast storms, message redundancy, and transmission resynchronization problems by applying the message routing protocols described in the first contribution of this thesis and addresses the effects of reverse path partitioning, source mobility, and network partitions by applying the concepts of AFS, VNDN-SCF, and FC. NDN assumes that content producers might advertise their newly produced content objects to the remaining nodes to inform them about the availability of content objects within the network. To enable this feature, MobiVNDN introduces a new type of messages called Advertisement messages. Unlike Interest and Data messages that are intended to a particular vehicle or a specific geographic location, the goal of Advertisement messages is to reach as many as possible nodes in the network. Considering this, MobiVNDN presents a new routing mechanism conceived explicitly for Advertisement messages. To route Advertisement messages, MobiVNDN applies the concept of sweet spots introduced by members of our computer networking research group at the University of Campinas [5].

As described in detail in Chapter 7, the intuition behind sweet spot is to preferably select as message forwarders the vehicles currently located in areas with higher probability of reaching a larger number of vehicles (i.e., sweet spots). Similar to the case of Interest and Data messages, the routing mechanism for Advertisement messages is timer-based, and vehicles within sweet spots calculate lower delay values to forward messages compared to vehicles outside sweet spots. The transmission by a single vehicle within each sweet spot is enough to perform the Advertisement message dissemination. Therefore, within each sweet spot, MobiVNDN applies a distance-based decision to select the best vehicle to forward a received Advertisement message and the vehicle farther away from the vehicle from whom they received the Advertisement message calculates shorter delays and forwards the Advertisement message.

One of the main advantages of VNDN is its potential to enable content production on demand. For instance, a vehicle might request an unavailable picture or video of an event occurring in a particular location. As the requested content object does not exist yet, it can be produced by any node (e.g., a vehicle, an RSU, a smartphone, etc.) that received the request and is currently at the requested location. Considering this, MobiVNDN provides supports for two different communication approaches. The first approach corresponds to the case where content requesters request content objects previously advertised by content source vehicles (i.e., Advertised content scenario) and the second approach corresponds to the case where content requesters request content objects that are not yet available and shall be produced on-demand (i.e., on-demand scenario). The simulation results show that MobiVNDN is efficient as it is able to provide higher ISRs compared to another solution from the literature and to the plain VNDN in both highway and urban scenarios at the cost of slightly increasing the delay and the utilization of the wireless communication medium. Moreover, MobiVNDN maintains high ISRs even in very sparse networks where the performance of existing solutions drops to zero.

1.3 Thesis Outline

The outline of this thesis is as follow:

Chapter 2 describes VANET, NDN, and VNDN, the base computer networking fields for this thesis, as well as floating content, which is applied as a solution to the problem of content source mobility, and reviews the contributions and limitations of related work. Chapter 3 describes the adaptation of NDN to VANETs in the context of this thesis, including the proposed message routing mechanisms for Advertisement, Interest, and Data messages, as well as the techniques used for preventing the problems of broadcast storm, message redundancy, and transmission resynchronization. Chapters 4, 5, and 6 study the problems caused by receiver mobility, network partitions, and content source mobility in VNDN communications and describe the solutions proposed in this thesis for each problem. Chapter 7 presents MobiVNDN, the general purpose VNDN framework that integrates all the solutions previously described to support mobility in VNDN communications. Chapter 8 concludes this thesis.

1.4 Conclusions

This Chapter presented the motivations that lead to the research topic for this doctoral program, it highlighted the objectives and contributions, and described the organization of this thesis.

Chapter 2

Background and Related Work

This Chapter summarizes the main aspects of VANETs, NDN, and VNDN that are the major computer networking fields on which this thesis bases, as well as FC that is applied as a solution to the problem of content source mobility. Besides, this Chapter also reviews the related work on message routing in VANETs, VNDN architectures, and mobility support in VNDN, which are the key topics where the contributions of this thesis fit.

2.1 Vehicular Ad-hoc Networks

As stated above in the Chapter 1 VANETs can be defined as a type of mobile ad-hoc networks (MANETs) in which the key nodes are vehicles. In VANETs, vehicles are equipped with On-Board Units (OBUs) that provide wireless communication, storage, and processing capabilities, enabling them to spontaneously create communication networks on the go [9]. VANETs feature the V2X communication model. In the V2X communication model, as shown in Figure 2.1, vehicles can communicate among them and also with other types of nodes such as in-road sensors, mobile devices carried by pedestrians, RSUs and other static communication infrastructures, including access points of wireless networks and base stations of cellular networks. In this way, vehicles can continuously exchange content while moving.

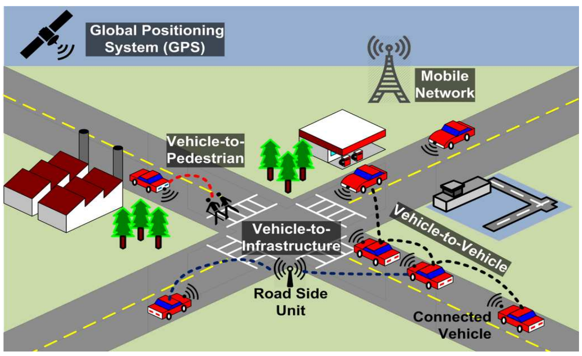


Figure 2.1: VANET communications [1]

The V2X communication model encompasses the following main approaches:

- *Vehicle-to-Vehicle (V2V)*: Allows direct vehicular communication without relying on the support of fixed infrastructure, and is mainly used for safety, security, and content dissemination applications;
- *Vehicle-to-Infrastructure (V2I)*: Allows vehicles to communicate with all sort of nodes other than vehicles (e.g., mobile devices, RSUs, on-road sensors, etc.) and is mainly used for information exchanging and data gathering applications;
- *Hybrid*: Combines V2V and V2I. Allows vehicles to communicate with distant vehicles and infrastructure nodes through multi-hop communication schemes.

VANETs can use different technologies according to the communication approach. For instance, the IEEE 802.11p standard provides a communication alternative specially designed for the V2V approach while other existing technologies, such as long-term evolution (LTE) can be applied for V2I cases.

2.1.1 VANET Characteristics

VANETs present a set of distinguishing characteristics, including:

- *Highly dynamic topologies*: Vehicles move with high relative velocities in the order of *50km/h* in urban environments to more than *100km/h* in highways. Vehicles may also move in different directions and can quickly join or leave networks in very short time periods, leading to frequent topology changes;
- *Frequent disconnections*: The highly dynamic topologies results in frequent changes in connectivity. Thus, links between vehicles can quickly disappear during communications;
- *Geographical communication*: Content objects in traditional VANET applications are typically useful for a limited number of vehicles that are moving within a particular geographical location. For instance, advertisements of available spots in a parking lot might only be of interest to vehicles near the parking lot;
- *Variable network densities*: As vehicles move they keep joining and leaving networks with variable number of neighbor nodes, ranging from sparse to dense networks according to the number of nodes;
- *Constrained mobility*: Despite that VANETs are characterized by very dynamic network topologies, the mobility of vehicles is constrained by diverse factors including the structures of roads, streets and highways, traffic lights, speed limits, traffic conditions, etc;
- *Variable signal propagation models*: Usually the operation environments of VANETs varies between highway, urban, and rural areas. In highways, the propagation model can be assumed as free-space, but the signal can still suffer interference by the reflection with wall panels and other objects located around the roads. In a city

typically signals suffer from shadowing, multi-path, and fading effects due to the existence of a large number of obstacles including buildings, trees, and other objects. In rural areas signal propagation also suffers degradation due to the presence of variable topographic forms including fields, hills, climbs, dense forests, etc.

2.1.2 Wireless Access in Vehicular Environments

The wireless access in vehicular environments (WAVE) derives from the IEEE 802.11p standard and defines a communication architecture specially designed for vehicular networks. The WAVE focuses on the lower layers of the protocol stack and presents a definition of the physical and medium access control (MAC) layers strongly based on previous standards of wireless networks [29][30]. The WAVE components are dedicated to the network and management functions with emphasis on the aspects relating to security, resource management and support for multiple operating channels. The MAC Layer Management Entity (MLME) and the Physical Layer Management Entity (PLME) represent the management entities of the MAC and physical layers.

The IEEE 1609.4 standard defines the operation of the WAVE based on multiple channels. As shown in Figure 2.2, the WAVE architecture has one control channel and six service channels of 10 MHz of bandwidth each. This design aims to provide proper treatment to different types of applications ranging from critical applications regarding safety requirements and tolerance to delay to less demanding applications in these contexts [2]. In WAVE only one channel is active at each time instant. WAVE applies a time division mechanism for channel switchings, which serves the control channel in alternate time intervals and distributes the remaining time intervals between the service channels according to the needs of the applications. The maximum multiplexing period is 100 milliseconds. In addition to using different frequencies for each channel, the transmission power also varies according to the channels. The control channel, which is reserved for critical applications in terms of security, uses the maximum transmission power. Within each channel, there are also four access categories denoted by AC0, AC1, AC2 and AC3. The lowest priority level corresponds to AC0 and the highest to AC3.

2.1.3 Routing in Vehicular Ad-hoc Networks

This Subsection reviews the main works available in the literature regarding message routing in VANETs.

In [14] the authors present a distributed and adaptive mechanism for information dissemination in VANETs. The goal is to disseminate a content object to the highest possible number of vehicles within a network. This mechanism employs a counter based scheme based on a fixed threshold value D to inhibit vehicles from rebroadcasting messages. The authors try to establish a relationship between the number of required retransmissions and the coverage area and argue that if a vehicle receives the same message more than D times, it is unlikely to rebroadcast the message due to negligible coverage area. When a vehicle receives a broadcast message it starts a random timer and a counter for the received message. While the timer is running anytime the vehicles receive another copy

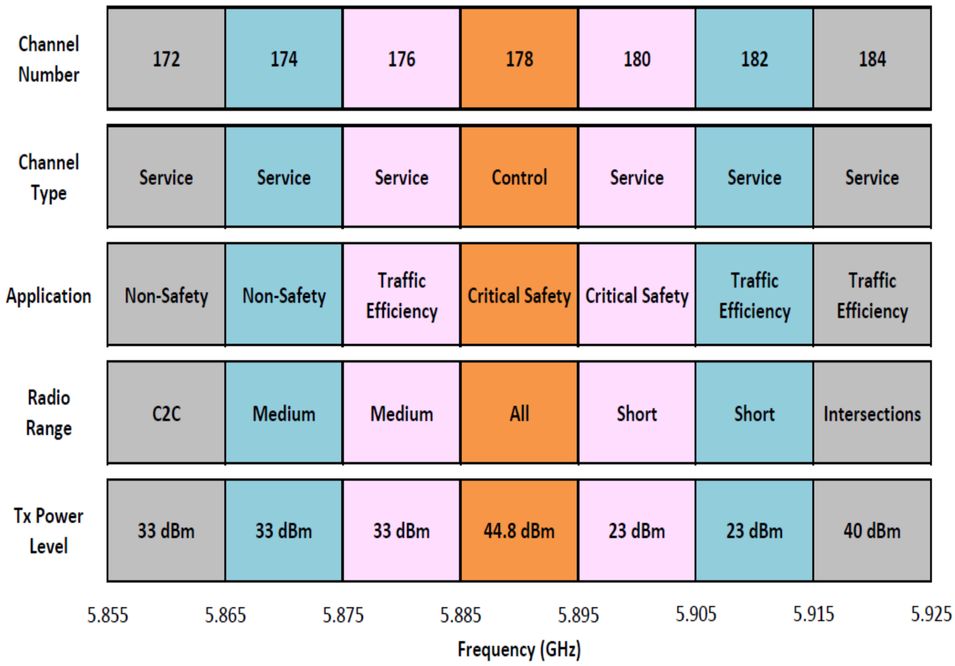


Figure 2.2: Wave architecture [2]

of the same message, it increases the counter. When the timer expires, if the counter value is less than the threshold value D, the vehicle broadcasts the message. Otherwise, it discards the message.

In [31] the authors present a message routing protocol for VANETs called road-based vehicular traffic (RBVT). RBVT relies on real-time vehicular traffic information to create road-based paths consisting of successions of road intersections based on the probability of network connectivity among the intersections. RBVT applies a geographical forwarding strategy to forward messages between intersections on the path. A receiver-based method is applied to select the best next hops for forwarding messages.

In [32] the authors present a prediction based mechanism for Data message routing in VANETs. The main idea behind this mechanism is to exploit the knowledge of vehicles predicted future locations as a metric to decide whether to forward Data messages, without the need for exchanging control messages between neighbor vehicles. When a vehicle produces a content object, it encloses the content object into a Data message, it assigns a geographic destination to the Data message and sends it over the wireless communication medium. When receiving the Data message, neighbor nodes schedule to forward the Data message using a timer based approach where vehicles with destinations closer to the destination of the Data message calculate shorter timer values. The transmission by one vehicle inhibits the remaining vehicles on its one-hop neighborhood from also forwarding the same Data message.

In [6] the authors propose a routing protocol for the broadcast of Data messages in VANETs, without relying on infrastructure support. The goal is to disseminate an existing content object to all vehicles in a geographical area of interest. Each vehicle periodically exchanges beacon messages with its neighbors to notify one-hop neighbors about its presence. Each beacon message has a 4-byte field called *hasMessage* that carries the value of

0 if the vehicle does not have the content object or *1* if the vehicle has the content object. Vehicles use the frequency rate of received beacon messages to determine whether they are in dense or sparse traffic scenarios. In dense scenarios when vehicles receive beacon messages from a neighbor vehicle that do not have the content object, they schedule a Data message containing the content object employing a delay based scheme. Vehicles located in geographical zones of preference calculate lower timer delays and prevent other vehicles from also sending the Data message. In sparse networks, whenever a vehicle receives a beacon message, indicating that it is within the transmission range of another vehicle that does not have the content object, the current vehicle automatically sends the content object using a Data message.

In [33] the authors propose a probabilistic mechanism for sharing road conditions, including accidents, detours, and congestion in VANETs. This mechanism assigns probabilities to roads around each of the intersections in the region of interest and use a graph representation of the road network to build a spanning tree of roads with the content source vehicle as the root node. Nodes below the root represent junctions, and the edges represent the road segments. Data messages propagate along the branches with the probability of replication decreasing as the Data messages propagate down the branches. Vehicles forward received Data messages until a threshold probability has been reached.

In [34] the authors propose a new data dissemination protocol for VANETs named ADD. The ADD protocol was conceived to operate in highly dynamic highway environments and consists of two main mechanisms. The first mechanism is dedicated to broadcast suppression whereas the second mechanism deals with delay desynchronization. ADD uses a preference zone approach to select the next hops to forward a received Data message and a delay desynchronization scheme to eliminate the synchronization problem caused by the 802.11p protocol.

In [5] the authors propose a new data dissemination protocol for VANETs called DRIVE. DRIVE addresses the broadcast storm and network partitions problems simultaneously by relying exclusively on local one-hop neighbor information to deliver messages under both dense and sparse networks. In dense scenarios, DRIVE applies an area-based scheme called sweet spot to select the best vehicles to rebroadcast messages to further vehicles. DRIVE employs implicit acknowledgments as confirmations of successful message delivery in sparse scenarios.

The works described above propose different mechanisms for disseminating Data messages in VANETs. However, these works assume applications where all vehicles in a region of interest are interested in the content object being disseminated. For other types of applications such as online-gaming, video-streaming, and video or voice calls, the broadcast communication approach shared by all these works generates high and unnecessary overhead in the wireless communication medium, which might not scale properly if the number of concurrent applications increases significantly. Therefore, we recognize the need for a new message routing mechanism to support general purpose applications when focusing in VNDN. The routing mechanism proposed in this thesis routes Interest and Data messages towards content requesters and content sources (i.e., not broadcast in all directions) respectively, only when content objects are requested, decreasing in this way the overhead generated in the available spectrum and supporting more applications running concurrently.

2.2 Named-Data Networking

Named-Data Networking (NDN) [3], which evolved from Content-Centric Networking (CCN), is currently one of the main Information Centric Networking (ICN) architectures among other examples such as NetInf [17], and PSIRP [35].

NDN identifies each networking entity (e.g., content objects, routers, etc.) by a unique name and decouples content objects from their original producers. As mentioned in Chapter 1, in NDN nodes retrieve content objects directly from the closest provider, decreasing content delivery delay and increasing the number of available content sources within the network. The original proposal of NDN presents the following two types of messages:

- *Interest messages*: Used by content requesters to request specific content objects regarding their unique names;
- *Data messages*: Used by content sources to send content objects towards content requesters in response to Interest messages received.

As Figure 2.3 shows, the core NDN messages forwarding engine maintains the following three data structures:

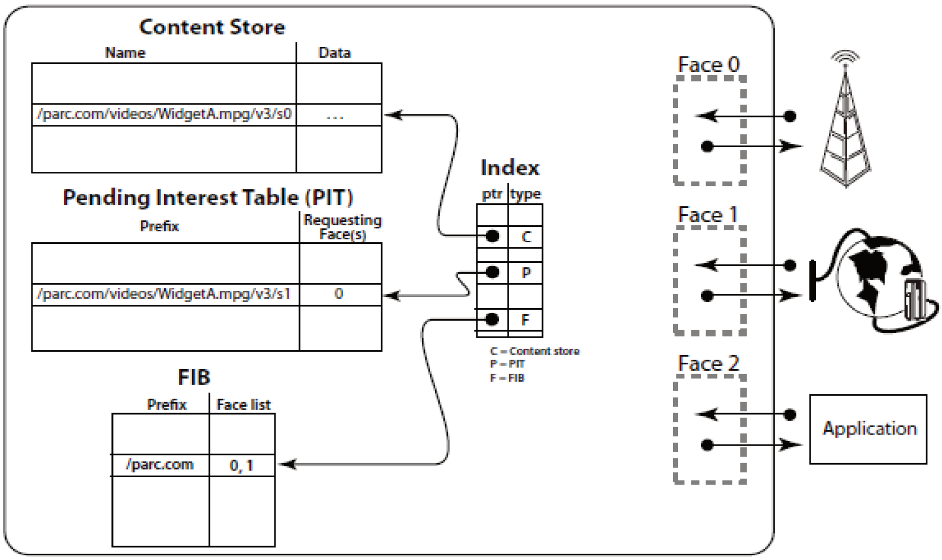


Figure 2.3: NDN Data structures [3]

- *Content Store (CS)*: Used for caching incoming content;
- *Pending Interest Table (PIT)*: Used to keep track of the forwarded Interest messages in order to send the corresponding Data messages back to requester nodes;

- *Forwarding Information Base (FIB)*: Used to store information about how to reach specific content objects.

In NDN when an Interest message propagates towards a potential content source, the intermediate nodes update their PIT by adding entries related to each Interest message that they forward. In this way, the corresponding Data messages travel back towards content requesters following the reverse path, relying on the information stored in the PITs.

An NDN content source only sends a Data message in response to an Interest message and a Data message satisfies an Interest message if the content name in the Interest message is a prefix of the content name in the Data message. Each NDN node receiving an Interest message looks up a prefix-based longest-match on the content name in its CS. If it finds a match, it sends the corresponding Data message. Otherwise, if there is already a matching PIT entry, it updates the PIT entry including the face in which the current Interest message arrived, and it discards the Interest message since a pending request already exists. If there is no PIT entry for the received Interest message, the NDN node creates a new PIT entry and performs a FIB lookup to learn the interface where to forward the Interest message.

Data messages follow the chain of PIT entries left by the corresponding Interest messages when traveling back to the original requester(s). Each node receiving a Data message, performs a longest-match lookup on the name of the Data message. If it finds a CS match, it considers the content as a duplicated and discards it. A PIT match means the content was solicited (i.e., using an Interest message). The content is validated and forwarded towards the requester node. If the node does not find any matching PIT entries, the Data message is considered unsolicited, and the node ignores it.

Some of the main NDN open research challenges are summarized in the following:

- *Content advertisement mechanisms*: Refers to efficient ways for informing potential consumer nodes about existing content in the network;

- *Mobility*: Refers to efficient ways for addressing the negative impact of node mobility (i.e., in highly mobile networks) in application performance;

- *Caching*: Refers to efficient caching management techniques to improve cache hit in NDN;

- *Security*: Refers to efficient ways for securing content objects.

This thesis presents solutions for the first two mentioned NDN challenges in the context of VANETs.

2.3 Vehicular Named-Data Networking

As explained in Chapter 1 Vehicular Named-Data Networking [21][22][23], which is the main focus of this thesis, refers to the use of the NDN communication model to improve communication in VANETs. The main application performance advantages of VNDN are described in Subsection 2.3.1, Subsection 2.3.2 reviews the main VNDN architectures proposed in the literature, and Subsection 2.3.3 reviews the solutions proposed in the literature to support mobility in VNDN.

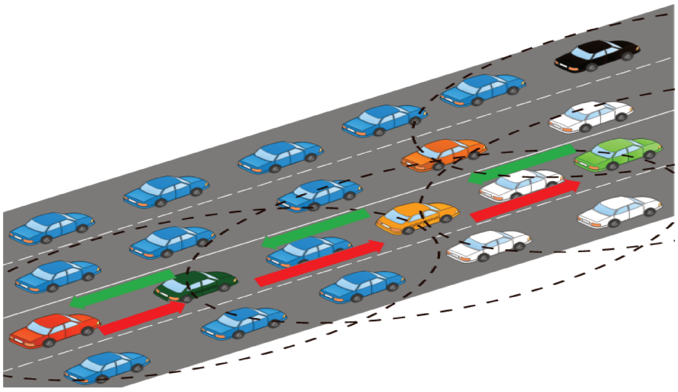


Figure 2.4: VNDN communication

2.3.1 Performance Advantages of Vehicular Named-Data Networking

This Subsection summarizes the main performance advantages introduced by VNDN in vehicular communications.

Reduced Delay

The example in Figure 2.4, shows a simple traffic scenario representing a portion of a highway with all vehicles driving in the same direction. At time t=$T0$ the light green vehicle issues an Interest message (green arrow) requesting a content previously advertised by the red vehicle. The vehicles in the one-hop neighborhood of the green vehicle receive the Interest message and only the yellow vehicle forwards the Interest message, as it is the vehicle farther away from the light green vehicle. Similarly, the dark green vehicle also forwards the Interest message and the red vehicle (i.e., source vehicle) receives it. When receiving the Interest message, the red vehicle sends the corresponding Data message (red arrow). Then, the dark green and yellow vehicles forward the Data message and the light green vehicle (i.e., content requester) receives it.

Each vehicle that receives the Data message adds it to its content store. Therefore, if the black vehicle requests the same content, a closer vehicle (e.g., the orange vehicle) can provide it. In this way, the delay decreases as the Interest message does not have to travel until the original producer (i.e., the red vehicle).

Robustness to Disruptions

In the same example shown in Figure 2.4, considering that the Data message forwarded by the yellow vehicle did not reach the light green vehicle (e.g., due to a message collision from other applications running simultaneously or signal attenuation due to temporary conditions of the wireless communication medium, or even due to a network partition), after a certain time interval the light green vehicle will recognize the Interest message as non satisfied and will re-issue the Interest message. In such a case, the yellow vehicle can provide the content. In this case, besides decreasing the delay, the probability of network disruptions also decreases as the number of hops decreases.

Increased Content Availability

As can also be observed in 2.4, after the first content request the number of vehicles caching the requested content increases significantly. This increase in the number of available content sources is advantageous as the content still available after the original producer disconnects from the network. Furthermore, this is useful to spread content to other regions according to the destinations of the vehicles carrying the cached copies.

Support for on-Demand Content

In VNDN, a vehicle might be interested in content that does not exist yet. For instance, a vehicle wishing to receive a picture of the traffic conditions in a location far away from its current location, might send an Interest message including the geographic coordinates of the location where the requested content shall be collected. When receiving the Interest message any vehicle currently in the specified region can collect the content and send the corresponding Data messages towards the original requester.

2.3.2 Vehicular Named-Data Networking Architectures

This Subsection reviews the main VNDN architectures available in the literature.

In [28] the authors propose to extend the Content Centric Networking (CCN) architecture and present a general-purpose content retrieval and distribution framework for vehicular applications, called CCVN, that is compliant with the WAVE architecture. The authors address the broadcast storm problem through a contention mechanism based on timers and channel overhearing to select next forwarding nodes in multi-hop scenarios. Data messages carry content source information, allowing requester vehicles to infer information about best content sources. All communications are broadcast and the FIB is suppressed and the authors modify the CCN forwarding engine to allow message broadcasts over the same network interface over which they arrived and introduce a new field in Interest messages to detect message redundancy. CCVN provides solutions to the broadcast storm and message redundancy problems. However, the solution proposed in CCVN does not apply for mobility scenarios with low vehicle densities and high vehicle speeds. Furthermore, unlike the work proposed in this thesis, CCVN does not address the effects of context parameters and communication conditions induced by mobility such as content source and content receiver mobility, network partitions, and transmission resynchronization. CCVN also does not have any mechanism to inform potential content requester vehicles about existing content objects within the network.

In [22] the authors present V-NDN, an architecture that modifies some of the NDN functional requirements in order to accommodate to VANETs. To take advantage of the wireless broadcast nature of VANETs, in V-NDN instead of only caching requested content objects, vehicles cache all received content objects, regardless of whether they were requested or not. This particularity is intended to facilitate content dissemination. Similarly to [28], the FIB table is suppressed, and Interest messages are forwarded to all available interfaces. To deal with the broadcast storm problem the authors apply a contention forwarding mechanism based on distance. They also use a small random delay to separate the transmission delays of vehicles located close to each other and prevent message redundancy. The limitations of V-NDN are similar to the limitations of CCVN [28]. Namely, V-NDN does not address the effects of content source and content receiver mobility, network partitions and transmission resynchronization and does not provide support for content advertisement.

In [36] the authors extend the CCN architecture by including an extra type of messages called Event Packet object. The Event Packet object is a modified and unsolicited Data message used for forwarding warning information to neighbor vehicles. The authors also modify the FIB behavior to consider the characteristics of existing faces and use the fastest faces for urgent messages. Similar to the work proposed in this thesis where a new type of messages in included for content advertisements, the work in [36] introduces a new type of messages for forwarding warning information. Unlike the work proposed in this thesis, [36] also does not deal with problems induced by content source and content receiver mobility, network partitions and transmission resynchronization.

In [37] 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. Unlike in the case of this thesis, CODIE does not focus on maintaining high application performance when mobility increases. Therefore, application performance decreases with high mobility as the content source and content receiver mobility, network partitions, transmission resynchronization, and message redundancy problems are not addressed.

In [38] the authors propose a V2V communication mechanism for traffic information dissemination in highways, based on content naming. Every vehicle can play three main roles. Content requester, content source or data mule, as each car might cache received content objects even if it is not requested, in order to spread existing content objects to different geographic locations. A set of timers are used to perform specific tasks, such as collision avoidance and Interest and Data messages retransmissions. This work further employs the CBF idea [39] where the vehicle farther away from the previous forwarder of an Interest message forwards the Interest message in order to achieve more progress in content dissemination.

In [40] the authors propose a mechanism to prevent broadcast storms in VNDN. In this mechanism, the authors apply the hop counter and Time-To-Live values of Interest and Data messages to limit the number of hops that Data messages travel on their way back towards content requesters. Similar to [37], the goal is to forward less copies of Data messages while still achieving similar Interest Satisfaction ratios compared to the plain

VNDN.

The authors in [41] propose a VNDN mechanism for message forwarding based on location. This VNDN mechanism allows vehicles to retrieve content chunks from multiple content source. A content discovery component is used to identify the best content sources across multiple geographic areas. This work also uses the concept of geographic faces to bind name prefixes to the geographic locations of their producer vehicles.

The limitations of the works proposed in [38], [40], and [41] compared with the work proposed in this thesis are similar to the limitations of the previous works as these solutions lack the support for high mobility, unreliable wireless communications, and content advertisement.

The works described in this Subsection present substantial contributions for the deployment of VNDN. These works provide solutions to the broadcast storm and message redundancy problems, support for notifications, and content discovery. However, the solutions proposed by these works only apply for mobility scenarios with moderate to high vehicle densities and low vehicle speeds. Therefore, these works lack some essential requirements for general purpose VNDNs. Moreover, the challenges derived from the VANET characteristics are beyond these issues. For instance none of these works addresses the effects of context parameters and communication conditions induced by mobility such as content receiver mobility, network partitions and transmission resynchronization that are of particular importance in the design of efficient VNDN communication mechanisms.

2.3.3 Mobility Support in Vehicular Named-Data Networking

This Subsection reviews the main solutions to support mobility in VNDN already proposed in the literature according to the approach used in each work.

Proxy-Based Mobility Support

In [42], the authors propose a proxy-based mobility support approach for mobile NDNs (PMNDN). They divide the entire network into multiple autonomous systems (ASs) and for each AS they deploy two new static functional entities. These new functional entities are called NDN access router (NAR) and proxy, respectively. NARs are used for tracking the mobility status of content sources and initiating mobility related signaling to the proxies. Proxies are used for maintaining reachability information about content sources. The authors also add two new types of data structures in NARs and proxies: the Source Location Table (SLT) and the Interest Packet Store (IPS). SLTs keep track of the content sources that are currently or previously resided in the management domain of the NAR (or the Proxy), while IPSs cache Interest messages that the NAR (or the Proxy) receives during the disconnection period of content sources. The core idea is that content sources only exchange signaling information with the proxies to avoid the overhead for tracking positions of content sources by other nodes. This decision intends to save the resources of the wireless communication medium as well as saving the amount of energy consumed by content sources. When a content source is not reachable due to mobility, the proxy caches Interest messages forwarded towards the old location of the content source, and when it reaches another AS and connects to a new proxy, the Interest messages are forwarded by the previous proxy to the new proxy and delivered to the content source. The content source then responds with the corresponding Data messages. Therefore, the information stored in the proxies, allows NDN nodes to recover communication links that are disrupted due to content source mobility. The solution proposed in [42] targets NDN scenarios with low mobility. In VNDN scenarios with high mobility, both content sources and content requesters join and leave ASs frequently. In dense scenarios particularly, where large number of content sources might coexist in the same AS, this approach might generate significant overhead due to signaling between content sources and proxies simultaneously with content requests and delivery. Furthermore, content objects are still tied to particular content sources, as opposite to the NDN idea of decoupling content objects from producers. This idea also requires significant modifications to the plain NDN structure to include the proxy and the NAR entities as well as the new data structures. This raises compatibility concerns regarding the deployment in real world scenarios.

Mobility Support Through Indirection Points

The work in [43] proposes the idea of Indirection Points (IP) to handle source mobility in NDN. An IP is a static node that is connected to a particular Internet Service Provider (ISP). This approach uses two different types of content names. A persistent name identifies a specific content object permanently, whereas a temporary name changes as the attachment points of the content source to the network also changes. Temporary names include a prefix under which the content source can temporarily receive Interest messages. Each IP maintains a new table, called Binding Table, that relates temporal content names with persistent content names. When an IP receives an Interest message with a specific persistent name, it first tries to satisfy it from its cache. If the content is not available in its cache, the IP performs longest-prefix matching on its Binding Table for the persistent name of the requested content object. If it finds a match, it encapsulates the Interest message with the current temporary name of the content source and forwards it. When a mobile content source receives the Interest message, it decapsulates the original Interest message and sends back the corresponding Data message. After receiving the Data message, the IP decapsulates the Data Message and sends it to the initial content requester. When a mobile content source connects to the NDN network the first time, it sends a binding request to the IP specifying the content objects that it can serve, as well as the prefix under which it currently can receive Interest messages. As mobile content sources move and change their attachment points, they request IPs to delete obsolete bindings. On their sides, IPs periodically check the reachability of temporary names. If a prefix is unreachable, it is removed from the Binding Table. This approach generates less overhead compared to [42]. Apart from the content requests and content delivery, only one extra message is exchanged within each content source and the IP. However, content requests received by an IP for content objects served by a vehicle that has already disconnected from that IP are not satisfied. Furthermore, all content requests and delivery in a given region are performed through the IP, which might generate congestions in IPs in dense scenarios. This is critical as IPs represent single points of failure in this approach. Besides, only vehicle-to-infrastructure communication is used, ignoring the potentials of vehicle-to-vehicle communications.

Mobility Support Through Greedy Routing

The work in [44] proposes a routing protocol (MobiCCN), which works in parallel with the CCN routing protocol. The goal is to support source mobility in CCN. To distinguish between the two routing protocols (i.e., MobiCCN and CCN), two different prefixes are used. Whenever a node receives a message with the prefix *greedy* the MobiCCN protocol is used whereas when the message prefix is *ccnx*, the CCN routing protocol is used. MobiCCN differentiates routers from other nodes. Each router is assigned a virtual coordinate (VC), which is embedded into the message content names, while the other nodes are identified by an ID. Each router maintains a table of neighbor VCs. To forward a message, a router first extracts the destination VC from the message, then it calculates the distance between the destination and each of its neighbors. The message is forwarded to the neighbor that is closer to the destination. The router then updates its FIB, so next messages to the same node are forwarded without having to calculate the distance again. In this approach, each node also has a dedicated router that is the one closest to it and acts as its host router in the network. The host router serves as a rendez-vous point and forwards traffic to the node. Whenever a content source moves to a new attachment point, it sends an update message to its host router. Each router that receives the update message updates the corresponding entries for that content source in its FIB. Then, Interest messages towards the content source can be forwarded to the new domain. This work in [44] differentiates consumer nodes from routers. However, in VANETs any vehicle might perform either as a router when forwarding messages, or as a content requester/source. Furthermore, all communications in a given region are performed through the VC. The V2V communication approach is not considered. For instance, a vehicle requesting a content object that could be satisfied by another vehicle in its one-hop neighborhood has to request the content object from the VC instead of retrieving the content object from its neighbor. This increases the delay and also creates single points of failure in VCs.

Feasibility Overview of Existing Solutions

The works described in this Subsection propose some preliminary ideas to address the problem of content source mobility in VNDN. These works rely on ideas such as vehicle tracking and existence of infrastructure. Vehicle tracking might apply to scenarios with low mobility. In the case of VNDN the distances between content requester vehicles and content sources can increase significantly making the tracking process very costly and making Interest messages travel very long distances towards content sources. In VNDN multi-hop scenarios long distances usually lead to application performance degradation. In theory, infrastructure support can be one of the best ways to support vehicle mobility in VNDN. However, the high cost associated with infrastructure deployment and maintenance discourages the broad deployment of infrastructure based intelligent transportation systems. Due to these reasons, deploying the solutions proposed in [42][43][44] in real life scenarios is not trivial currently. Unlike these works, this thesis proposes a solution to the problem of content source mobility in VNDN based on the concept of floating content, which eliminates the weaknesses of the solutions proposed in the literature, provides high application performance, and incurs no deployment cost, as it is completely distributed.

The mobility problems caused by receiver/requester mobility and network partitions have not been studied yet in the specific context of Vehicular Named-Data networking.

The limitations of the works available in the literature show the need for a general purpose VNDN framework able to support both on-demand and advertised content retrieval, as well as addressing the negative effects of mobility and the unreliability of the wireless communication medium, in order to support VNDN communication with high performance. This thesis proposes such a framework.

2.4 Floating Content

Floating Content [4] is an opportunistic communication scheme, which supports infrastructure-less distributed content sharing over a given geographic area, called Anchor zone (AZ). In Floating Content (FC), when a node generates a content item, it assigns to the content an AZ and a time to live (TTL). FC was conceived to suit settings, in which a fraction of nodes within the AZ are interested in receiving an available content object.

The idea behind FC is to store a given content within its AZ without any fixed infrastructure, making it available through opportunistic communications to all users traversing that region. Whenever a node possessing the content object is within the transmission range of some other nodes not having it, the content object is replicated. When a node with the content object moves out of the AZ, it might delete the content object. The content object may be available on a set of nodes and moves over time within the AZ, even after the node that has originally generated it has left the AZ.

Authors in [45] describe the following main requirements for FC:

- *Survivability*: A content object is alive if it is stored in some nodes but not necessarily within the AZ;
- *Availability*: A content object is available if it is stored within the AZ;
- *Accessibility*: A content object is accessible to a specific node A if it is stored in a neighbor node B with whom A can communicate.

Figure 2.5 shows the basic architecture of FC. A set of nodes having a content object (i.e., nodes with blue core) replicate the content object to the remaining nodes that have just arrived in the AZ and do not have the content object (i.e., nodes with yellow core). Nodes leaving the AZ can delete the content object. For simplicity this example considers a circular shape defined by a center and a radius r. However, the AZ shape can vary according to the requirements of each application. For instance, in an application designed to work in a urban sitting, a circular AZ shape might reach more vehicles whereas for an application designed for highways, rectangular AZ shapes might perform better.

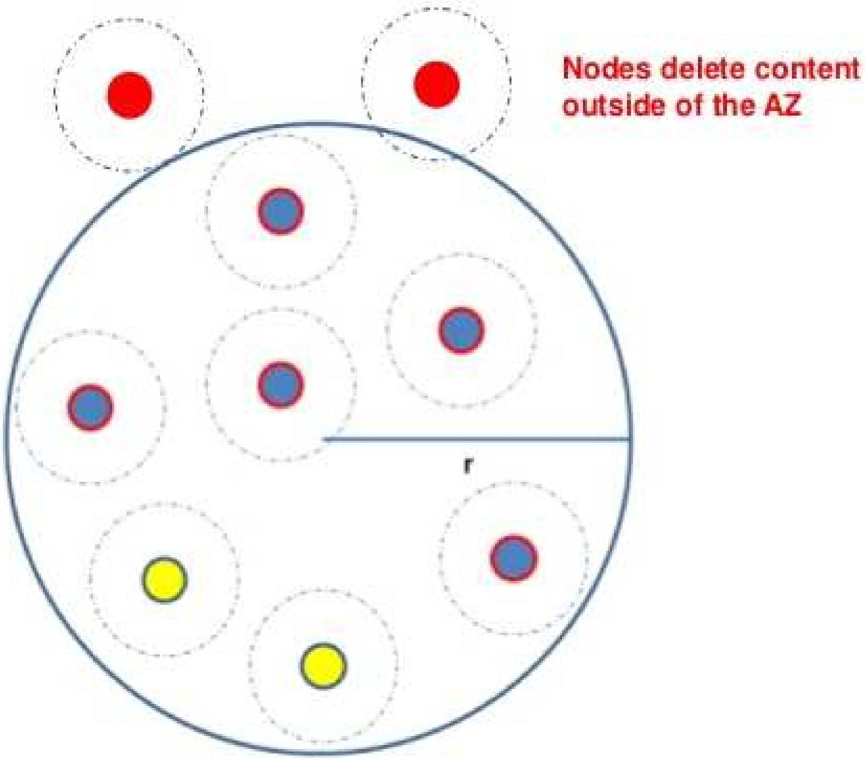


Figure 2.5: Floating Content architecture [4]

2.5 Conclusions

This Chapter described the key aspects of Vehicular Ad-hoc Networks, Named-Data Networking, and Vehicular Named-Data Networking that are the key computer networking fields on which this thesis bases, as well as Floating content that is used to address the effects of content source mobility as explained in Chapter 6. In addition a review of contributions and limitations of related work was also presented.

Chapter 3

Adaptation of Named-Data Networking to Vehicular Ad-hoc Networks

This Chapter describes how NDN was adapted to VANETs (i.e., VNDN) in this thesis. The main goal of this adaptation is to support vehicle mobility. As explained above the employment of the NDN communication approach over VANETs carries a set of significant performance advantages including reduced delay, higher robustness to disruptions, increased content availability within the network, and support for on-demand content production. However, some modifications in the structure of NDN are required to fit highly mobile VANETs. Section 3.1 describes the assumptions and modifications performed in the default NDN message types and data structures, as well as the roles attributed to the vehicles and the supported communication approaches. Section 3.2 describes the proposed content advertisement mechanism. The goal of the content advertisement mechanism is to inform potential content requester vehicles about existing content objects within the network. Section 3.3 describes the proposed routing protocol used to route Interest messages and Data messages towards potential content sources and content requesters respectively, whereas Section 3.4 concludes this Chapter.

3.1 Proposed Vehicular Named-Data Networking Communication Model

The VNDN communication model presented in this thesis assumes that each vehicle is equipped with an on-board unit (OBU) that provides processing power, storage, wireless communication, and navigation system. This assumption is valid since currently various manufacturers are already incorporating OBUs in their vehicles, and this trend is expected to increase in the coming years, allowing vehicles to take advantage from a broad set of IoT related applications.

As shown in Figure 3.1, this VNDN communication model relies on three different types of messages. In addition to *Interest messages* and *Data messages*, it introduces *Advertisement messages* that are used by content sources to inform potential content requesters about their available content objects and are intended to reach as many as possible vehicles within the network. Therefore, Advertisement messages operate in a

Interest message

Name	ID	TTL	Type	Int. Origin	Cont. Location	Vehic. Speed

Data message

Name	ID	TTL	Type	Cont. Location	Content

Advertisement message

Name	Adv. origin	Cont. location	RoI

Figure 3.1: Structure of VNDN messages

completely different way compared to Interest and Data messages. While Interest and Data messages are routed towards specific content requesters and content sources respectively, Advertisement messages are spread across the whole network. The navigation system provides vehicles with online access to their geographical locations. In this way, this information can be included in the messages exchanged between vehicles. Based on this, the Interest message structure includes the following seven fields:

- *Name*: The unique name that identifies the requested content object within the network;
- *ID*: Identifies each chunk that form a content object;
- *Time-to-Live (TTL)*: Tracks the lifetime of the Interest message;
- *Type*: Differentiates content requests for on-demand content from advertised content;
- *Interest origin*: Identifies the geographic location where the Interest message was produced;
- *Content location*: Identifies the geographic location where the content object is available;
- *Vehicle speed*: Provides the instant speed of vehicles when sending Interest messages. As explained in Section 4, vehicle speed information is used along with other parameters as inputs to calculate the probability of reverse path partitioning.

The Data message structure includes the following fields:

- *Name*: The unique name that identifies each content object within the network;
- *ID*: Identifies the content chunk carried in the Data message;
- *Time-to-Live (TTL)*: Tracks the lifetime of the Data message;
- *Type*: Distinguishes between requested content and replicated content (As described in Chapter 6 content replications are used as part of the solution to the content source mobility problem);

- *Content location*: Identifies the geographic location where the content object is available;

- *Content*: Carries the requested chunk of the content object;

The Advertisement message structures includes the following fields:

- *Name*: The unique name that identifies the content object that is being advertised;

- *Advertisement origin*: Identifies the geographic location of the last vehicle that sent or forwarded the Advertisement message;

- *Content location*: Identifies the geographic location where the content object is available;

- *RoI*: Identifies the region of interest where the content object shall be advertised.

In the proposed VNDN communication model a vehicle can play the following three main roles:

- *Content requester*: When the vehicle requests a content object (i.e., using an Interest message);

- *Message forwarder*: When the vehicle forwards a received Interest, Data or Advertisement message;

- *Content source*: When the vehicle provides the requested content object.

Similar to NDN, this model maintains the following three types of data structures:

- *Content Store (CS)*: Used for caching incoming content objects;

- *Pending Interest Table (PIT)*: Used to keep track of forwarded Interest messages, so that the vehicle can forward the corresponding Data messages towards the content requesters;

- *Forwarding Information Base (FIB)*: Used to store the geographic coordinates where content objects are available. The FIB utilization in this VNDN communication model differs from NDN. In NDN node use FIB to store the outgoing faces that connects them to the next hop in the path towards a content source of a specific content object. This modification is applied because in VANETs communications occur over the shared wireless medium, and a message sent or forwarded by a single vehicle reaches with high probability all the vehicles in its one-hop neighborhood instead of only specific vehicles.

As explained above, one of the advantages of VNDN is that a content requester can request either available content objects, which have been previously advertised, as well as content objects that do not exist yet and can be produced by request. Considering this, the proposed VNDN communication model supports the following two different content dissemination approaches:

- *Advertised content*: In this approach, whenever a content source produces a content object it creates and sends an Advertisement message to inform potential content requesters about the existence of the content object and the geographic location where it is available. When receiving the Advertisement message vehicles store the name and location of the content object in their FIBs and can then request it using Interest messages, either immediately or later on;

- *On-demand content*: In this approach, vehicles can request content objects that have not been advertised yet. Vehicles can send an Interest message of type on-demand specifying the name and the location where the content object shall be produced (e.g., video/traffic/latitude/longitude) and any vehicle currently at the indicated location that receives the Interest message can then produce the content object and send the corresponding Data messages.

3.2 Content Advertisement

This Section describes the content advertisement mechanism applied in the proposed VNDN communication model. This content advertisement mechanism applies the concept of sweet spots that was proposed by members of our computer networking research group at the University of Campinas [5].

As illustrated in Figure 3.2, a sweet spot is a geographical area in which messages sent by vehicles have higher probability of reaching larger number of vehicles. Among all vehicles that receive an Advertisement message, only one vehicle within each sweet spot forwards the same Advertisement message.

As mentioned above, content sources use Advertisement messages to advertise available content objects to potential content requesters, and the goal of Advertisement messages is to reach as many as possible vehicles quickly. Besides, this communication model also focuses on generating as less as possible overhead in the shared wireless communication medium. Therefore, a duplicate suppression mechanism is used to tune the number of vehicles that forward Advertisement messages and avoid unnecessary retransmissions. As explained in [25], the differences between existing duplicate suppression mechanisms lie mainly in the technique used to select the best forwarders. Each approach is more suitable for specific scenarios. In the case of the proposed content advertisement mechanism, and in general for applications that are intended to all or to a large number of vehicles in a particular geographic region, area-based approaches [5][46] perform better. On the other hand, in scenarios where messages are intended for specific vehicles, distance-based schemes [39] present lower delays while still providing high content delivery performance. Considering the above stated, the proposed content advertisement mechanism applies the area-based concept of sweet spot.

The diagram in Figure 3.3 shows the operation of the proposed content advertisement mechanism. Each vehicle that receives an Advertisement message first checks if the Advertisement message still in its region of interest. In such a case, if it is the first time that the current vehicle receives this Advertisement message, it schedules to forward it according to a timer delay. To calculate the delay vehicles consider as inputs both their current

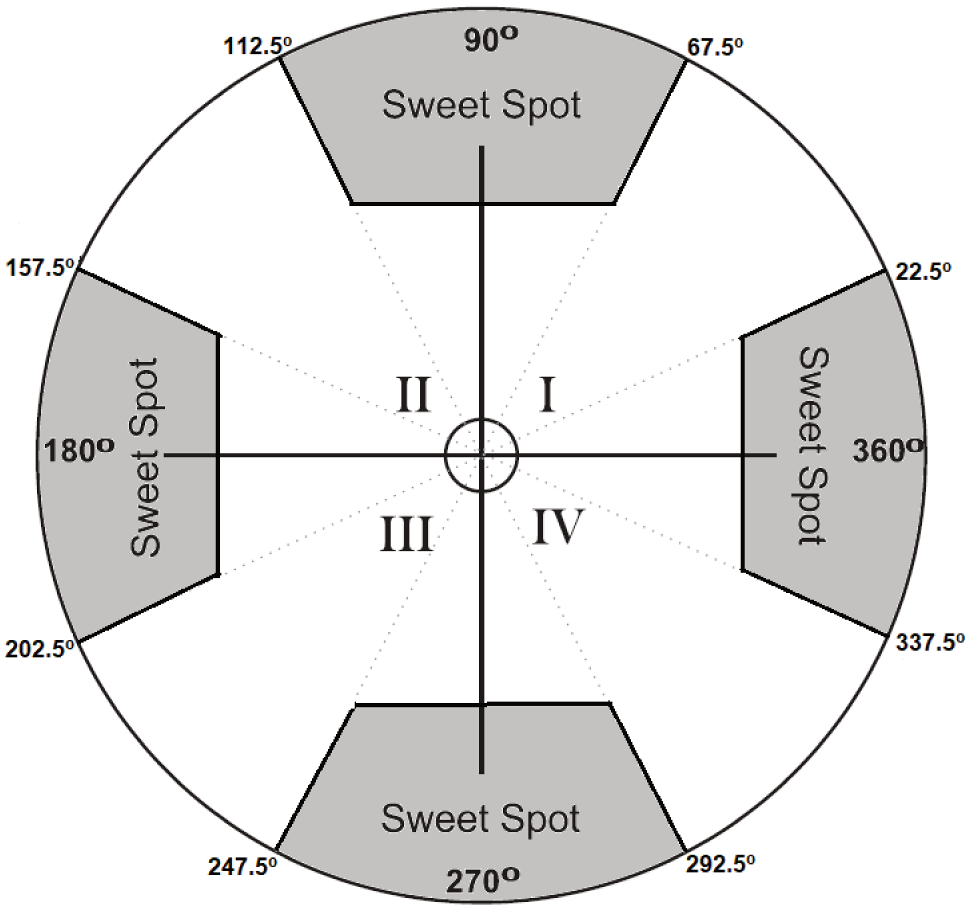


Figure 3.2: Sweet Spot [5]

positions and the distances relative to the vehicle from which they received the Advertisement message. Vehicles within sweet spots calculate shorter delays as shown in Algorithm 1. Among vehicles within the same sweet spot, the one farther away from the vehicle from which they received the Advertisement message also calculates shorter delays. Therefore, vehicles inside sweet spots and that are farther away from the previous sender/forwarder of an Advertisement message are selected to forward the message. If a vehicle receives a duplicate copy of an Advertisement message that is scheduled for forwarding the vehicle cancels the forwarding. Figure 3.4 illustrates this process. Vehicle 1 forwards an Advertisement message that is received by all the vehicles in its one-hop neighborhood (i.e., the area limited by the transmission range of vehicle 1). All vehicles that receive the Advertisement message schedule to forward it. Vehicles 2,3,4, and 5, currently located in sweet spots, calculate shorter timer delay values and forward the Advertisement message first. When perceiving that the Advertisement message has been forwarded, by other vehicles located in better positions, the remaining vehicles do not forward the same Advertisement message. For the cases where there are no vehicles inside sweet spots, the vehicles farther away from the previous sender/forwarder of the Advertisement message forward the message.

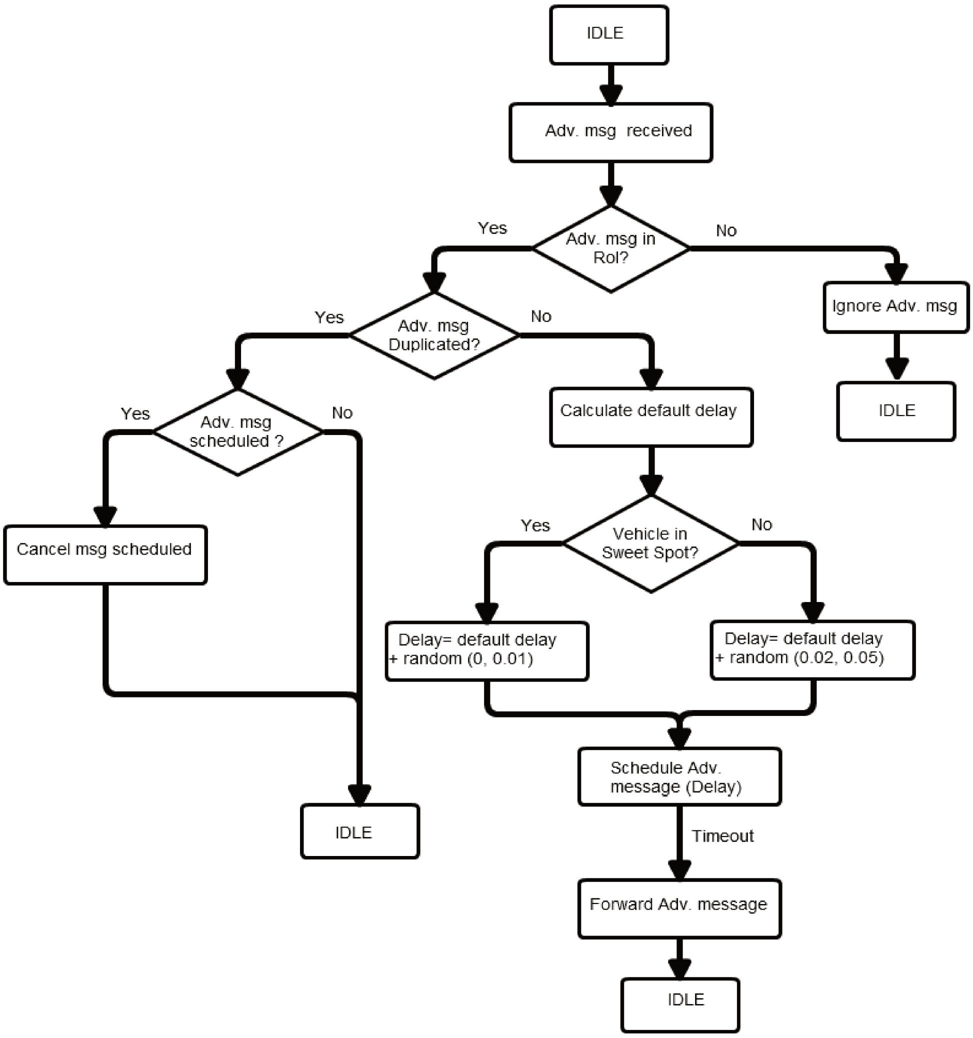


Figure 3.3: Advertisement message routing

3.3 Interest and Data Message Routing

This Section describes the routing mechanisms applied in the proposed VNDN communication model to route Interest messages towards content sources and Data messages towards content requesters.

3.3.1 Overview of VNDN Interest and Data Message Routing

As explained in Section 3.2, due to its wireless nature, VANETs require routing schemes that are able to decrease the number of required message retransmissions and avoid unnecessary usage of network resources. Position-Based Routing (PBR) schemes meet this criterion as they do not require global routes connecting content requesters to content sources and are efficient under frequent topology changes. For instance, Contention-Based

Algorithm 1: Sweet Spot

$(S_x, S_y) \leftarrow$ Coordinates of the last sender vehicle;
$(R_x, R_y) \leftarrow$ Coordinates of the current vehicle;
$Tx \leftarrow$ Transmission range;
$RoI \leftarrow$ Region of Interest; // The 2-argument function atan2 is a variation of the arctangent function;
$angle \leftarrow atan2(S_y - R_y, S_x - R_y)$;
$distToLastSender \leftarrow$ Distance between the current vehicle and the last sender/forwarder;
$defaultDelay \leftarrow 0.01X(distToLastSender/Tx)$;
if *Adv. msg Received* **then**
  if *Adv. msg in RoI* **then**
    if *!duplicated* **then**
      if *(angle* $\geq 67.5°$ *and angle* $\leq 112.5°$*) or (angle* $\geq 157.5°$ *and angle* $\leq 205.5°$*) or (angle* $\geq 247.5°$ *and angle* $\leq 292.5°$*) or (angle* $\leq 22.5°$*) or (angle* $\geq 337.5°$*)* **then**
        $delay \leftarrow defaultDelay + random(0, 0.01)$
      else
        $delay \leftarrow defaultDelay + random(0.02, 0.05)$
return *delay*

Forwarding (CBF) [39] introduced a PBR model, which has been adopted by various subsequent protocols [47] [48][49], and relies on distances to select message forwarder vehicles. CBF selects the next forwarder of a received message according to the positions of all vehicles in the 1-hop neighborhood of the previous sender/forwarder, in a way that most progress towards the message destination is achieved.

PBR schemes can also be divided into the two following categories according to where the selection of the next hop is taken.

- *Source-based* schemes: In Source-based schemes, the sender of a message indicates which neighbor vehicle is more suitable to forward the message. Therefore, this approach requires that vehicles know the topology of their one-hop network. A common method to acquire this knowledge is through the exchange of beacon messages. However, while the mobility and density of vehicles increase, the number of beacon messages required to maintain acceptable application performance also quickly increases, potentially leading to congestion on the communication channel.

- *Receiver-based* schemes: The decision on whether to forward a received message, is taken by each vehicle after receiving the message. This decision is achieved through the use of timers set in a way that vehicles located in better positions are favored, and the transmission by one vehicle inhibits the remaining vehicles from also forwarding the same message. Since receiver-based schemes do not require the exchange of beacons among vehicles [50][15][16], they are suitable for VANETs as they generate less load on the communication channel compared to source-based schemes.

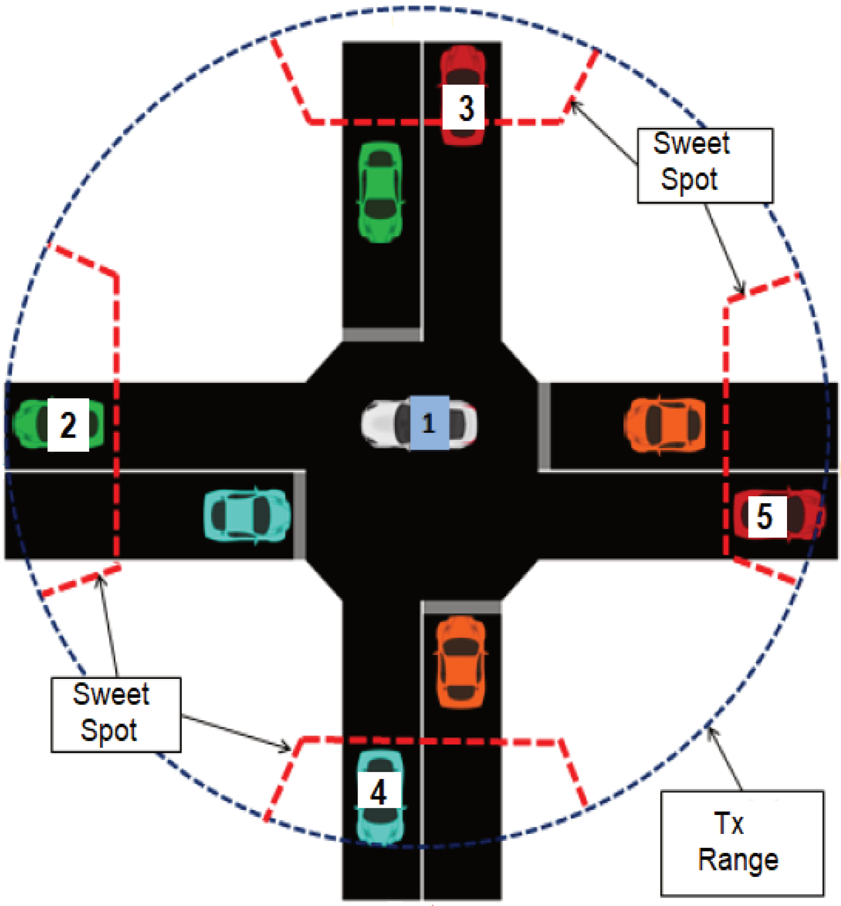


Figure 3.4: Example of sweet spot operation [6]

Other key points that influence the design of routing protocols for VANETs are the limitations of wireless communication technologies regarding coverage and signal attenuations. Considering this, multi-hop communication mechanisms are currently the most feasible way to enable wireless communication between geographically distant nodes. Taking into account the above stated, the proposed message routing mechanisms present the following characteristics:

- *Multi-hop*;
- *Beacon-less*;
- *Receiver-based*;
- *Distance-based*.

As stated in Section 3.1, the VNDN communication model proposed in this thesis allows vehicles to retrieve either already existing content objects, which were previously advertised, as well as content objects to be produced on-demand. In the first case, content requests can be satisfied either by the content producer or by any other vehicle that has cached copies of requested content objects. In the second case, when a vehicle receives

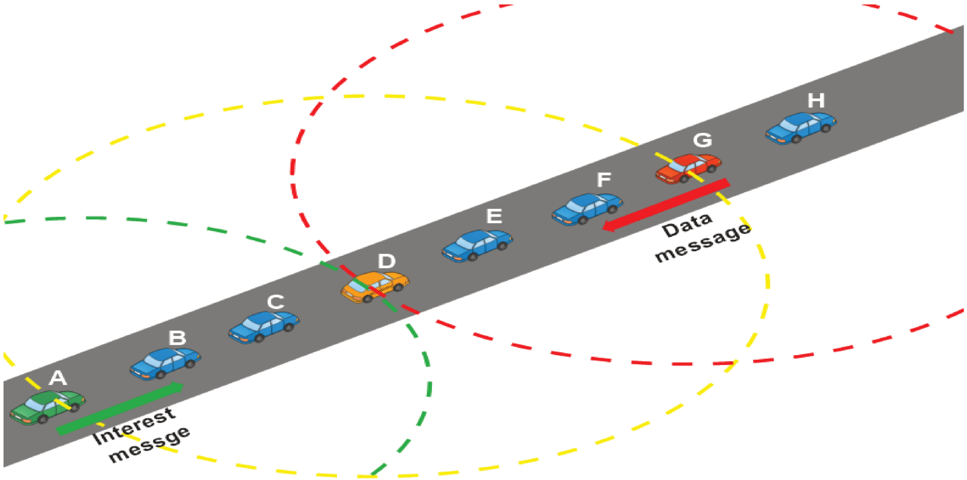


Figure 3.5: VNDN Routing

an Interest message, if it does have the requested content object, it checks whether it is currently located in the region where the content object is requested. In case affirmative, the vehicle produces the content object and can send it towards the content requester.

3.3.2 Interest Message Routing

This Subsection describes the proposed VNDN routing mechanism for Interest messages. Figure 3.6 shows the operation of this routing mechanism for the on-demand content case. The operation for the advertised content case is very similar except that the verification of whether the current vehicle can produce the requested content object is not needed since the content object already exists.

Considering the simple two hops scenario shown in Figure 3.5, vehicle *A* sends an Interest message requesting a content object that can be provided by vehicle *G*. The Interest message is first received by the vehicles in the one-hop neighborhood of *A* (i.e., *B, C,* and *D*). Each one of these vehicles then performs a lookup for the requested content object in its CS. If the requested content object is not found in the CS, for the case of requests for on-demand content objects, each vehicle analyses the destination of the Interest message to determine whether it can produce the requested content. In the case of requests for advertised content objects, this step is ignored. Since none of these vehicles can provide the requested content object, all of them schedule to forward the received Interest message towards the content location (i.e., the location of vehicle *G*) according to an Interest timer delay scheme. To calculate delay values for forwarding Interest messages a vehicle considers as inputs its distance respective to the vehicle from whom it received the Interest message as well as its remaining time in the current driving direction. This process is described in Algorithm 2.

As it can be observed, vehicles that are farther away from the previous sender or forwarder of a received Interest message and that will not change driving direction in the next four seconds (i.e., reference message propagation delay for NDN) calculate lower delay values. This condition is applied to minimize the probability of Interest message forwarder vehicles leaving the communication path established by the Interest message

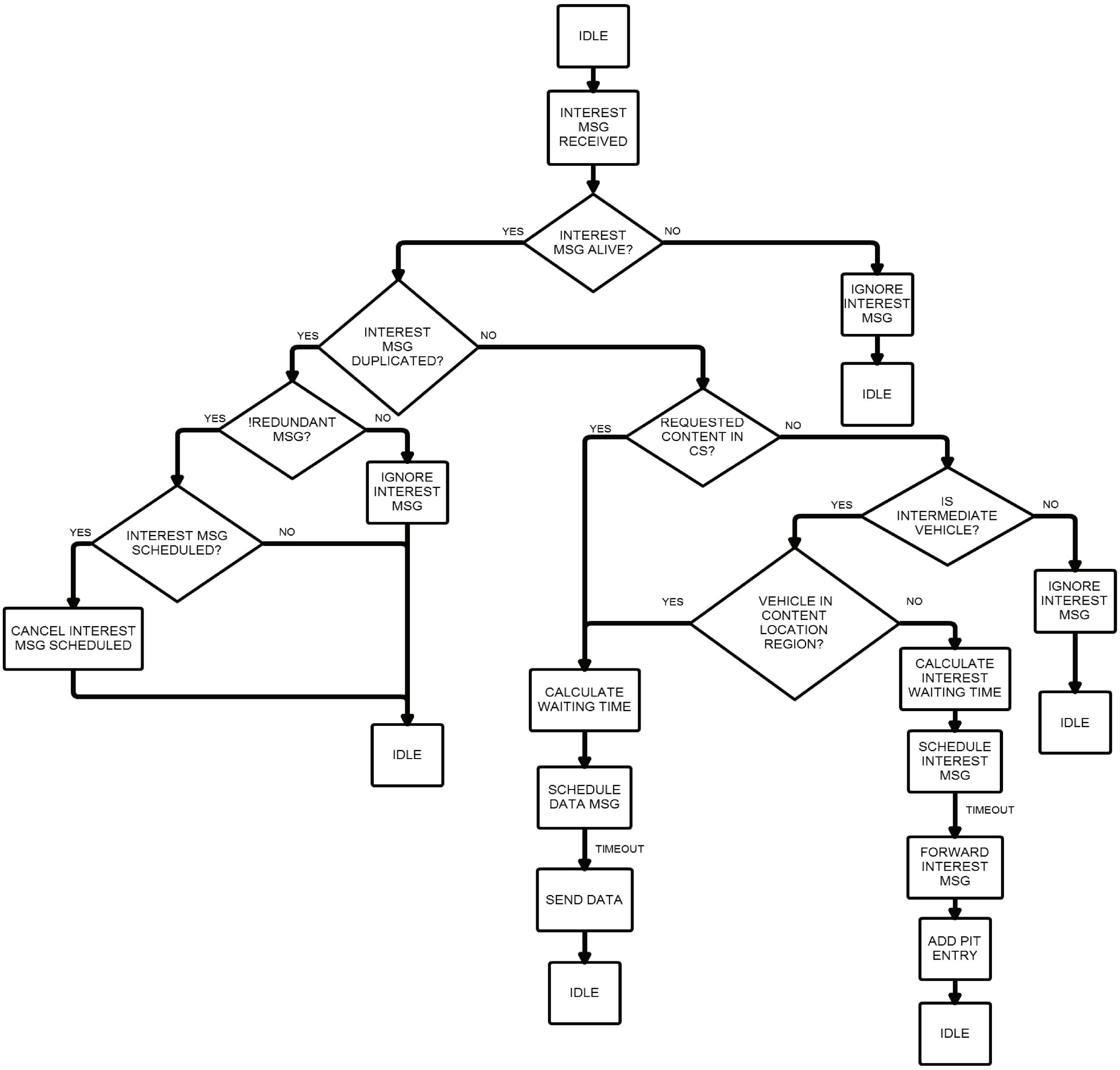


Figure 3.6: Interest message Routing

propagation before forwarding the corresponding Data message.

When the timer of a given vehicle expires, the vehicle forwards the Interest message and adds a PIT entry corresponding to the requested content object. In the example in Figure 3.5 vehicle *D* forwards the Interest message. The remaining vehicles cancel their own scheduled Interest message forwarding when perceiving that the Interest message has been forwarded by another neighbor vehicle (i.e., a vehicle that calculated a lower timer delay). This process continues until the Interest message reaches a content source vehicle or it expires.

3.3.3 Data message routing

When a vehicle receives an Interest message requesting a chunk of a content object that it can provide (i.e., a content source has been reached), the vehicle initiates the process

Algorithm 2: Calculating Interest timer delay values

```
CS ← Content Store;
(S_x, S_y) ← Coordinates of the last sender vehicle;
(R_x, R_y) ← Coordinates of the current vehicle;
Tx ← Transmission range;
t ← Expected remaining time on the road for the current vehicle;
distToLastSender ← Distance between the current vehicle and the last sender;
if InterestMessageReceived then
    if !CS then
        distToLastSender = sqrt((S_x − R_x)^2 + (S_y − R_y)^2);
        delay = Tx / (distToLastSender + min{t, 4});
        scheduleInterestMessage(delay);
return;
```

Algorithm 3: Calculating Data timer delay values

```
CS ← Content Store;
(S_x, S_y) ← Coordinates of the last sender vehicle;
(R_x, R_y) ← Coordinates of the current vehicle;
Tx ← Transmission range;
distToLastSender ← Distance between the current vehicle and the last sender;
if InterestMessageReceived then
    if CS then
        distToLastSender = sqrt((S_x − R_x)^2 + (S_y − R_y)^2);
        delay = distToLastSender / Tx;
        scheduleDataMessage(delay);
return;
```

of sending the corresponding Data message. A single Interest message can reach multiple content sources. Considering this, for avoiding that multiple content source vehicles send the same Data message, vehicles schedule the forwarding of the Data message according to a Data timer delay (Data timer delay values are lower than Interest timer delay values). Data timer delay values are directly proportional to the distance between each vehicle and the vehicle from whom it received the Interest message. Thanks to this, vehicles closer to the last Interest message forwarder calculate lower Data timer delay values as shown in Algorithm 3. When the Data timer of a given vehicle expires, the vehicle sends the corresponding Data message towards the Content requester. When the remaining vehicles receive the Data message, they cancel either their scheduled Interest or Data messages forwarding. Again considering the example in Figure 3.5, let us now assume that both vehicles F and G have the requested content object. In this case when receiving the Interest message forwarded by vehicle D vehicles F and G schedule the forwarding of the corresponding Data message while vehicle E schedules the forwarding of the Interest message. The timer in F expires first, and F sends the Data message. When receiving the Data message G cancels its scheduled Data message forwarding while E cancels its scheduled Interest message forwarding. When the intermediate nodes receive the Data message, they perform a PIT lookup, and if they find an entry related to the requested

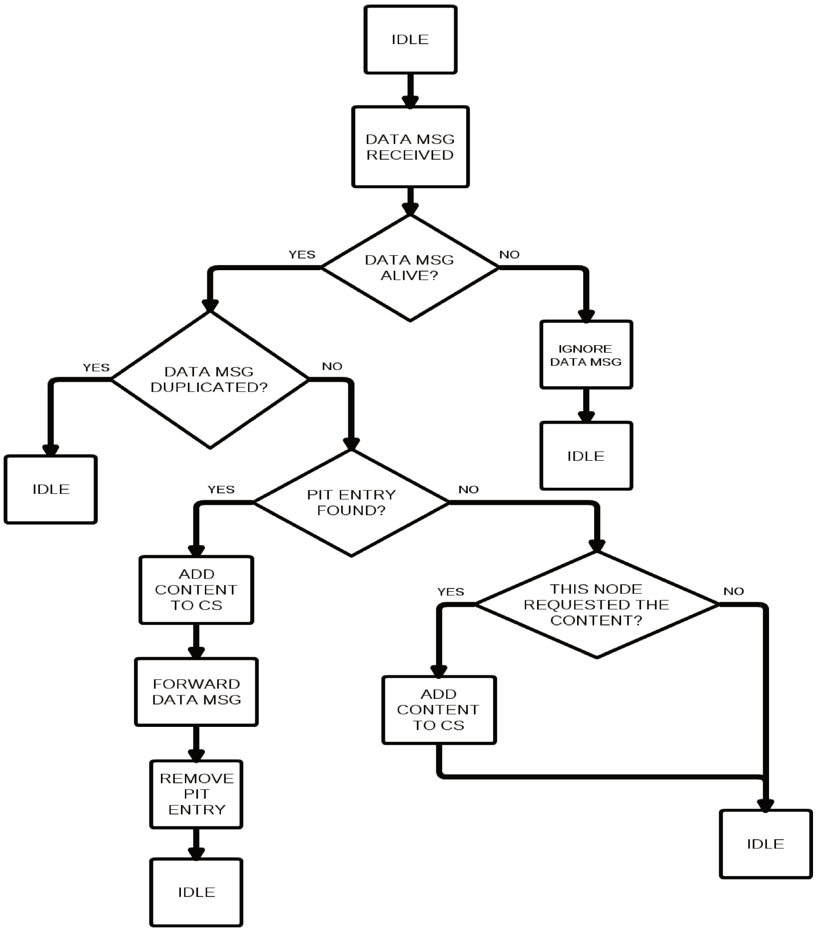


Figure 3.7: Data message Routing

content object, they forward the Data message and remove the PIT entry. If a vehicle receives a Data message and finds no related PIT entry (i.e., the current vehicle did not forward the corresponding Interest message), it discards the Data message. In this example, only vehicle *D* forwards the Data message received from *F*. This process continues until the Data message reaches the original content requester or the last Data forwarder vehicle forwards it. Figure 3.7 and Algorithm 4 illustrate this process.

Applying these message routing approaches the number of vehicles that forward Interest and Data messages decreases significantly. In this way, the broadcast storm problem is mitigated. Subsection 3.3.4 describes how the proposed routing mechanisms address the problems of message redundancy and transmission resynchronization.

3.3.4 Message Redundancy

This Subsection describes how to prevent the occurrence of the message redundancy problem. To understand how the message redundancy problem occurs let us consider the case shown in Figure 3.8. Vehicle *A* sends an Interest message requesting content *C1* that can be provided by vehicle *F*. The Interest message is first received by vehicles *B* and *C*. In delay based routing mechanisms, such as the routing mechanisms proposed in this thesis, both *B* and *C* will schedule the Interest message forwarding with the one farther

Algorithm 4: Data message routing

```
CS ← Content Store;
PIT ← Pending Interest Table;
if !DataMsgInCS then
    if DataMsgAlive then
        if PITentry then
            Add Content to CS;
            Forward Data msg;
            Remove PIT entry;
        else
            if ContentRequester then
                Add Content to CS
return;
```

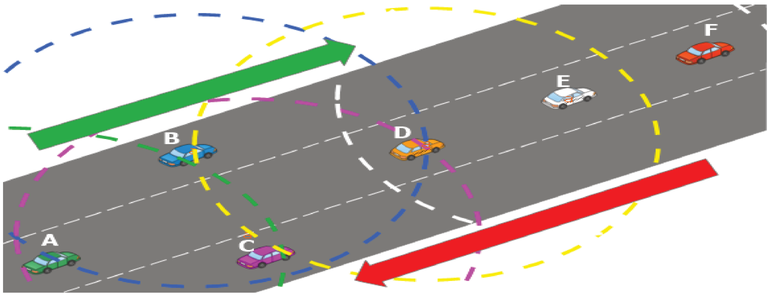


Figure 3.8: Message redundancy

away from A calculating a shorter timer delay value. In theory B, which is a little bit farther away from A, forwards the Interest message and inhibits C from also forwarding it. The Interest message is then received and forwarded by D and E, and finally it reaches F. F then sends the corresponding Data message.

In practice, the time interval between *t1*, the time instant when the timer in vehicle B expires, and *t2*, the time instant when C receives the Interest message forwarded by B is not zero and it can lead to the occurrence of the message redundancy problem, negatively affecting the message propagation.

Since the distances A-B, and A-C respectively are very similar, vehicles B and C will calculate similar delay values. Let us assume that at time *T0=0s* both vehicles B and C receive the Interest message sent by A. Vehicle B calculates a delay of *30ms* while vehicle C calculates a delay of *40ms* to forward the Interest message. At time *T1=30ms* the timer in vehicle B expires and its network layer requests the MAC layer to deliver the Interest message. However, the MAC layer takes some time to process the message (e.g., *7ms* before the Interest message is actually sent over the wireless communication medium. If the radio signal carrying the Interest message forwarded by B takes *5ms* to reach vehicle C, it will only be received by C at time *T3=42ms*. At time *T2=40ms*, the timer in vehicle C had already expired and C has also requested its MAC layer to send the Interest message. Therefore, both vehicles B and C forward the same Interest message. As the timer delay values are different, no collision occurs. Then, vehicle D receives the Interest message forwarded by vehicle B, it calculates its own delay value and schedules the forwarding of the Interest message. However, some time instants later vehicle D also receives the Interest message forwarded by vehicle C. In such a case vehicle D will erroneously recognize the second Interest message as forwarded by another neighbor vehicle located closer to the destination (thus, with shorter delay) and D will cancel the forwarding of the Interest message. In this way, the Interest message does not reach the content source (i.e., vehicle F) and the content object is not delivered.

This thesis solves the *message redundancy* problem with a simple step. Every time that a vehicle receives a duplicated Interest message, it checks the message *Interest origin* and *Content location* fields. If the vehicle that sent the Interest message is closer to the content location compared to the current vehicle, the duplicated Interest message is recognized as a forwarding by a neighbor vehicle that calculated a shorter timer delay and the vehicle inhibits itself from also forwarding the Interest message. Otherwise, the Interest message is considered as redundant and is ignored.

3.3.5 Transmission Resynchronization

This Subsection describes how the VNDN communication model proposed in this thesis prevents the occurrence of the transmission resynchronization problem. The transmission resynchronization problem affects VNDN due to the WAVE channel switching mechanism. The transmission resynchronization problem contributes to increase the probability of message collisions and degrades VNDN application performance by allowing multiple vehicles to transmit simultaneously, even when the vehicles correctly schedule to forward received messages with different timer delay values.

Overview of the Transmission Resynchronization Problem

As described in Subsection 2.1.2 the WAVE standard presents an architecture based on multiple channels that includes a control channel and six service channels. As the WAVE standard does not require the use of multiple antennas, a channel switching mechanism is applied based on time division multiplexing. At each Tc seconds the radio is allowed to switch from the CCH to SCH and then, after more Tc seconds, switch from SCH to the CCH, and so on. The standard establishes Tc=*50ms*. Given this, when the MAC layer receives from the above layer a message to be transmitted in SCH, but the CCH is active, the message must wait until the SCH becomes active, so that the transmission can happen. Every message passed to the MAC layer must specify which channel it should be transmitted to.

To understand how the transmission resynchronization problem can occur, let us consider the example shown in Figure 3.9. In Figure 3.9 vehicles A and B are trying to forward a message that they received from a common neighbor. At time $t=T1$ both vehicles schedule to forward the Interest message. Vehicle A calculates a delay of *10ms*, while B calculates a delay of *25ms*. In theory A forwards first and inhibits B from forwarding the same Interest message. However, in practice the following case might happen. At time $t=T2=T1+10ms$ A requests its MAC layer to deliver the Interest message over the wireless communication medium using a service channel. Since the control channel is active, the MAC layer of vehicle A stores the message until the SCH becomes active. At time

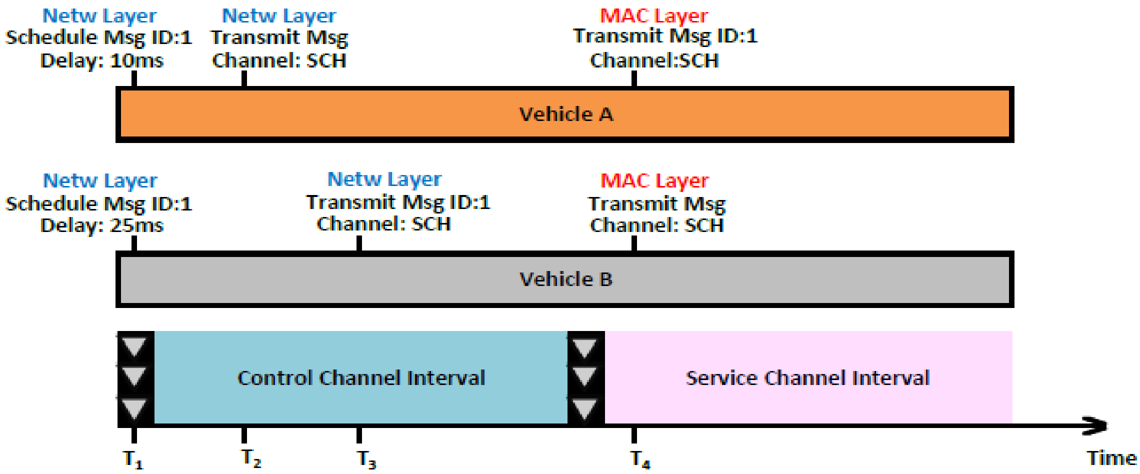


Figure 3.9: Transmission resynchronization problem

t=T3=T1+25ms B requests its MAC layer to also deliver the Interest message over the shared wireless communication medium also using *SCH*. As the *CCH* is still active, similar to *A*, the MAC layer of *B* also stores the Interest message. Finally, at time *t=T4* when the *SCH* becomes active, the MAC layers of both vehicles perceive the channel as free and forward the message at the same time, resulting in a collision. Despite that the duplicate suppression mechanisms at the network layer calculated different delay values for each vehicle (desynchronization), both vehicles forwarded the message simultaneously (resynchronization). Since vehicular communications presuppose channel synchronism between vehicles, the occurrence probability of the transmission resynchronization problem is high and increases as vehicles densities also increase, degrading application performance.

Proposed Solution for the Transmission Resynchronization Problem

To solve the transmission resynchronization problem, this thesis adds a component that provides awareness to channel switchings to the routing mechanisms described in Sections 3.2 and 3.3 to recalculate the forwarding delays. The main idea is to add an extra delay to the calculated delay if the *CCH* is active. Algorithm 5 describes this process.

In this case, the extra delay is *Tc*, a channel time (i.e., for how long each channel can be active). For example, a vehicle receives the message *m* in time *T1* in Figure 3.9. The protocol used to perform the data dissemination calculates a delay *T=70ms* to forward the message *m*. In this example, Algorithm 5 calculates the number of whole channel cycles before *T*, (i.e., *cicles=1*). This number is needed to find out if *CCH* is active after the waiting delay *T*. Since *Tc=50ms*, at time *T1* the CCH is active and will remain so for more *Ts=5ms*. In the first case, if the network layer sends *m* to the MAC layer at time *T1* and the MAC layer waits *T=70ms* before attempting to forward *m* in the SCH, then the vehicle will perceive *CCH* as active for *45ms*. If the network layer does not use the proposed desynchronization mechanism, it schedules the forwarding of *m* with a time delay *T*. Thus, at time *T2*, it sends *m* to the MAC layer for forwarding in the *SCH*. However, the forwarding will not occur promptly as the *CCH* is active, which can lead to a resynchronization, as explained earlier. On the other hand, if the network layer uses

Algorithm 5: WAVE desynchronization

Initialize

$T \leftarrow$ waiting delay passed to the function; $Tc \leftarrow$ channel time (50ms); $Ts \leftarrow$ remaining time for a channel switch;

$delayAux \leftarrow T - Ts$; **if** $delayAux < 0$ **then**

  $delayAux \leftarrow 0$;

$cycles \leftarrow \left\lfloor \frac{delayAux}{Tc} \right\rfloor$;

if *CCH is active* **then**

  if $cycles\%2 == 1$ **then**

    $Td \leftarrow T + Tc$;

else

  if $cycles\%2 == 0$ **then**

    $Td \leftarrow T + Tc$;

return Td

Algorithm 5, it schedules the forwarding of m with a delay $Td{=}T{+}Tc$. Thus, at time $T3$, the network layer relays m to the MAC layer and it can immediately forward it, as the *SCH* is active. In fact, the use of the delay $Td{=}T{+}Tc$ ensures that the *SCH* will always be active when the network layer relays m to the MAC layer, thus consequently avoiding the effect of resynchronization of the delay.

3.4 Conclusions

This Chapter described the implementation of the basic VNDN communication model proposed in this thesis. This VNDN implementation is used as a base case for performance evaluations in the following Chapters. Section 3.1 described the main modifications performed to the NDN architecture in order to accommodate to highly dynamic VANETs, regarding the available message types, data structures and communication approaches. Section 3.2 described the content advertisement mechanism that is used to inform potential content requester vehicles about existing content objects within the network. This content advertisement mechanism applies the concept of sweet spot that selects vehicles located in areas with higher probabilities of reaching larger number of neighbors to forward Advertisement messages with the goal of maximizing Advertisement message dissemination. Section 3.3 described the proposed routing approaches to route Interest and Data messages. The multi-hop routing approaches proposed in this thesis focus on achieving high application performance without generating unnecessary overhead in the wireless communication medium and avoid VANET communication problems such as broadcast storms, message redundancy, and transmission resynchronization. However, to efficiently support VNDN communications a set of challenges derived from the high mobility of VANETs and the unreliability of the wireless communication medium shall also be mitigated. This thesis addresses these challenges in the following Chapters.

Chapter 4

Receiver Mobility

This Chapter investigates the effects of content receiver mobility in the performance of Vehicular Named-Data Networking (VNDN) applications. The terminology *receiver mobility* is used in this thesis to represent the simultaneous mobility of content requesters and message forwarder vehicles. In particular, this Chapter identifies the problem of Reverse Path Partitioning (RPP) that often prevents Data messages from reaching Content requesters, degrading application performance. To mitigate the effects of RPP the MobiVNDN model proposes a mechanism called Auxiliary Forwarding Set (AFS). AFS takes several mobility factors as inputs and extends the NDN core philosophy where only the vehicles that forwarded an Interest message forward the corresponding Data message, by identifying an extra set of eligible nodes to forward Data messages due to RPP.

4.1 Reverse Path Partitioning

This Section describes the RPP problem and highligths the factors that can lead to its occurrence.

4.1.1 Problem Statement

A Reverse Path Partitioning (RPP) can be defined as a disruption on the communication link between two consecutive Data message forwarders, preventing them from routing the Data message to the content requester. To decrease the delay and avoid unnecessary message retransmissions, similar to other ICN routing mechanisms for VANETs such as V-NDN [22] and CCVN [28], the VNDN Interest message routing proposed in this thesis also selects as message forwarders the vehicles farther away from the previous senders or forwarders of Interest messages. However, as the distance between two consecutive Interest message forwarders increases, the probability of them moving out of the transmission range of each other also increases. In the case of VNDN, where Data messages travel along the reverse path through the same vehicles that the corresponding Interest message traveled, frequently consecutive Data message forwarders are temporary unable to communicate with each other and the reverse path breaks before the Data message is delivered to the content requester. Figure 4.1 illustrates how RPP can occur even in dense traffic scenarios (i.e., scenarios where the probability of network partitions is low).

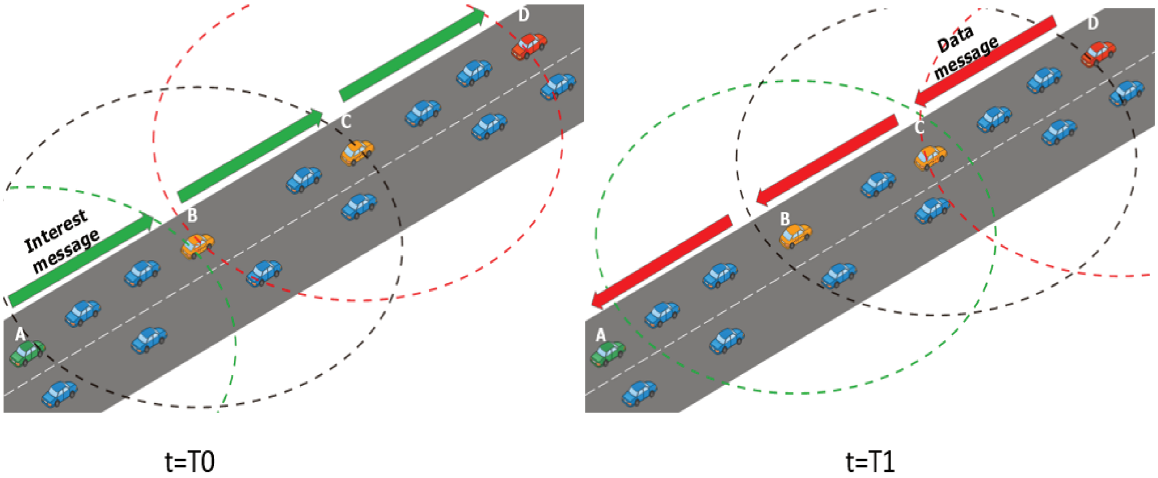


Figure 4.1: Reverse Path Partitioning in Dense Scenarios

In Figure 4.1, at time *t=T0* (left side of Figure 4.1), vehicle *A* (green vehicle) is interested in a content object that can be provided by vehicle *D* (red vehicle). To request the content object, *A* sends an Interest message towards the geographic location of *D*. Vehicle *B*, which is the farthest away intermediate vehicle in the one-hop neighborhood of *A*, forwards the Interest message. Similarly, Vehicle *C* also forwards the Interest message. Since vehicle *D* is a one-hop neighbor of *C*, it receives the Interest message forwarded by vehicle *C*. When receiving the Interest message at time *t=T1* (right side of Figure 4.1), vehicle *D* sends the corresponding Data message towards vehicle *A*. Vehicles *C* and *B*, which are on the reverse path since they previously forwarded the Interest message, receive and forward the Data message. However, as illustrated in the right side of Figure 4.1, at time *t=T1*, vehicle *A* is not in the transmission range of *B*. Therefore, the Data message is not delivered due to a partition in the reverse path between vehicles *B* and *A*. Although there is no network partition between vehicles *A* and *B* since there are two more vehicles in between, these vehicles are not part of the reverse path and reverse path partitioning occurs. Reverse path partitioning can occur between any two consecutive message forwarder vehicles and it can be caused by diverse factors. Subsection 4.1.2 describes three different causes of RPP.

4.1.2 Causes of Reverse Path Partitioning

The probability of RPP increases as the distance between vehicles forwarding Interest messages also increases due to diverse causes including:

- *Vehicle speeds and distance:* For instance, in Figure 4.1 let us consider that at time *t=T0*, when vehicle *A* requests the content object, the distance between *A* and *B* is equal to 190m, that both vehicles have a maximum transmission range equal to 200m and that *A* is traveling at 80 km/h while *B* is traveling at 100 km/h. Due to this, if the corresponding Data message takes three seconds (3s) to reach *B*, at the time when *B* receives the Data message, the distance between *B* and *A* will have increased to 250m. In this case, an RPP occurs preventing *B* from delivering

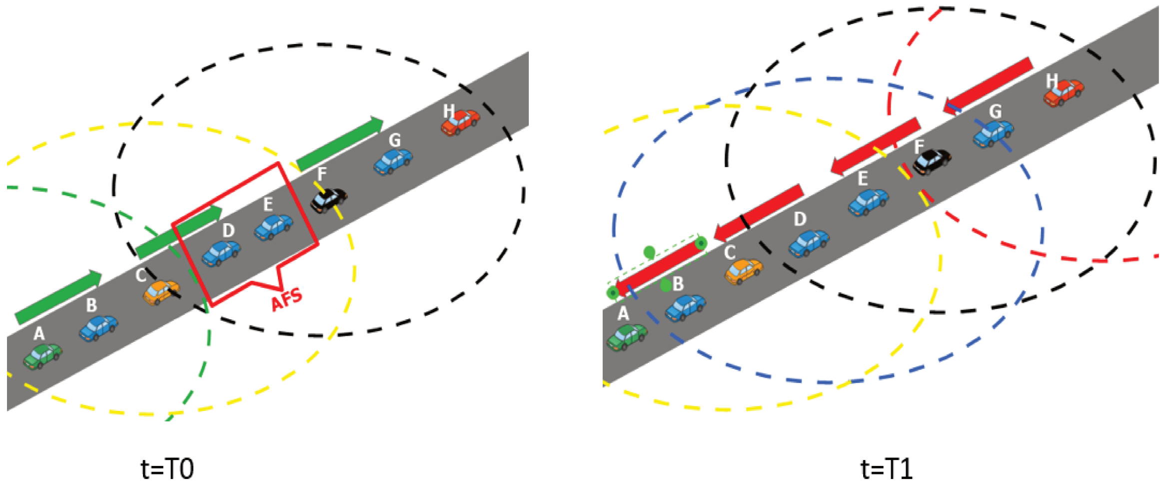


Figure 4.2: Auxiliary Forwarding Set

the Data message to A despite that B previously forwarded the Interest message received from A.

- *Transmission range:* The transmission range of vehicle A might be larger than for vehicle B. This situation can happen since vehicles may be equipped with devices of different communication capabilities or because antennas in higher vehicles may have better lines of sight and reach larger distances. For instance in Figure 4.1 let us consider that the maximum transmission ranges of A and B are equal to 250m and 200m respectively and that the distance between both vehicles is equal to 225m. In such a case, A can directly deliver an Interest message to B for forwarding, whereas B is unable to deliver the corresponding Data message to A even if there is no change in the vehicles speeds and the distance between them.

- *Unreliability of the wireless communication medium*: Signal propagation over the wireless medium may suffer temporary attenuations due to obstacles, weather conditions, etc, which might also prevent B from delivering the Data message to A.

To mitigate the RPP problem this thesis applies the concept of Auxiliary Forwarding Set (AFS) described in Section 4.2.

4.2 Auxiliary Forwarding Set

In the VNDN communication model proposed in this thesis, when the intermediate vehicles detect high RPP probability between two consecutive Interest message forwarders, they form an AFS group. Vehicles in an AFS are eligible as candidates to forward Data messages in addition to the original Data message forwarder, as opposite to NDN where a single node in each one-hop neighborhood forwards a Data message. Similar to the Interest, Data, and Advertisement message routing approaches described above, vehicles that are members of the same AFS group do not exchange messages between them to share state information. AFS employs a timer delay mechanism in addition to other input parameters as described below to select the vehicle in the AFS that should forward a received Data message in case of RPP.

Let us consider the case shown in Figure 4.2, where vehicle *A* is interested in a content object *C1* that was advertised by vehicle vehicle *H*. At time t=*T0* (left side of Figure 4.2) vehicle *A* sends an Interest message (green arrow) requesting the content object *C1*. The Interest message is first received by vehicles *B* and *C* and forwarded by *C* that is farther away from *A* compared to *B*. Similarly, vehicle *F* forwards the Interest message, delivering it to vehicle *H*. Then, vehicle *H* sends the corresponding Data message. In case of no RPP, vehicles *F* and *C* forward the Data message and *A* receives it. However, Figure 4.2 shows that at time t=*T0*, the distance between vehicles *F* and *C* is high (for instance, 190m for a maximum transmission range of 200m) and *F* is very close to the limit of the maximum transmission range of *C*. In such a case, vehicles *D*, and *E* calculate the probability of RPP between vehicles *C* and *F* and if the RPP occurrence probability is high they form an AFS group by adding a PIT entry for the corresponding Data message.

To determine the probability of RPP vehicles use the following parameters as inputs:

- Distance between the vehicles that forwarded the Interest message (e.g., vehicles *C* and *F* in the example in Figure 4.2). The geographic positions of Interest message forwarders can be obtained from the Interest origin field in the received Interest messages;
- Speed difference between the vehicles that forwarded the Interest message. Vehicle speeds can be obtained from the Vehicle Speed field in the received Interest messages;
- The maximum transmission range of vehicles (i.e., 200m in this example);
- The maximum expected content delivery delay;

For instance, in Figure 4.2 assuming a maximum expected content delivery delay of 4s and a maximum transmission range of 200m, if vehicle *C* is traveling at 80km/h while vehicle *F* is traveling at 100km/h, after 4s the distance between vehicles *C* and *F* increases by 22.4m. Therefore, RPP occurs with high probability if at the time of forwarding the Interest message the distance between vehicles *C* and *F* is equal or larger than 177.6m (i.e., transmission range - 22.4m). As explained above, RPP may also be caused by other factors. Due to this, an error of 10% is introduced in the calculated value. Therefore, in this example vehicles *D* and *E* actually form an AFS if the distance between *C* and *F* is equal or larger than 159.84m (i.e., 90% of 177.6m). When vehicle *F* forwards the Data message if vehicle *C* does not receive it, the vehicle in the AFS that is farther away from vehicle *F* (i.e. vehicle *D* in this example) forwards the Data message towards vehicles *C*. To distinguish regular Data Forwarders from AFS forwarders, an AFS flag is added to each PIT entry. Vehicles belonging to an AFS use Data messages forwarded by neighbor vehicles as implicit acknowledgments of content reception. Figures 4.3 and 4.4 illustrate this process.

In summary, AFS extends the core concept of NDN by electing an extra set of nodes as candidates to forward Data message in the cases where due to the high VNDN mobility

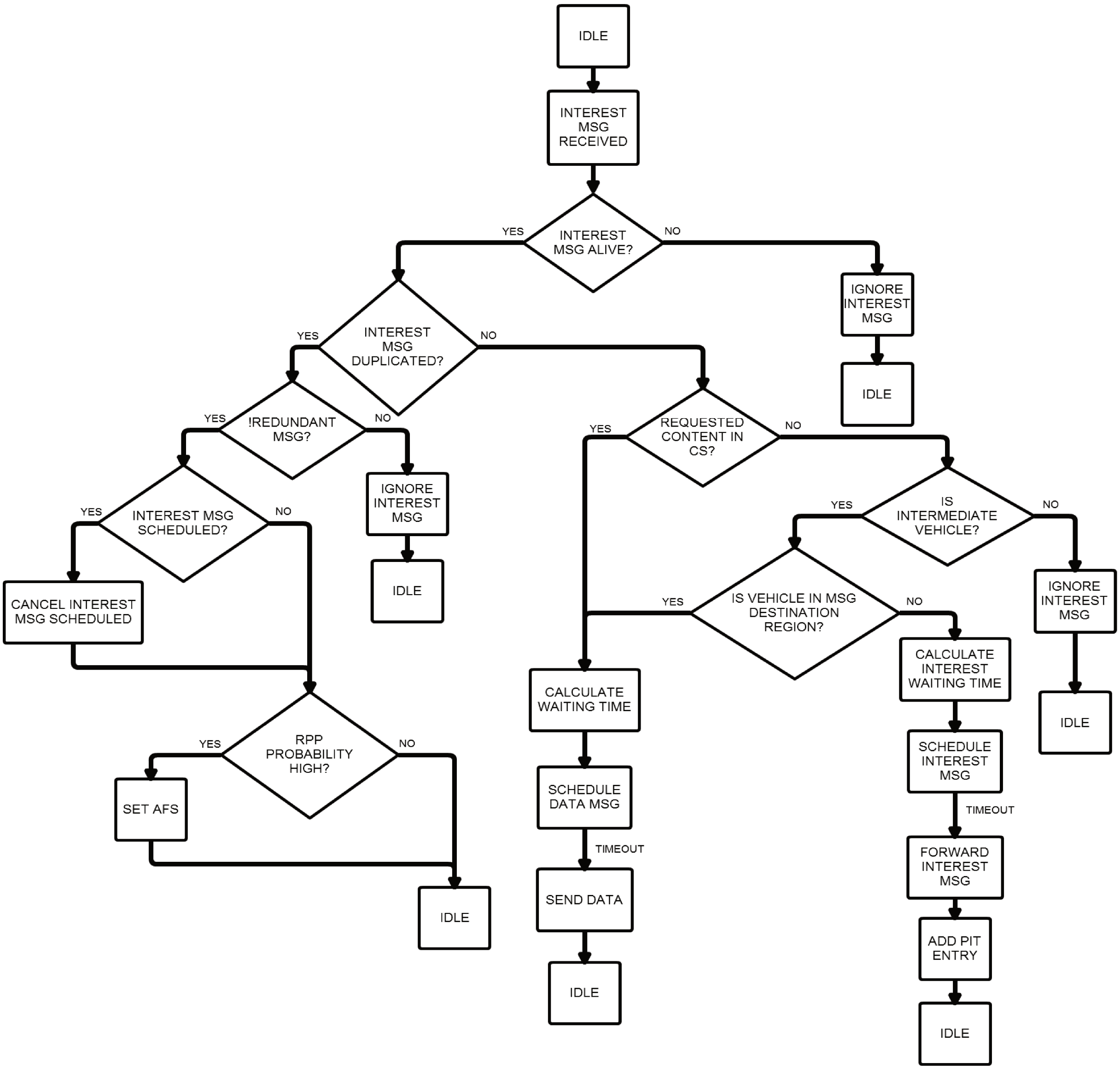


Figure 4.3: Interest message routing with Auxiliary Forwarding Set

the set of vehicles that forwarded the Interest message (i.e., vehicles belonging to the original reverse path) are not enough to deliver the corresponding Data message to the content requester.

4.3 Performance Evaluation

This Subsection presents the evaluation performance of VNDN with and without the Auxiliary Forwarding Set mechanism performed through a set of simulations. This Subsection also lists the simulation tools and parameters, it describes the simulation scenario as well as the performance metrics and finally discusses the obtained results.

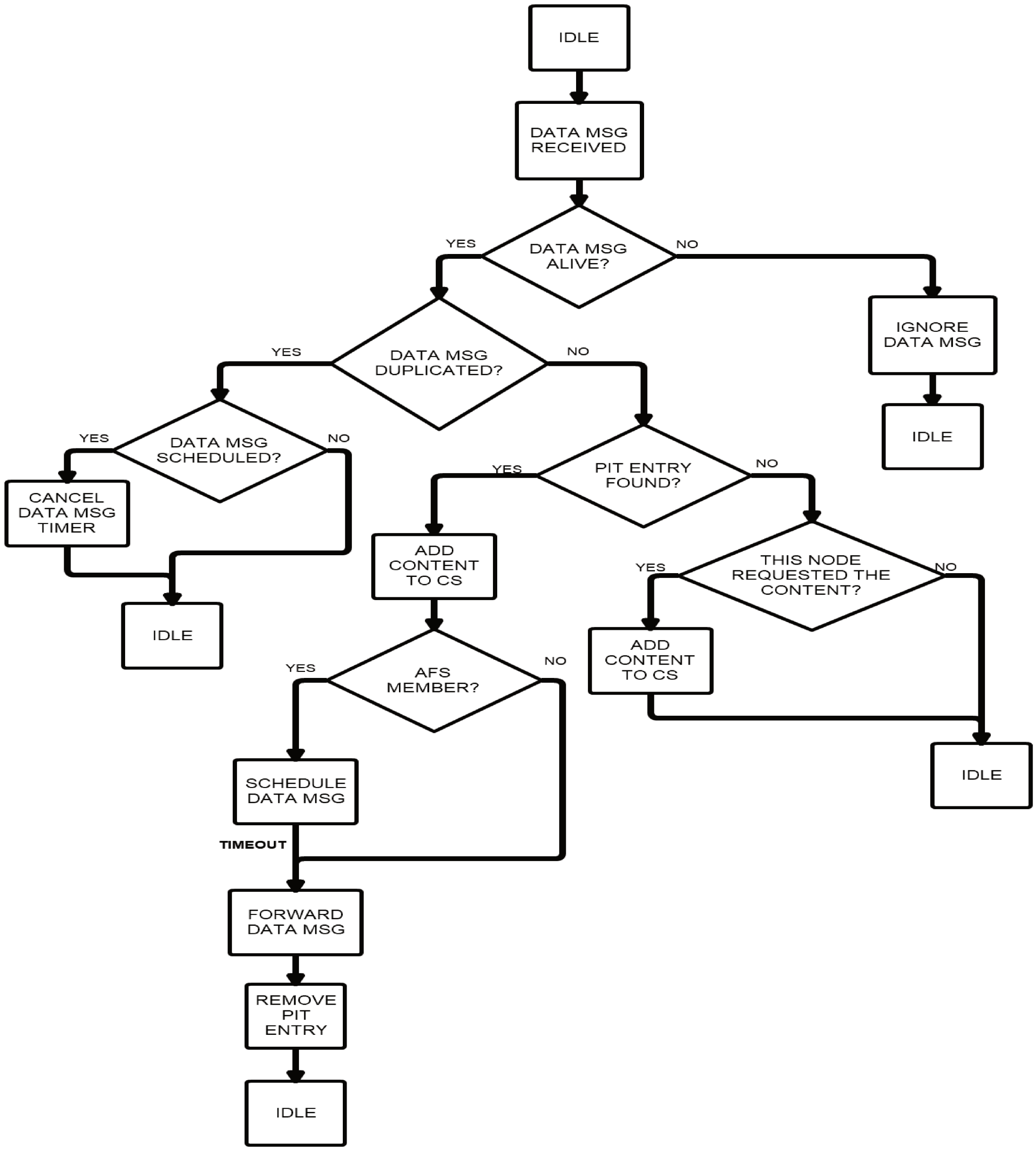


Figure 4.4: Data message routing with Auxiliary Forwarding Set

4.3.1 Simulation Tools

To evaluate the performance improvements provided by the AFS mechanism, the following set of network simulation tools that are widely used in the scientific community, were used.

- *Omnet ++ (Objective Modular Network Testbed) [51]*: A C++ based discrete event simulator for modeling communication networks, multiprocessors and other distributed or parallel systems. OMNeT++ is public-source, and can be used under the Academic Public License;

- *SUMO (Simulation of Urban Mobility) [52]*: An open source road traffic simulation package designed to handle large road networks. SUMO is licensed under GPL;

- *Veins (Vehicles in Network Simulation) [53]*: An open source framework for running vehicular network simulations. Veins is based on OMNeT++ and SUMO and it offers a suite of models for IVC simulation;

4.3.2 Simulation Parameters

Table 4.1: AFS - Simulation parameters

Parameters	**Values**
Number of vehicles	100, 200, 300, 400 vehicles
Vehicles maximum speeds	50, 80, 100 Km/h
Number of Content Requesters	10, 20, 30, 40
Carrier frequency	5.9GHz
WAVE channel type	Service Channel
Size of Interest messages	1024bytes
Size of data Messages	4096bytes
Number of chunks per content	100
Communication technology	IEEE802.11p
Communication types	V2V and V2I
Maximum transmission range	200m
Shareability	shareable data

The simulations were performed for the cases of 100, 200, 300, and 400 vehicles. For each case, the speeds of vehicles vary between 0-50km/h, 0-80km/h and 0-100km/h. All vehicles were equipped with 802.11p (WAVE) [2] communication capabilities. Table 4.1 lists the main simulation parameters. The goal of this Chapter is to study the effects of receiver mobility and the proposed solution in VNDN application performance apart from other factors. Considering this, the simulations were performed in a highway scenario with an average vehicle distance of 150m to decrease the probability of network partitions (Chapter 5 studies the effects of network partitions in VNDN communications). To eliminate the effects of content source mobility (Chapter 6 studies the effects of content source mobility in VNDN communications), an RSU (static node) is used as Content producer, configured with the same parameters compared to the vehicles.

4.3.3 Metrics and Scenarios

The following three metrics were applied to evaluate the performance of the proposed solution:

- *Interest Satisfaction Rate/Ratio (ISR)*: Average percentage of Data messages received per Interest messages sent;

- *Delay per Interest Satisfied (delay)*: Average time difference between sending an Interest message and receiving the corresponding Data message by a Content Requester;

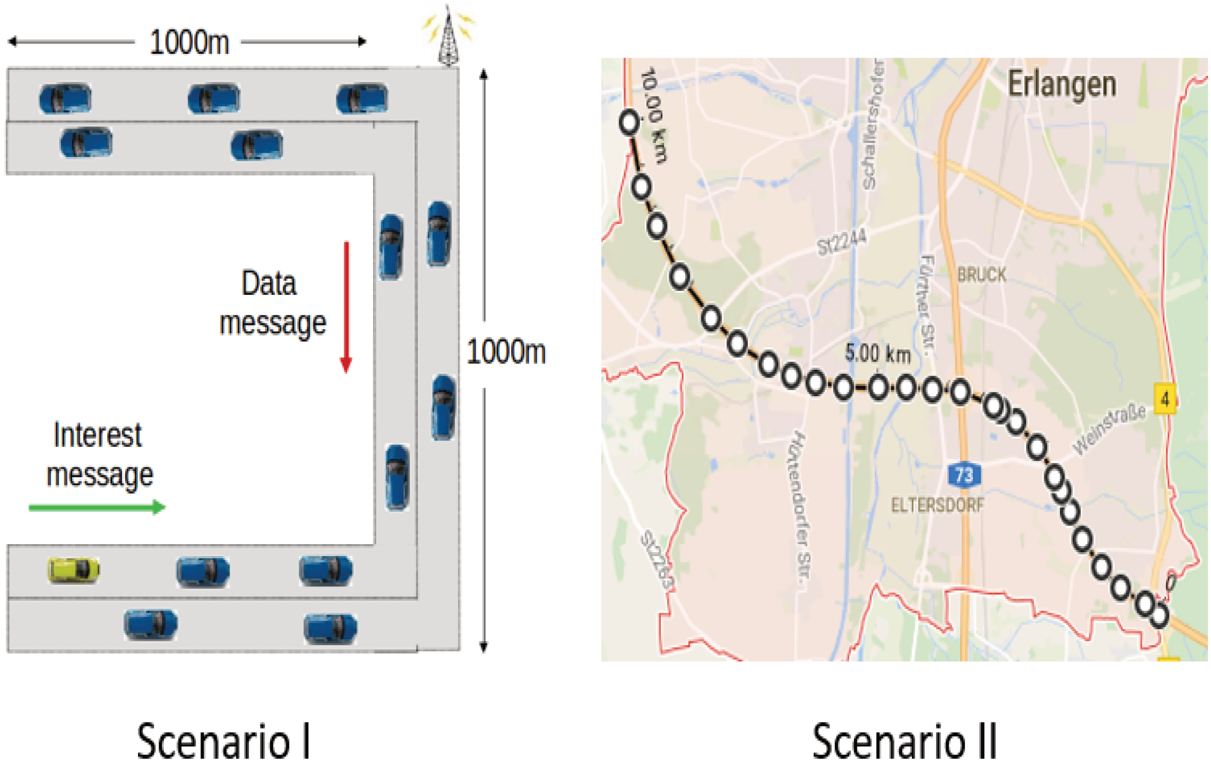


Figure 4.5: Mobility scenarios

- *Data Forwarded*: Average number of Data messages forwarded to neighbor vehicles per content object requested.

The mobility scenarios used in this Chapter are illustrated in Figure 4.5 and described in the following:

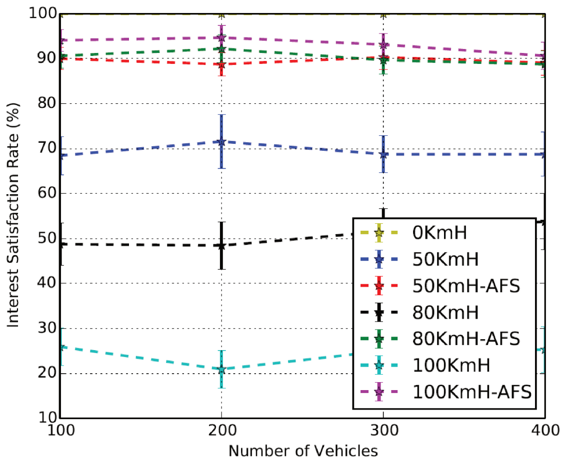
- *Scenario I*: This scenario consists of a 3km, two lane, one-way road. For this case the original Content producer (RSU) is placed at a distance 2km away from the vehicles starting position along the road;

- *Scenario II*: This scenario consists of a 10 km long portion of the E45 Route in the city of Erlangen, Germany. The E45 Route is a 2-way highway with 4 lanes with several street junctions. For this case the original Content producer (i.e., the RSU) was placed at a roundabout located close to the center of the road at a latitude and longitude of 49.56 and 10.99 degrees respectively. This Sumo traffic was developed as part of the VEINS project [53];

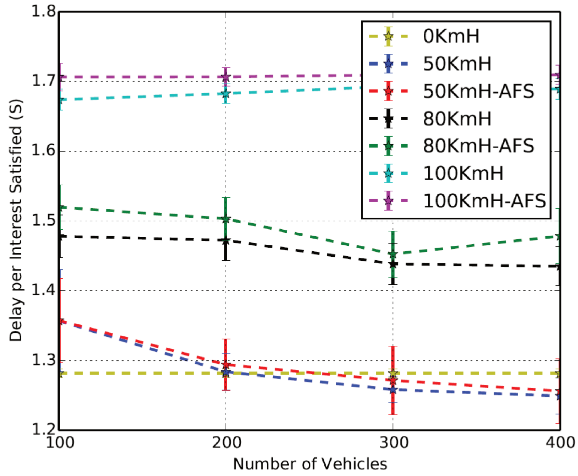
Subsection 4.3.4 shows the performance results of the proposed AFS mechanism.

4.3.4 Performance Results

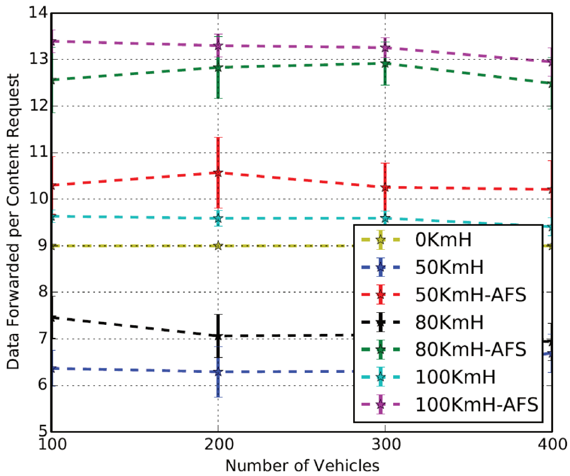
The results presented in this Subsection were calculated from the average of 33 simulation runs with a confidence interval of 95%. As a benchmark, first the proposed solution was



(a) ISR - Scenario I



(b) Delay - Scenario I



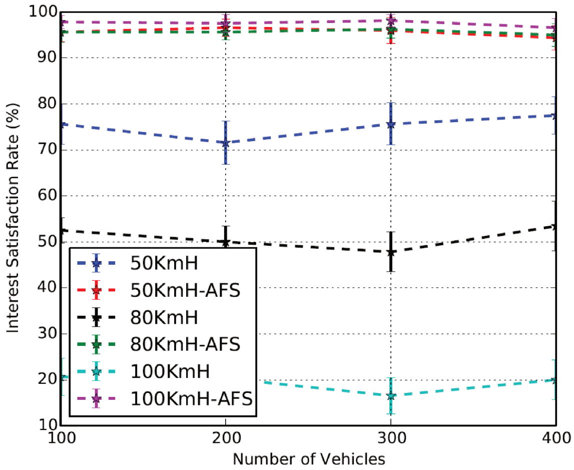
(c) Data Forwarded - Scenario I

Figure 4.6: AFS Results - Scenario I

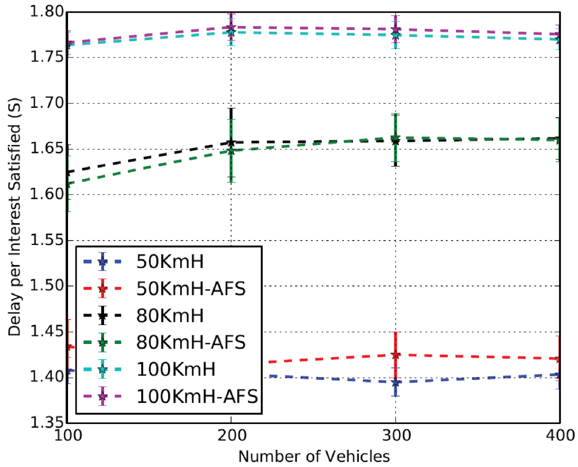
evaluated in the simplistic case of no mobility (i.e., vehicles speeds equal to 0km/h) in scenario I. Vehicles were placed evenly along the road with an inter-vehicle distance of 100m, and one single vehicle was selected to request a content object (i.e., the minimum possible overhead in the wireless communication medium). The results showed an Interest Satisfaction Rate (ISR) of 100%, a delay lower than 1.3s and 9 Data messages forwarded per content segment requested. The reason for having a benchmark case is to show how close the obtained results are compared to the best case when mobility and the number of content requesters increase (i.e., generating more overhead in the wireless communication medium).

Considering the cases with mobility, as it can be observed here as well as in [28], when AFS is not applied, the VNDN performance degrades when the speed of vehicles increases.

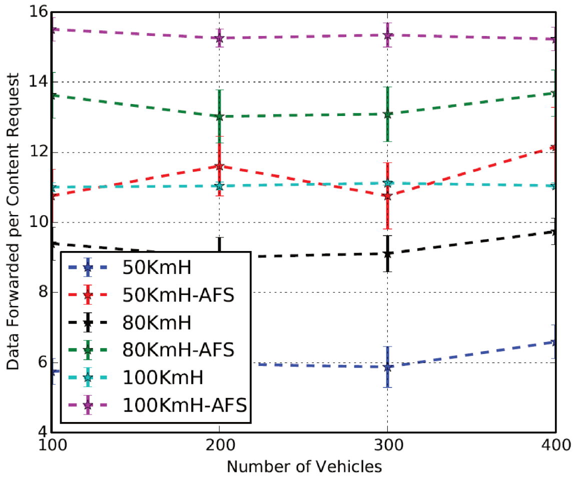
When applying AFS the RPP problem is addressed and high ISR is achieved regardless of neither receiver mobility nor the number of vehicles, at the cost of slightly increasing the amount of space used in PITs, the number of Data messages forwarded and the average delay. Furthermore, the results show that AFS even favor higher speed cases



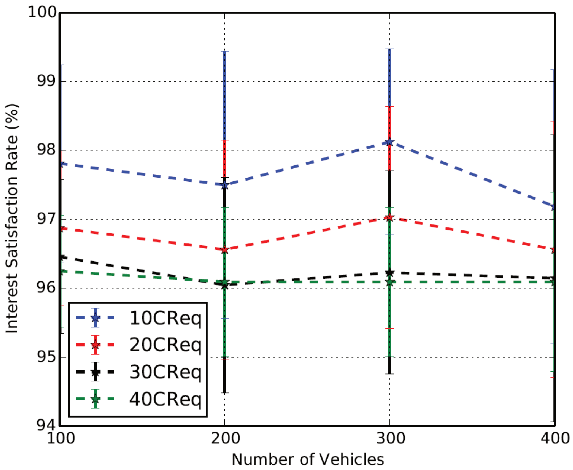
(a) ISR - Scenario II



(b) Delay - Scenario II



(c) Data Forwarded - Scenario II



(d) Delay - Scenario II

Figure 4.7: AFS Results - Scenario II

presenting slightly better ISR for higher speeds. This happens because when vehicle speed increases more AFSs are formed, which better mitigates RPP. However, this also impacts the number of Data messages forwarded as it can be observed in Figure 4.6.

Figure 4.6(a) shows that when AFS is not applied ISR decreases significantly as mobility increases. For the cases where vehicles drive with speed limits of 50km/h (vehicle speeds varying between 0 to 50km/h), ISRs around 70% are achieved. ISR decreases to approximately 50% when vehicle speed limits increase to 80km/h and reach its lowest values, of around 20% to 30% when vehicle speed limits reach 100km/h. This fact happens because as speed limits increase, the traffic becomes more dynamic, the distances between vehicles change faster, and the probability of RPP increases. When AFS is applied, high ISRs over 90% are maintained regardless of vehicle speed limits and the number of vehicles. Figure 4.6(b) shows that the delay per Interest message satisfied increases as vehicle speeds also increase, varying from around 1.3 seconds for the cases of static network and 50km/h of vehicle speed limits to 1.7 seconds for the case of vehicle speed limits of 100km/h. Figure 4.6(b) also confirms that, as explained above, AFS contributes to slightly increase the delay. This happens because when Data message retransmissions are required due to RPP, vehicles belonging to the same AFS apply a delay-based decision to select the vehicle that shall forward the Data message (i.e., the vehicle farther away from the last Data message forwarder). Figure 4.6(c) shows that AFS increases the number of Data messages forwarded. This behavior was also expected because apart from the vehicles belonging to the original reverse path, AFS selects an extra set of vehicles to forward Data messages whenever RPP occurs.

Considering the second scenario, the results shown in Figure 4.7 are similar to the obtained in the first scenario, except for a small increase in delays and Data forwarded, which are due to larger distances.

To evaluate the AFS scalability, scenario II is applied. The number of content requesters is increased from 10 to 40, with vehicle speed limit of 100km/h. Figure 4.7(d) shows that high ISRs are maintained despite a slight decrease when the number of content requesters increases. These results show that AFS is an efficient and scalable solution to mitigate the effects of receiver mobility under realistic mobility scenarios and enable high VNDN application performance.

4.4 Conclusions

This Chapter investigated the effects of receiver mobility in VNDN communications. The problem of RPP that degrades VNDN application performance when receiver mobility increases was identified and AFS was proposed as a solution. A series of simulations were conducted showing that the proposed solution is efficient and scalable since it is able to provide high VNDN application performance without excessive load on the communication channel regardless of receivers mobility and the number of content requests.

Chapter 5

Network Partitions

This Chapter investigates the problems generated by variations of network densities in Vehicular Named-Data Networking. In particular, the effects of low vehicle density in VNDN scenarios with high mobility are considered. In VNDN scenarios with low vehicle densities, the probability of finding neighbor vehicles to forward Interest and Data messages towards their destinations decreases, leading to the occurrence of network partitions and contributing to degrade application performance. Network partitions can occur as well in VNDN scenarios with high vehicle densities due to message collisions and signal attenuations caused by obstacles, weather conditions, and other disturbances in the wireless communication medium. However, network partitions are more frequent and harmful in sparse VNDN scenarios where the density of vehicles is low, and often vehicles get out of the transmission range of each other for long periods of time.

5.1 Problem Statement

To understand how network partitions can occur, let us rely on the example shown in Figure 5.1

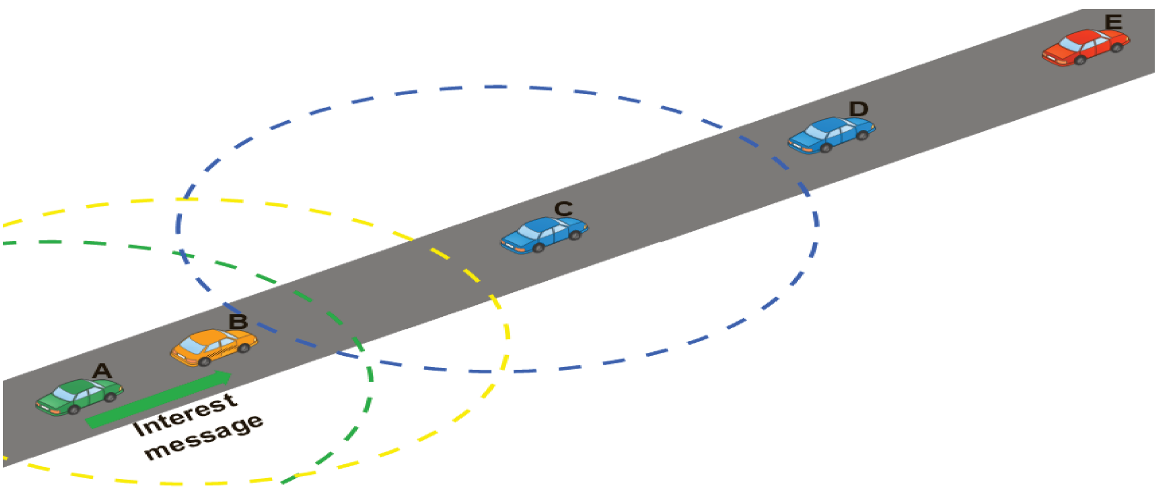


Figure 5.1: Network partition example

Figure 5.1 shows a simple VNDN traffic scenario where communication is disrupted by a network partition.

In Figure 5.1, vehicle A is interested in receiving a content object that can be provided by vehicle E. Therefore, A sends an Interest message towards E. Vehicle B receives the Interest message and forwards it. However, B is unable to communicate with any other vehicle closer to the content location since vehicle C, which is the closest vehicle, is out of its transmission range. In such a case, a network partition has occurred stopping the message progression towards the content source and preventing the content object from being delivered to the content requester. Since low density scenarios are frequent in VANETs due to the dynamics of vehicle movements, this Chapter proposes two different ways to address the problem of network partitions and improve communication performance in VNDN. The first solution, named as VNDN agent delegation and described in Section 5.2 targets scenarios with infrastructure support. Since infrastructure deployment and maintenance incurs large costs and currently road side infrastructure is still not broadly available, alternatives to infrastructure based VNDNs are required. In this context, the second solution named as VNDN store-carry-forward (VNDN-SCF) and described in Section 5.3 targets scenarios without infrastructure support.

5.2 Agent Delegation for Vehicular Named-Data Networking

The Agent Delegation approach for Vehicular Named-Data Networking (VNDN agent delegation) proposed in this Section targets scenarios with infrastructure support and is an adaptation to VNDN of the concept of agent delegation [20].

The Agent delegation approach was originally conceived for mobile scenarios with low mobility and not for VANETs. In sparse networks, when nodes are not able to connect to content sources (i.e., either through single or multi-hop communication), content requests can be delegated to other nodes (i.e., agents), with different trajectories than the requester node. This approach assumes that due to their trajectories, agents might be able to meet with a content source within a certain time interval and that the agent will also be able to communicate with the content requester in the future, to deliver the content object.

To fit the requirements of VNDN applications, regarding Interest Satisfaction Ratio and delay, a VNDN communication mechanism for RSUs was developed and deployed in a set of interconnected RSUs (i.e., VNDN-RSUs) along roads. These VNDN-RSUs are then used as agents for content retrieval. In this way, vehicles requesting a content object, available at a specific geographic location, might delegate the content retrieval to the closest VNDN-RSU, using an Interest message. This process is illustrated in Figure 5.2.

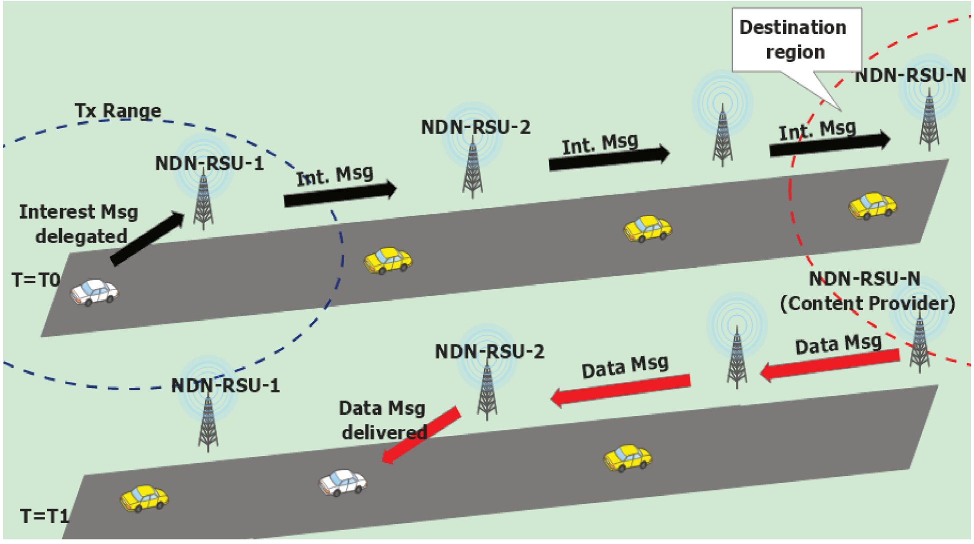


Figure 5.2: Agent delegation example

In Figure 5.2, at time $t=T0$, the content requester vehicle (white vehicle) delegates the content retrieval to VNDN-RSU-1. VNDN-RSU-1 extracts the Interest message and learns about the content location. Then, VNDN-RSU-1 forwards the Interest message to the next VNDN-RSU along the path towards the content location (i.e., VNDN-RSU-2 in this example) and adds a PIT entry for the corresponding content object. This process continues until the Interest message reaches its destination region, where VNDN-RSU-N receives it.

Upon receiving the Interest message, VNDN-RSU-N collects the content object and sends the corresponding Data message on the reverse path towards VNDN-RSU-1 (i.e., the agent). When the intermediate VNDN-RSUs receive the Data message, they perform a PIT lookup, and if they find an entry corresponding to the received content object, they forward the Data message to the next VNDN-RSU and remove the PIT entry. Otherwise, they discard the Data message. When receiving the Data message, VNDN-RSU-1 delivers it to the requester vehicle. Since the communication medium is wireless and the requester vehicle is moving, the content requester might get into the transmission range of a VNDN-RSU, other than VNDN-RSU-1, that received the content object before the VNDN-RSU-1 receives it. In such a case, the content object can also be delivered to the content requester by another VNDN-RSU and not only by the Agent. For instance, in Figure 5.2 VNDN-RSU-2 delivers the content object to the requester vehicle. The communication mechanism used by VNDN-RSUs is similar to the mechanism described in Section 3. However, it is simpler as there is no need for the timer delay employed by vehicles for forwarding Interest messages since RSUs are static and geographically separated from each other.

Figure 5.3 shows the Interest message routing mechanism used in the VNDN Agent Delegation communication approach. The Data message routing approach applied in the VNDN Agent Delegation communication approach is similar to the Data message routing approach described Chapter 3.

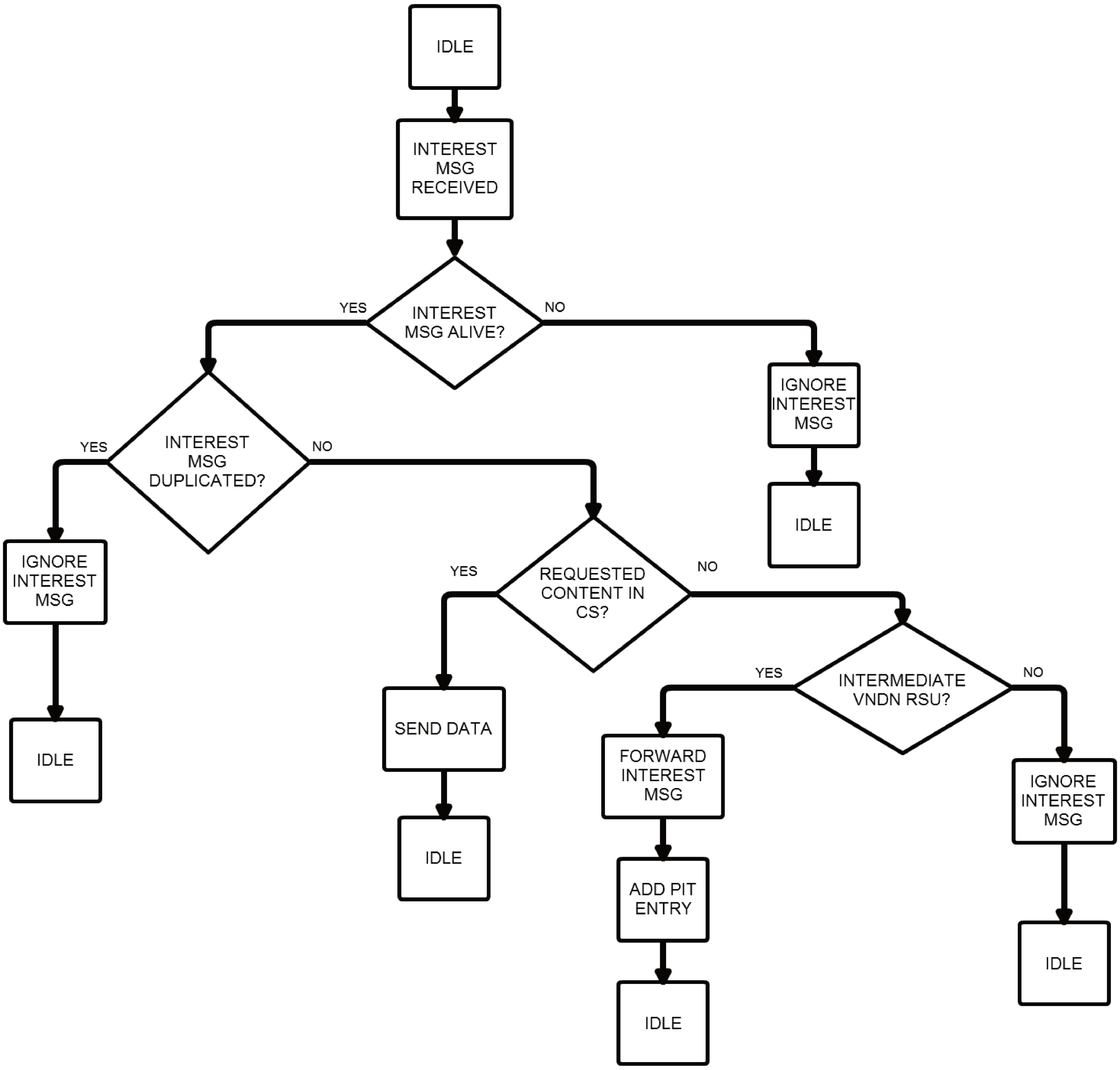


Figure 5.3: Interest message routing in Agent Delegation

In Figure 5.3, when a VNDN-RSU receives an Interest message (i.e., either from a vehicle that is delegating the retrieval of a content object or by another VNDN-RSU that forwarded a received Interest message), it first checks if the Interest message is alive (i.e., through the TTL field) and not duplicated. In such a case, the VNDN-RSU checks if it can provide the requested content segment and sends the corresponding Data message. Otherwise, it forwards the Interest message to the VNDN-RSU that is closer to the destination of the Interest message and adds a PIT entry for the requested content segment. This process repeats until a content source has been found. Then the content source sends the corresponding Data message. The Data message travels through the set of VNDN-RSUs along the reverse path and is delivered to the requester vehicle by the VNDN-RSU closer to it.

5.3 Store-Carry-Forward for Vehicular Named-Data Networking

Despite that infrastructure support might be the most efficient solution to address the effects of low vehicle density, the number of RSUs currently available on roads over the world is still very low due to high deployment and maintenance costs. Considering this, solutions to address the effects of mobility and support VNDN applications, in cases of no infrastructure are also needed.

The solution described in this Section targets scenarios without infrastructure support and proposes a store-carry-forward mechanism for VNDN (VNDN-SCF). The core idea behind VNDN-SCF is that a vehicle 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 nodes, so that it propagates towards its intended destination. This mechanism uses messages forwarded by intermediate vehicles as implicit acknowledgments of successful message reception by subsequent vehicles. If the message is not forwarded by any other neighbor vehicle (i.e., a network partition has occurred, preventing the current vehicle from communicating with other vehicles that are closer to the message destination), the vehicle periodically forwards the message (i.e., 3s in this case), until it delivers it to a next vehicle. Figure 5.4 depicts this case.

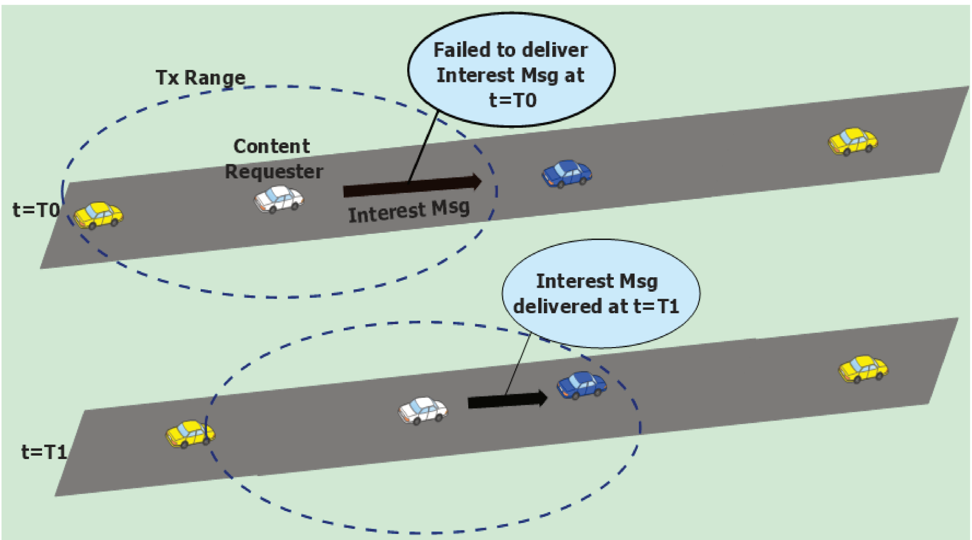


Figure 5.4: SCF example

In Figure 5.4, at time t=$T0$ the content requester (white vehicle) sends an Interest message requesting a content object from a distant location ahead on its trajectory. Since none of the vehicles on the road ahead of the content requester are within its transmission range, it is not able to deliver the Interest message immediately. However, at time t=$T1$, with the dynamics of vehicle movements, the distance between the content requester and the subsequent vehicle (blue vehicle) decreases and both vehicles become within the transmission range of each other. Therefore, the content requester delivers the message to the subsequent vehicle. This process continues until the Interest message reaches its destination. This mechanism is applied between any two consecutive vehicles, whenever network partitions occur.

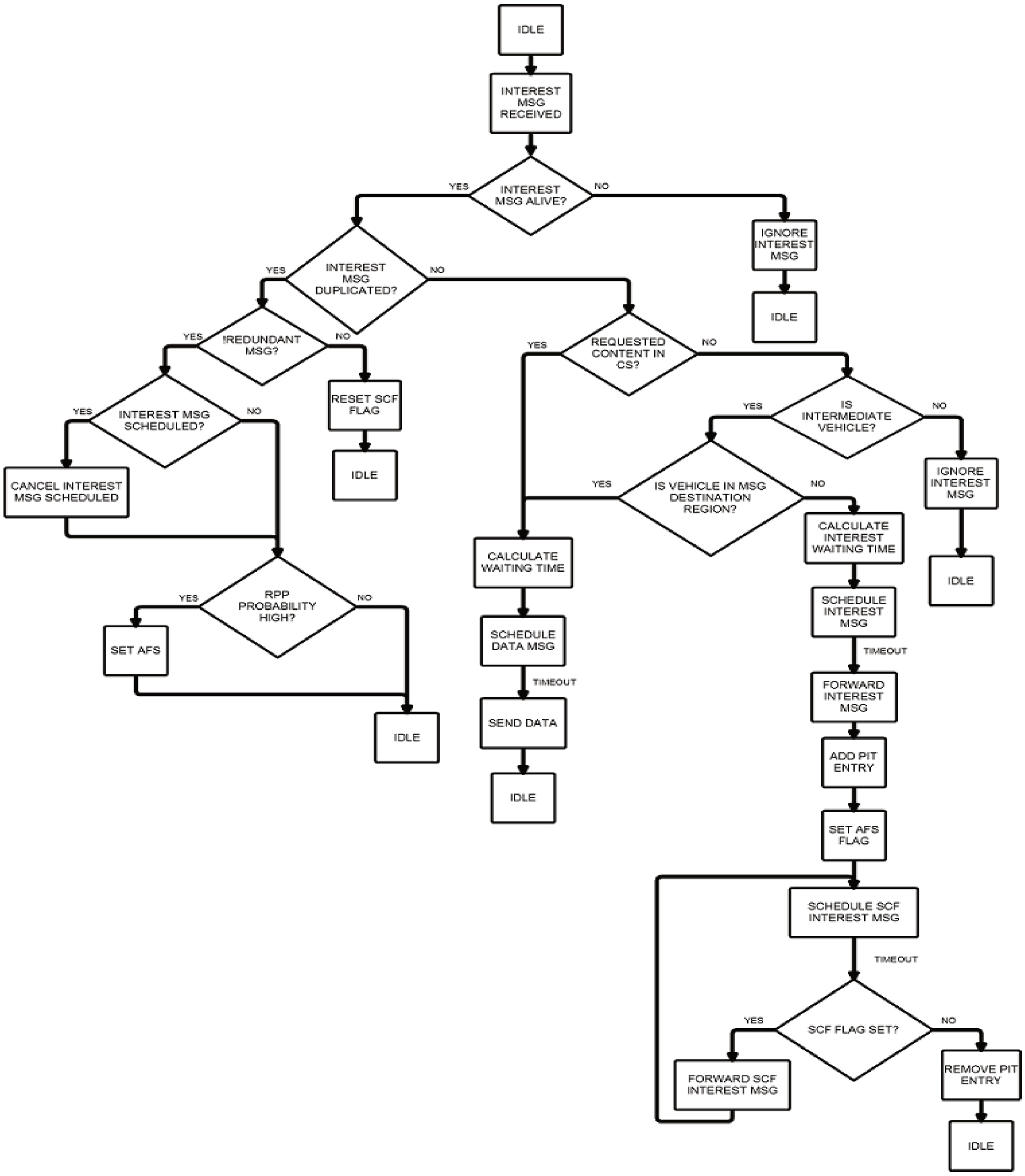


Figure 5.5: Interest message routing in SCF

The VNDN-SCF mechanism extends the VNDN PIT concept by adding a flag to each Interest message entry called SCF flag. When forwarding an Interest message, vehicles add a PIT entry and set the SCF flag for the corresponding content object. If the Interest message is delivered and forwarded by a subsequent vehicle, the SCF flag is reset. While the SCF flag is set, the vehicle periodically forwards the Interest message until it is delivered. On the other hand, when a vehicle receives a Data message in response to an Interest message previously forwarded, the Data message is forwarded to the forwarder vehicle and the SCF flag is set again. If the message is successfully delivered, the corresponding PIT entry is removed and the SCF flag is reset. While the PIT entry is not removed and the

SCF flag is set, the vehicle keeps periodically forwarding the Data message. This process continues until the Data message is delivered to the content requester.

Figures 5.5 and 5.6 show how VNDN-SCF extends the MobiVNDN Interest and Data message routing mechanisms.

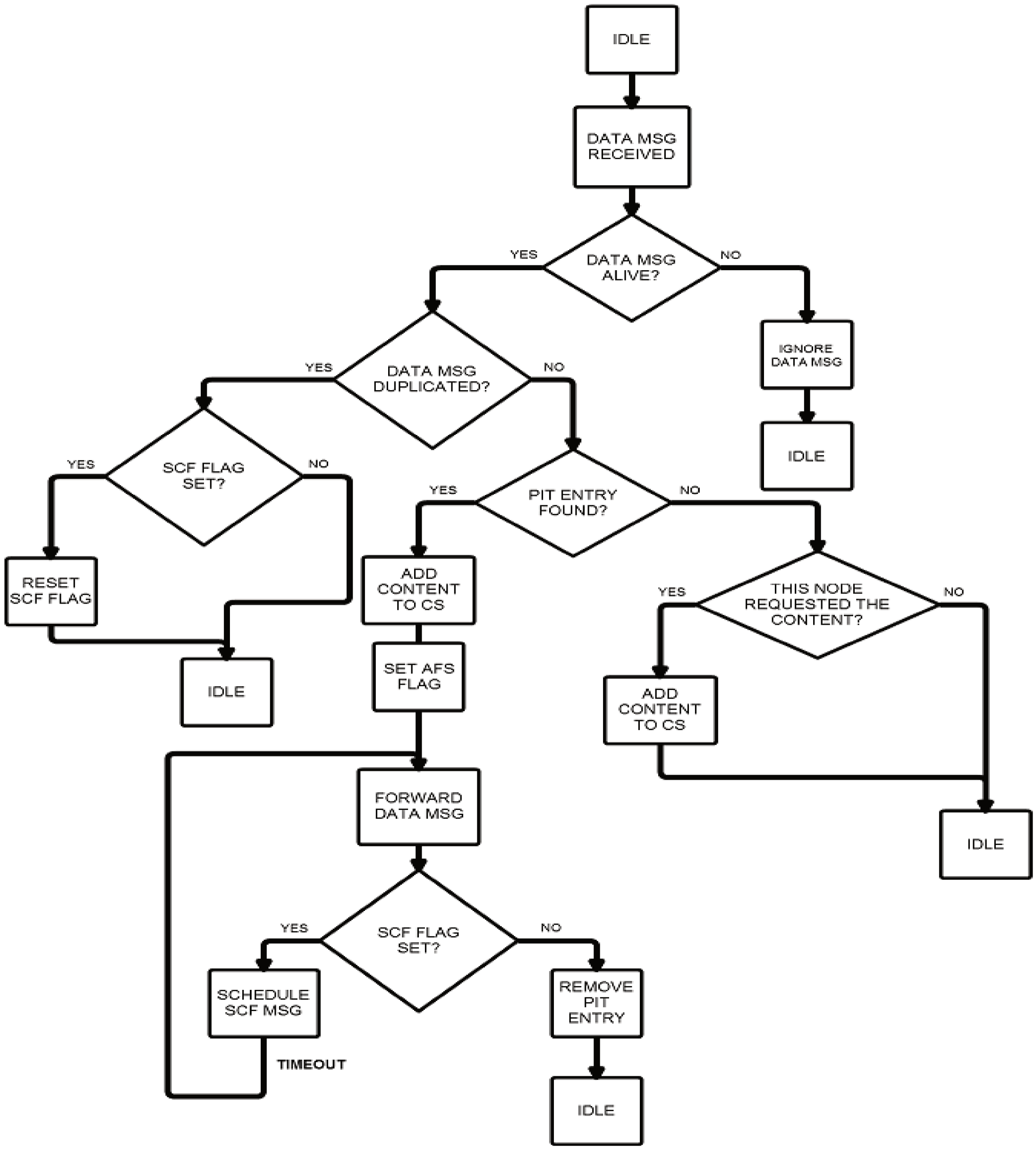


Figure 5.6: Data message routing in SCF

5.4 Performance Evaluation

This Section presents the performance evaluation of VNDN when the proposed solutions are applied through a set of simulations. This Section also lists the simulation tools and parameters, it describes the simulation scenarios as well as the performance metrics and finally discusses the obtained results.

5.4.1 Simulation Tools and Parameters

To evaluate the performance of the VNDN agent delegation and the VNDN-SCF mechanisms, a set of simulations were performed using both highway and urban traffic scenarios and the simulation tools omnet++, SUMO, and Veins described in the Chapter 4. The first traffic scenario corresponds to the Route45 highway scenario described in Chapter 4, whereas for urban simulations the Manhattan grid traffic scenario [54] is applied.

5.4.2 Performance Metrics

The following performance metrics were applied:

(i) *Interest Satisfaction Ratio*: Average percentage of content objects received in response to content requests;

(ii) *Delay per Interest Satisfied*: Average time difference between sending an Interest message and receiving the corresponding Data message by a content requester;

5.4.3 Evaluation of VNDN Agent Delegation and VNDN-SCF in Highway Scenarios

This Sub-section describes the evaluation of the proposed VNDN Agent Delegation and VNDN-SCF solutions in highway traffic scenarios. First, the performance of VNDN with and without the VNDN Agent Delegation mechanism is compared in the case of infrastructure support. With this in mind a set of connected VNDN-RSUs were deployed along roads. The plain VNDN version only uses neighboring vehicles as next hops to forward Interest and Data messages. When applying the agent delegation approach, content retrieval is delegated to the VNDN-RSUs (i.e., agents).

In the second case, the performance of VNDN with and without store-carry-forward (SCF) is compared. In the plain version of VNDN, vehicles only forward Interest and Data messages once, while when applying SCF, after forwarding an Interest or a Data message, vehicles wait for the delivery confirmation to decide whether to continue forwarding the message periodically.

To evaluate the effects of vehicle density, the average inter-vehicle distances vary from 100m to 250m, which corresponds to decreasing the average vehicle density between 10 vehicles/km and 4 vehicles/km.

A flow of 300 vehicles driving with speeds between 0km/h and 100km/h was used. Table 5.1 shows the main simulation parameters.

Performance Results

The results presented in this Subsection were calculated from the average of 33 simulation runs, with a confidence interval of 95%. Ten to thirty vehicles were selected to act as content requesters to request one of the ten available content objects. In this way, some of the content requests are satisfied directly from the content producer while others are satisfied by neighbor vehicles caching copies of requested content objects.

Table 5.1: Network Partitions - Simulation parameters for the highway scenario

Parameters	Values
Number of vehicles	300 vehicles
Vehicles speeds	0-100 km/h
Number of content requesters	10; 20; 30
Carrier frequency	5.9GHz
WAVE channel type	Service Channel
Size of Interest messages	1024bytes
Size of Data messages	4096bytes
Number of chunks per content	20
Number of content objects	1; 5; 10
Communication technology	IEEE802.11p
Communication types	V2V and V2I
Maximum vehicle transmission range	200m
Shareability	Shareable data

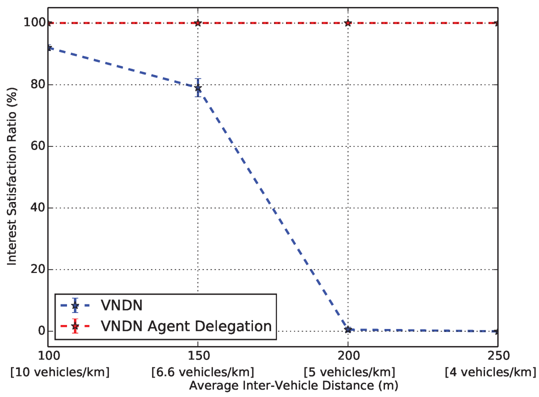
Infrastructure Support Case

Figure 5.7(a) shows that in the case of the plain VNDN, as vehicle density decreases the average Interest Satisfaction Ratio (ISR) decreases significantly. This average ISR reaches values close to zero when the average inter-vehicle distances gets close to the maximum transmission range of vehicles (i.e., 200m). When average inter-vehicle distances are larger than the maximum transmission range of vehicles, no Interest messages are satisfied. This happens because when the density of vehicles decreases, the probability of network partitions increases. Under network partitions, Interest and Data messages are not able to propagate towards their destinations. Therefore, content requests are not satisfied.

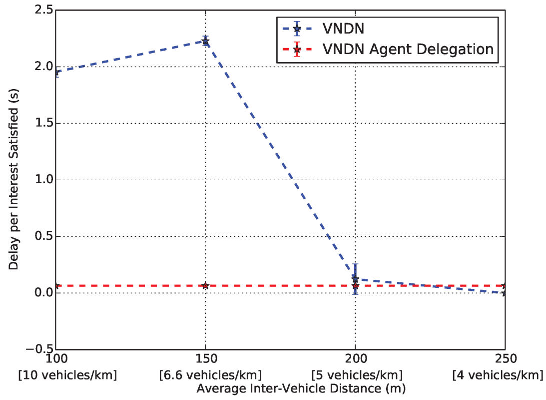
As it can also be observed in Figure 5.7(a), in scenarios with infrastructure support, where content retrieval can be delegated to VNDN-RSUs, the proposed VNDN agent delegation approach is an efficient solution to address the negative effects introduced by low vehicle densities. When applying VNDN agent delegation, assuming that there will be at least one available agent to delegate the content retrieval 100% of ISR is achieved, regardless of vehicle densities.

Furthermore, Figure 5.7(b) shows that VNDN Agent Delegation outperforms the plain VNDN in terms of Interest Satisfaction Delay. This happens because most of the plain VNDN delay is due to the time applied by vehicles to decide whether to forward Interest messages, in order to avoid unnecessary message retransmissions and prevent broadcast storms. As VNDN-RSUs are static and connected to each other, this waiting time is not required.

Regarding scalability, Figures 5.8(a), and 5.8(b) show that the performance of the VNDN agent delegation approach is not affected when the number of content requesters and content objects increase. ISRs of 100% are still being achieved in either case.

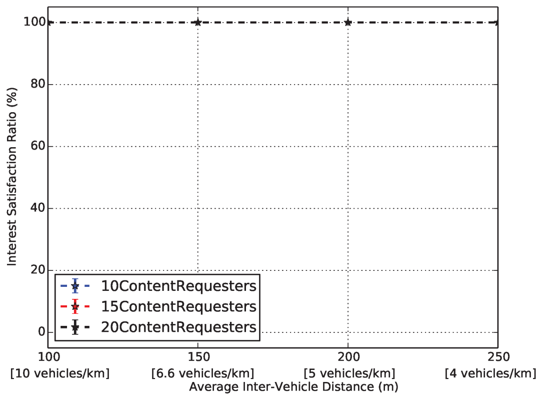


(a) Interest Satisfaction Ratio

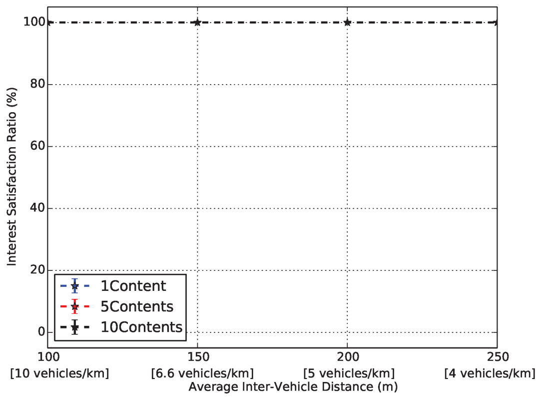


(b) Delay

Figure 5.7: Performance of VNDN Agent Delegation in Highways



(a) Interest Satisfaction Ratio



(b) Interest Satisfaction Ratio

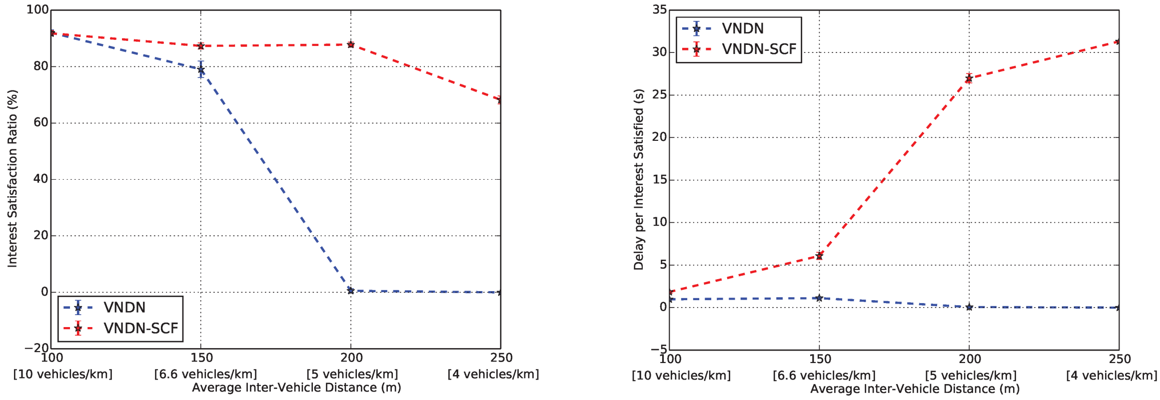
Figure 5.8: Scalability of VNDN Agent Delegation in Highways

No Infrastructure Support Case

For the cases where no infrastructure support is available, as shown in Figure 5.9(a), the proposed VNDN-SCF is an efficient alternative. When applying VNDN-SCF, high ISRs are maintained regardless of vehicle densities.

In terms of Delay per Interest Satisfied, as it can be observed in Figure 5.9(b), when vehicle density is high, the delay is similar for both the plain VNDN and VNDN-SCF. However, when vehicle density decreases, Figure 5.9(b) shows higher delays for VNDN-SCF. This happens because when vehicle density is low, the probability of Interest messages propagating long distances is low due to lack of intermediate forwarder vehicles. In such cases, if the plain VNDN is used, only requests for content objects cached in CSs of close neighbor vehicles might be satisfied. Therefore, the average Interest Satisfaction Delay corresponds to the delay for retrieving content objects from vehicles located on the same one-hop neighborhood or very few hops away. This also explains the corresponding low ISRs.

In the case of VNDN-SCF, when vehicle densities are low and network partitions occur,

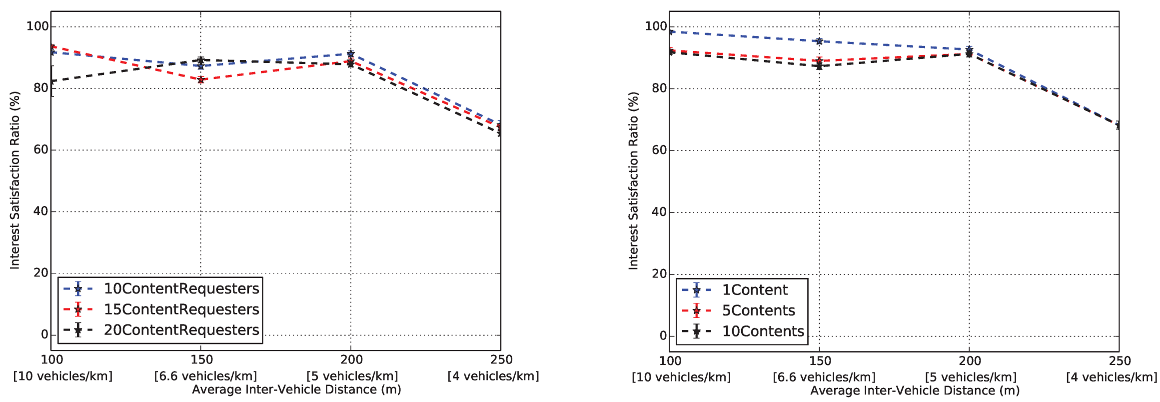


(a) Interest Satisfaction Ratio (b) Delay

Figure 5.9: Performance of VNDN Store Carry Forward in Highways

vehicles buffer Interest and Data messages and deliver them, as soon as communication links with subsequent vehicles are re-established, providing high ISRs at the cost of increasing the delay. These results show that most of the contribution for the VNDN-SCF delay comes from content requests that are not satisfied when the plain VNDN is used instead of the VNDN-SCF and that the proposed VNDN-SCF is an efficient alternative to infrastructure support for non delay-sensitive VNDN applications.

Regarding scalability, Figures 5.10(a) and 5.10(b) show that similar to the case of VNDN Agent Delegation, VNDN-SCF performs well as high ISRs are still achieved when the numbers of content requesters and content objects increase. Therefore, both solutions are efficient and scalable.



(a) Interest Satisfaction Ratio (b) Interest Satisfaction Ratio

Figure 5.10: Scalability of VNDN Store Carry Forward in Highways

5.4.4 Evaluation of VNDN-SCF in Urban Scenarios

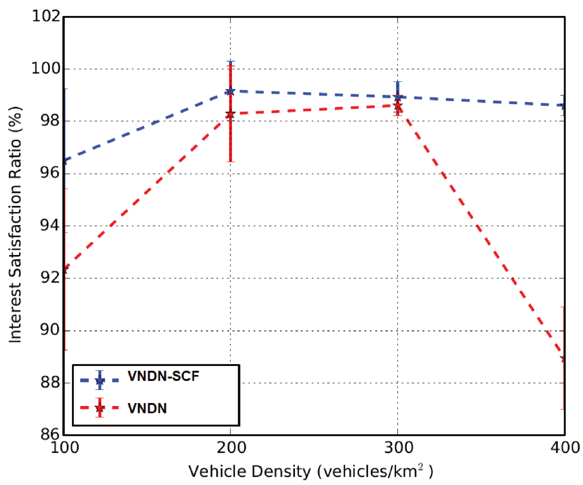
As shown in Subsection 5.4.3, in the case of infrastructure support, if a set of connected VNDN-RSUs is available, high VNDN application performance is obtained. This high application performance is achieved regardless of the mobility scenario, as VNDN-RSUs are static nodes. Considering this, this Subsection only focuses on cases without infrastructure support. The objective is to show how the proposed VNDN-SCF mechanism performs in urban scenarios, where vehicles change driving directions frequently, and content objects might be requested from content sources outside of the driving path of the content requester vehicle.

For this case, the Manhattan grid traffic scenario [54] is used. The Manhattan grid traffic scenario is composed of ten two-lane streets evenly spaced in the vertical and horizontal directions in an area of $1km^2$. Table 5.2 shows the main simulation parameters.

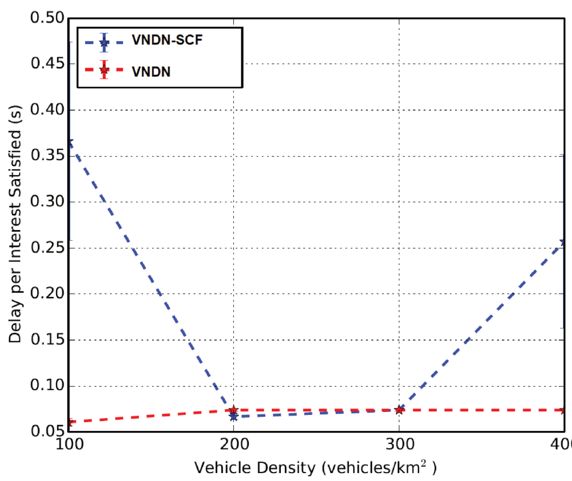
Table 5.2: Network Partitions - Simulation parameters for the urban scenario

Parameters	Values
Density of vehicles	100-400 Vehicles/km^2
Vehicles speeds	0-50 km/h
Number of content requesters	30
Carrier frequency	5.9GHz
WAVE channel type	Service Channel
Size of Interest messages	1024bytes
Size of Data messages	4096bytes
Number of chunks per content	20
Number of content objects	10
Communication technology	IEEE802.11p
Communication types	V2V and V2I
Maximum vehicle transmission range	200m
Shareability	Shareable data

Figures 5.11(a) and 5.11(b) show the obtained results. Similar to Subsection 5.4.3, ISR and Delay were applied as performance metrics.



(a) Interest Satisfaction Ratio



(b) Delay

Figure 5.11: Performance of VNDN-SCF in Urban Scenarios

Figure 5.11(a) shows that in the case of VNDN-SCF high ISR over 90% is maintained. The lower ISR values correspond to the case of lower vehicle densities. This case happens because as the density of vehicles decrease the probability of network partitions and RPP occurrences increases. In the case of plain VNDN, ISR decreases more sharply since network partitions and RPP are not addressed. For the case of higher vehicle densities, ISR also decreases in VNDN. This happens because as vehicle densities increase, the probability of message collisions also increases, preventing Interest messages from being delivered to content source vehicles. Since SCF is not applied, vehicles are not aware of unsuccessful delivery of forwarded messages and no retransmissions occur. Considering Figure 5.11(b), the delay for VNDN-SCF is higher for the cases of both lower and higher vehicle densities compared to the cases of medium vehicle densities. However, in both cases the increase in delay is not significant enough to affect application performance. This extra delay is introduced by the retransmission mechanism applied in VNDN-SCF (i.e., retransmissions occur every second in case of network partitions).

Despite the performance improvements of VNDN-SCF, the plain VNDN also presents high performance in this case. This happens because in the Manhattan traffic scenario (i.e., $1km^2$), requested content objects are relatively close to content requesters. As explained later in Chapter 7, when the distance between content requesters and content sources increase significantly, the performance of the plain VNDN quickly degrades and the advantages of VNDN-SCF become more obvious.

5.5 Conclusions

This Chapter investigated how network partitions affect the performance of VNDN applications, in scenarios with high mobility. Two different solutions were proposed. VNDN agent delegation, targeting cases with infrastructure support and VNDN-SCF for cases without infrastructure support. The proposed solutions were evaluated through a series of simulations showing that both solutions are scalable and able to efficiently address the negative effects caused by network partitions and improve VNDN application performance.

Chapter 6

Source Mobility

This Chapter investigates the effects of content source mobility in Vehicular Named-Data networking. The content source mobility problem often prevents Interest messages from reaching content sources, degrading application performance in VNDN. To mitigate the negative impact of content source mobility this thesis applies the concept of floating content (FC) described in Chapter 2. FC is an infrastructure-less mechanism that relies on in-network caching and content replication to support content sharing within a specific geographic region in a distributed way. The following Sections describe the content source mobility problem as well as the integration of FC in VNDN and evaluates the performance improvements in VNDN application performance provided by FC.

6.1 Problem Statement

To understand the problem of content source mobility in VNDN, let us consider the example depicted in Figure 6.1.

In Figure 6.1 at time *t=T0*, vehicle *A* advertises a content object *C1* from its current location by applying the message advertisement mechanism described in Section 3.2. The Advertisement message is received by the vehicles currently in the region of interest (RoI) (also called AZ) defined for the content object *C1*, including vehicles *B* and *C*. These vehicles then update their FIBs by adding an entry that matches the content object *C1* with the location where it is available. Later on, at time *t=T1*, vehicles *B* and *C* decide to request the content object *C1*. To do so, they send Interest messages towards the location, where vehicle *A* advertised *C1* (i.e., content location). However, when the Interest messages arrives at the content location, vehicle *A* has already moved to a new location. Therefore, vehicle *A* is not able to receive the Interest message. Consequently, vehicle *A* does not send the corresponding Data messages and the content requests are not satisfied.

The VNDN decentralized in-network caching property provides an alternative for the source mobility problem in cases of popular content objects (i.e., content objects that are frequently requested in a given geographic region). In such a case the content request might be satisfied by other neighbor vehicles that have a cached copy of the requested content object in their Content Stores (CSs). However, in the case of less popular content

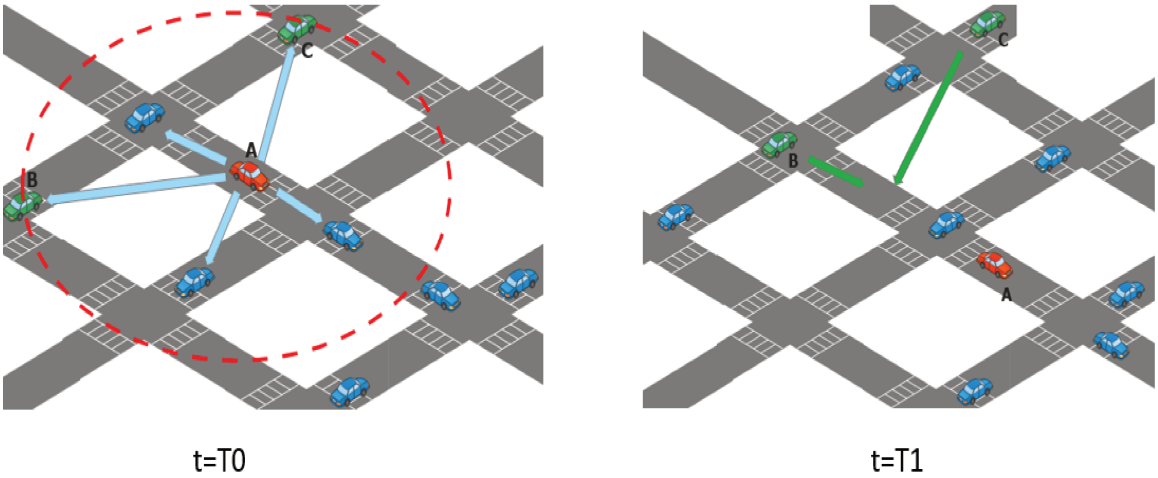


Figure 6.1: The content source mobility problem

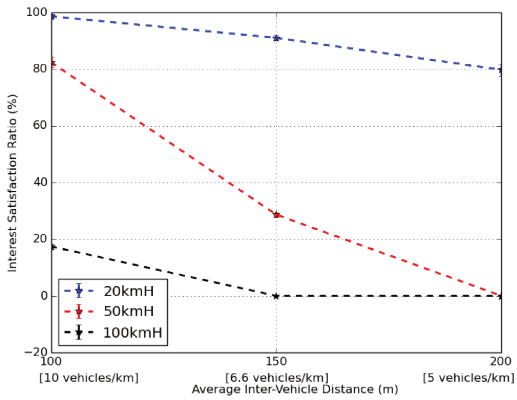
objects, which might be requested by a single vehicle, the probability of finding the requested content object in the CSs of neighbor vehicles is low.

To analyze the effects of the content source mobility problem in VNDN application performance, a simulation of a flow of 400 hundred VNDN enabled vehicles was performed considering three different cases by varying the speed limits of vehicles. In the first case, vehicles drive with speeds between 0 and 20km/h. In the second and third cases, the speed limit increases to 50km/h and 100km/h respectively. For each case, the density of vehicles also varies. The results were analyzed regarding Interest Satisfaction Ratio and Delay. Figure 6.2 show the obtained results.

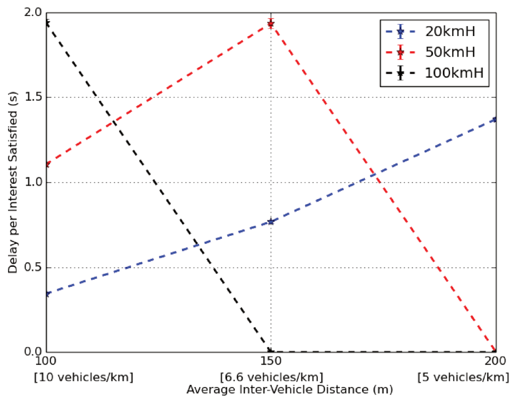
Figure 6.2(a) shows that for the case of low mobility (20km/h), high ISRs are achieved, and that ISR decreases as the mobility increases. To understand why this happens, let us consider the case of two different vehicles, *VA* and *VB*, advertising two different content objects, *CA* and *CB*, from the same place, at the center of a region *R*. Let us also assume that the region *R* has a circular shape and a radius r=200m. Both vehicles are following the same trajectory. However, *VA* is driving at 20km/h (i.e., 5.6m/s) whereas *VB* is driving at 50km/h (i.e.,13.9m/s). Due to higher speed, *VB* only stays within the region *R* around 14.4s after advertising the content object while *VA* stays within the region *R* around 35.7s. Considering this, Interest messages sent by other vehicles towards the region *R* reach *VA* with higher probability than *VB*. Therefore, the ISRs for content objects requested from *VA* is higher compared to *VB*. Furthermore, the negative effects of source mobility are exacerbated by the decrease in the density of vehicles.

Figure 6.2(b) shows that the content delivery delay also increases as the mobility increases. In the case of vehicles driving with maximum speeds of 100km/h and 50km/h, the delay drops to zero when average inter-vehicle distances reach 150m to 200m. This happens due to complete disruptions on the communication links between vehicles that prevent content objects from being delivered to requester vehicles making ISR reach values close to zero, as shown in Figure 6.2(a).

Considering the above stated, solutions to efficiently address the content source mobility problem in VNDN are required. Section 6.2 describes the proposed solution to address the problem of content source mobility in VNDN.



(a) Interest Satisfaction Ratio



(b) Delay

Figure 6.2: Effects of source mobility

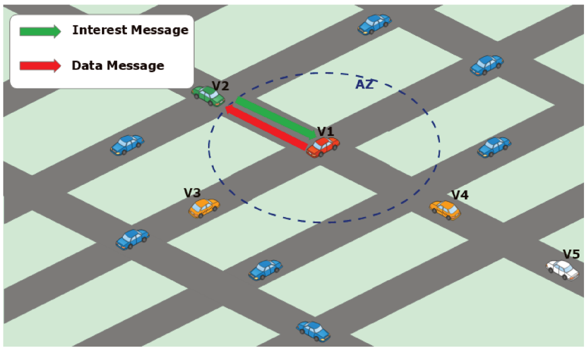
6.2 Solution for the Content Source Mobility Problem

This Section describes the approach used in this thesis to address the problem of source mobility. The main goal is to simultaneously provide high application performance regarding content delivery and delay while simultaneously avoiding single points of failure and large overhead in the wireless communication medium. The proposed mechanism combines the NDN property of decentralized in-network caching with the content replication approach employed in Floating Content (FC), discussed in Section 2, to decouple content objects from the original producers making them available to vehicles within the geographic region (i.e., the Anchor Zone (AZ)) where they were advertised, independent from whether the original producers are still reachable or not.

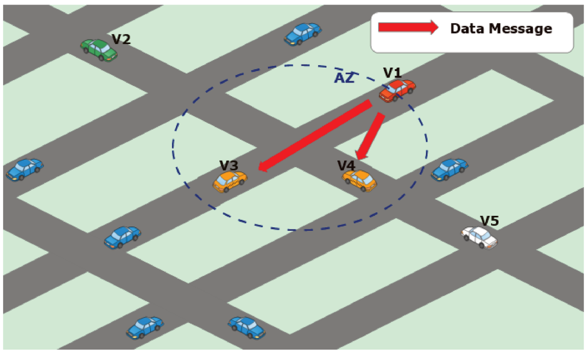
In the proposed mechanism, whenever a vehicle possessing a content object leaves the AZ, it might replicate the content object to other vehicles currently within the AZ. In this way, after the vehicle that produced the content object leaves the AZ or disconnects from the network, the content object can still be requested from the same region and provided by other vehicles that received the content through replications from vehicles that previously left the AZ. Figure 6.3 illustrates this process.

In Figure 6.3(a), vehicle *V2* requests a content object *C1*. The Interest message is received by vehicle *V1* that possesses the content object and sends the corresponding Data message. Later on, as shown in Figure 6.3(b), when vehicle *V1* leaves the AZ, it replicates the content object to vehicles *V3* and *V4* that are within the AZ. When vehicle *V5* requests the same content object, as shown in Figure 6.3(c), *V4* provides the content object, as it is the content source closer to vehicle *V5*.

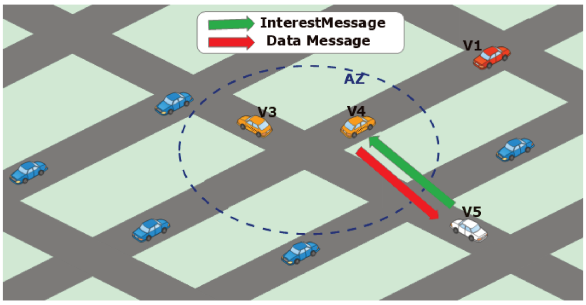
In FC, a single vehicle caching a content object within the AZ might be enough to satisfy all content requests for that specific content object from different vehicles. Therefore, to prevent extra overhead in the wireless communication channel, the number of vehicles that is required to replicate a specific content object can be tuned according to the density of vehicles within the AZ. In dense scenarios, vehicles might receive multiple content replicas of the same content object according to the number of vehicles leaving the



(a) VNDN content retrieval



(b) FC replication



(c) FC content retrieval

Figure 6.3: Floating Content

AZ. Therefore, vehicles leaving the AZ can decide whether to replicate a specific content object according to the number of content replicas previously received.

Figure 6.4 shows the updated Data message routing mechanism including the replication component to address the problems generated by content source mobility. When a vehicle receives a replica of a Data message it extracts the content location information and according to its current speed the vehicle calculates the time interval left until it leaves the AZ of the content object received in the Data message replica. The current vehicle then schedules its own replication of the received Data message according to the calculated time interval. For each duplicated copy of a replica received by the vehicle, it increments a replication counter by one. When the scheduled timer expires, if the number of replicas of the same Data message received is less than a threshold value (i.e., 3 replicas in this thesis) the vehicle replicates the Data message. Otherwise it cancels the replication.

6.3 Performance Evaluation

This Section presents the evaluation performance of VNDN when the proposed VNDN-FC solution, which combines the NDN decentralized in-network caching with FC replications, is applied. This Section also lists the simulation tools and parameters, it describes the simulation scenario, as well as the performance metrics, and finally discusses the obtained results.

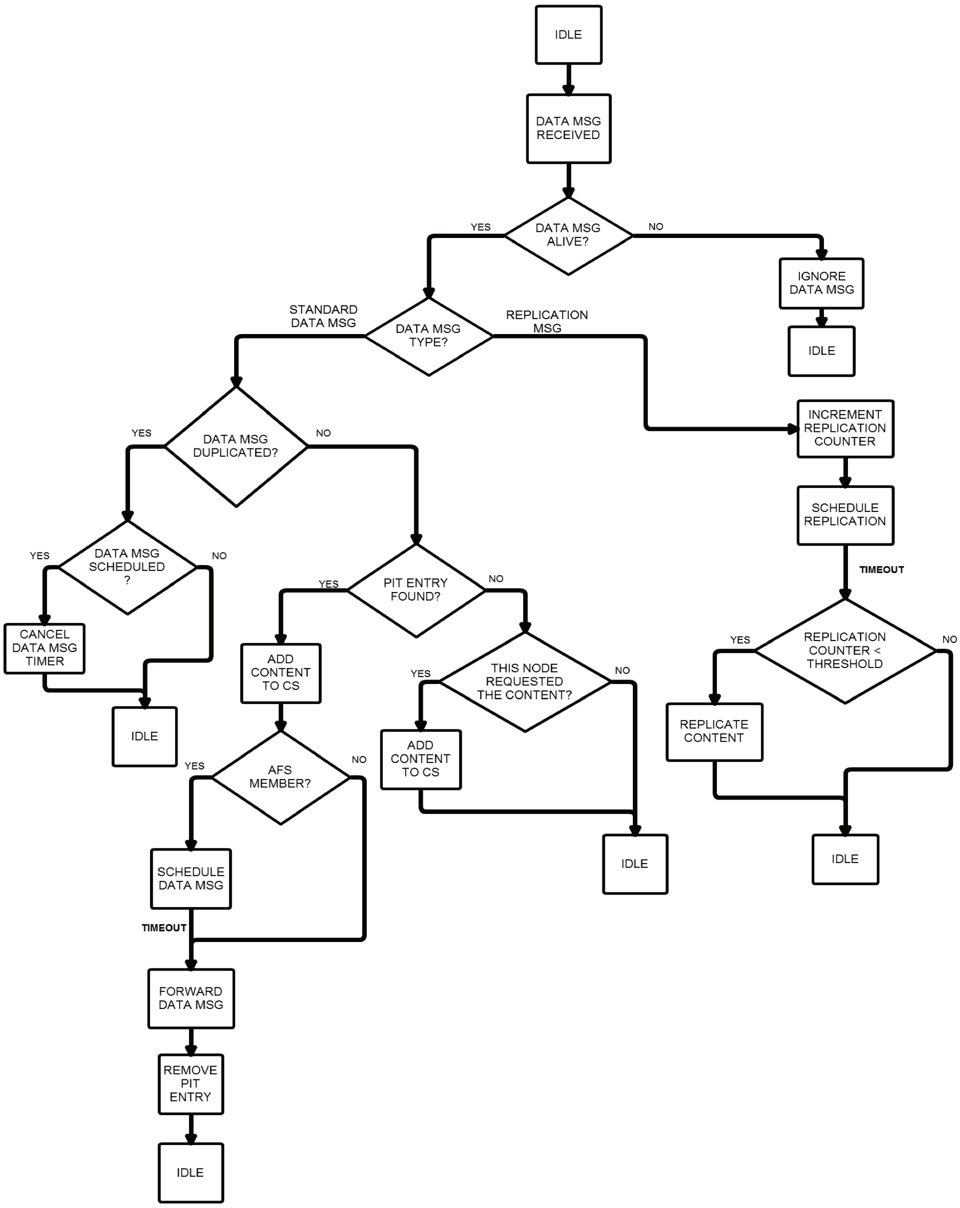


Figure 6.4: Data message routing with replication

6.3.1 Simulation Tools Parameters and Performance Metrics

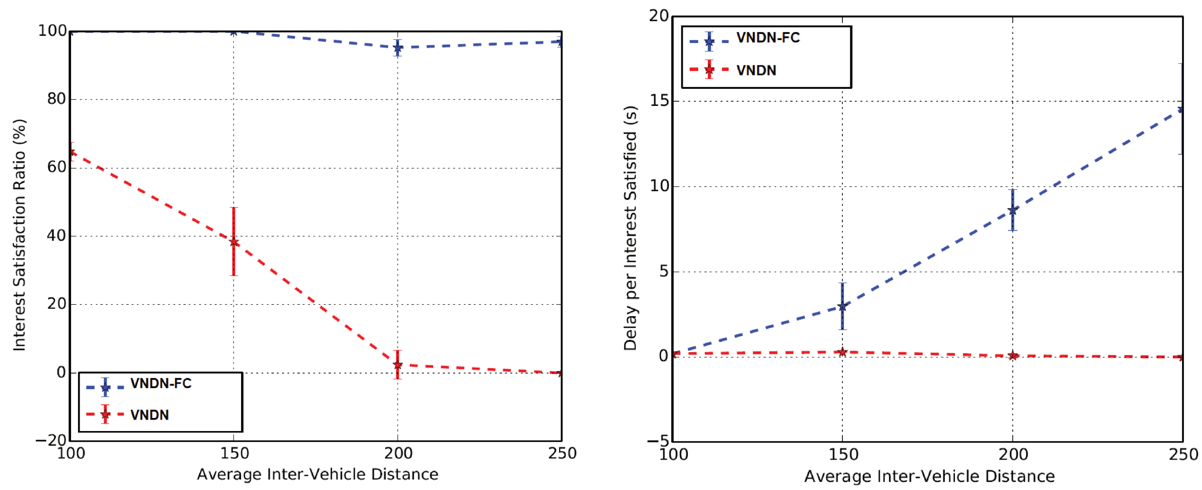
To evaluate the performance of VNDN when the proposed solution is applied, a set of simulations were performed using the E45 highway scenario and the simulation tools Omnet++, SUMO, and Veins described in Section 4.3. The performance metrics Interest Satisfaction Ratio and Delay per Interest Satisfied, also described in Section 4.3 were employed. Table 6.1 shows the main parameters used for simulations.

6.3.2 Performance Results

The results presented in this Subsection were calculated from the average of 33 simulation runs with a confidence interval of 95%. Figure 6.5(a) shows that when the proposed

Table 6.1: Source Mobility - Simulation parameters

Parameters	**Values**
Number of vehicles	300 vehicles
Vehicles speeds	0-100 km/h
Number of content requesters	30
Carrier frequency	5.9GHz
WAVE channel type	Service Channel
Size of Interest messages	1024bytes
Size of Data messages	4096bytes
Number of chunks per content	20
Number of content objects	10
Communication technology	IEEE802.11p
Communication types	V2V and V2I
Maximum vehicle transmission range	200m
Shareability	Shareable data



(a) ISR - Scenario I (b) Delay - Scenario I

Figure 6.5: Content Source Mobility Results

solution is applied (i.e., VNDN-FC) high ISR, reaching values close to 100% are achieved. On the other hand, for the case of the plain VNDN, lower ISR is achieved. Moreover, as the average inter-vehicle distances increases, ISR quickly decreases and reaches values close to zero for average inter-vehicle distances equal or larger than 200m (i.e., equal or larger than the maximum transmission range of vehicles). This happens due to the combination of diverse factors. For instance, the probability of network partitions and RPP occurrence also increases as average inter-vehicle distances increase, making it harder for Interest messages to propagate and reach highly mobile content source vehicles. In the case of VNDN-FC, it combines SCF, AFS, and FC. Therefore, it can provide high ISRs regardless of the mobility of the content source vehicles. Interest messages can still propagate towards content locations even in partitioned scenarios, and content objects can be provided by either the original content producer or any other vehicle that received replicas of the requested content object.

Figure 6.5(b) shows that for the case of average inter-vehicle distances equal to 100m, where the probability of network partitions and RPP is low, VNDN-FC and the plain VNDN have similar delay values. As inter-vehicle distances increase, the delay for VNDN-FC increases. This happens due to the delay introduced by the SCF and the AFS retransmissions to allow Interest and Data messages to propagate towards their destinations. The FC mechanism allows for more content source vehicles within the network and contributes to decreasing delays. Although the delay is higher for VNDN-FC, most of the contribution to the final delay corresponds to content requests that would not be satisfied if the FC, SCF, and AFS mechanisms were not applied.

6.4 Conclusions

This Chapter investigated the problem of content source mobility in VNDN. The problem of content source mobility often prevents Interest messages from reaching content sources, decreasing ISR and consequently degrading VNDN application performance. To solve this problem, this thesis applied the concept of floating content and proposed VNDN-FC, which relies on in-network caching and content replication to make content objects available in the geographic region where they were produced after the original producers move to other locations. In addition VNDN-FC also applies the concepts of SCF and AFS to increase the probability of Interest message reaching content locations. Simulation results show that VNDN-FC is efficient to address the problems caused by content source mobility in VNDN.

Chapter 7

Mobility Support for Vehicular Named-Data Networking

This Chapter proposes a new VNDN framework named as MobiVNDN. MobiVNDN is a distributed framework and integrates all the solutions proposed in previous Chapters. The goal of MobiVNDN is to simultaneously address all the identified VNDN problems caused by mobility and the unreliability of the wireless communication medium in order achieve high application performance and show the efficiency of VNDN as a communication model for vehicular communications. The remaining of this Chapter describes the operation and the components of the MobiVNDN framework in Section 7.1, Section 7.2 evaluates the performance of MobiVNDN compared with both the plain VNDN, as described in Chapter **??**, and the message routing approach presented in V-NDN [22], a VNDN architecture proposed in the literature. Section 7.3 concludes this Chapter.

7.1 MobiVNDN operation

The MobiVNDN framework presents a modular architecture that includes several components. The advantages of these components were described and evaluated separately in the previous Chapters. In the current Chapter these components are evaluated working simultaneously within the MobiVNDN framework. The list of MobiVNDN components can be summarized in the following manner:

1. *Content advertisement*: This component provides the mechanism for Content sources to advertise the content objects that they can provide. It includes the sub-components to address the problems of broadcast storms, message redundancy, and transmission resynchronization;

2. *Message routing*: This component provides the protocol for routing Interest and Data messages within the network and also includes the sub-components to address the problems of broadcast storms, message redundancy, and transmission resynchronization;

3. *Receiver mobility*: This component provides the mechanism to avoid the problem of Reverse Path Partitioning that occurs in VNDN scenarios with receiver mobility

(i.e., AFS);

4. *Network partitions*: This component provides the store carry forward mechanism to mitigate the effects of network partitions (i.e., VNDN-SCF);

5. *Content source mobility*: This component provides the mechanism to mitigate the effects of content source mobility in VNDN (i.e., VNDN-FC);

Figure 7.1 shows how MobiVNDN integrates in the TCP/IP networking model.

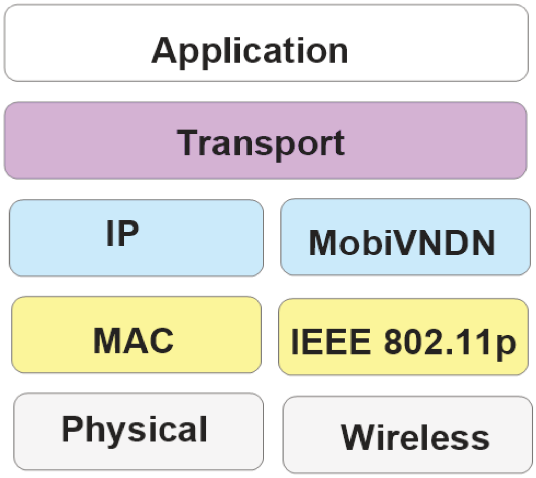


Figure 7.1: Integration of MobiVNDN in the TCP/IP model

MobiVNDN works along with IP in the Internet layer. For vehicular communications MobiVNDN is used, while for communication within the Internet, IP is still applied. Similarly, in the MAC layer the WAVE standard is used for vehicular communications while the traditional MAC protocols (e.g., other IEEE 802 standard protocol) are still applied within the Internet.

Figures 7.2 and 7.3 show the operation of the MobiVNDN framework for Interest and Data messages.

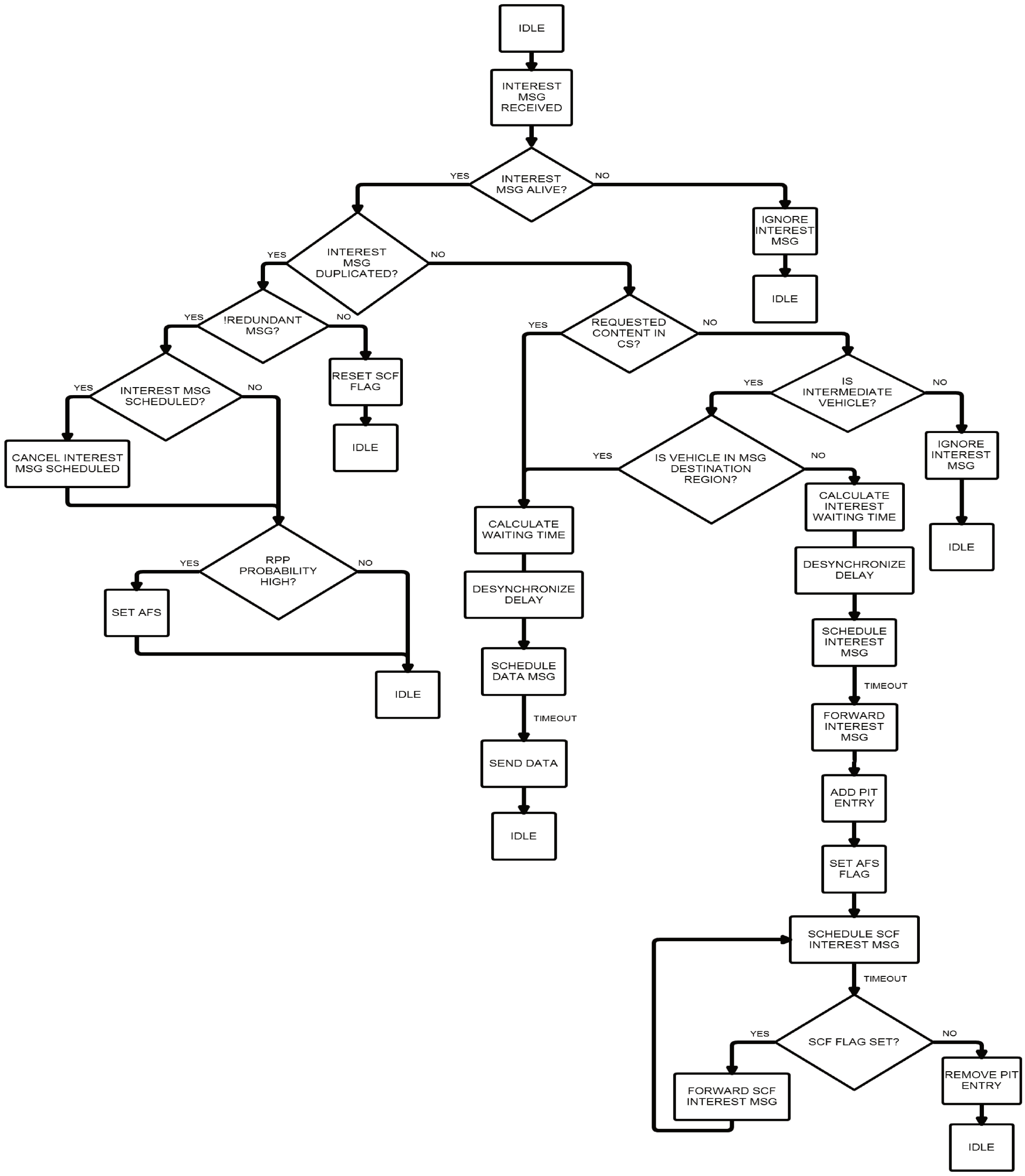


Figure 7.2: MobiVNDN Interest message processing

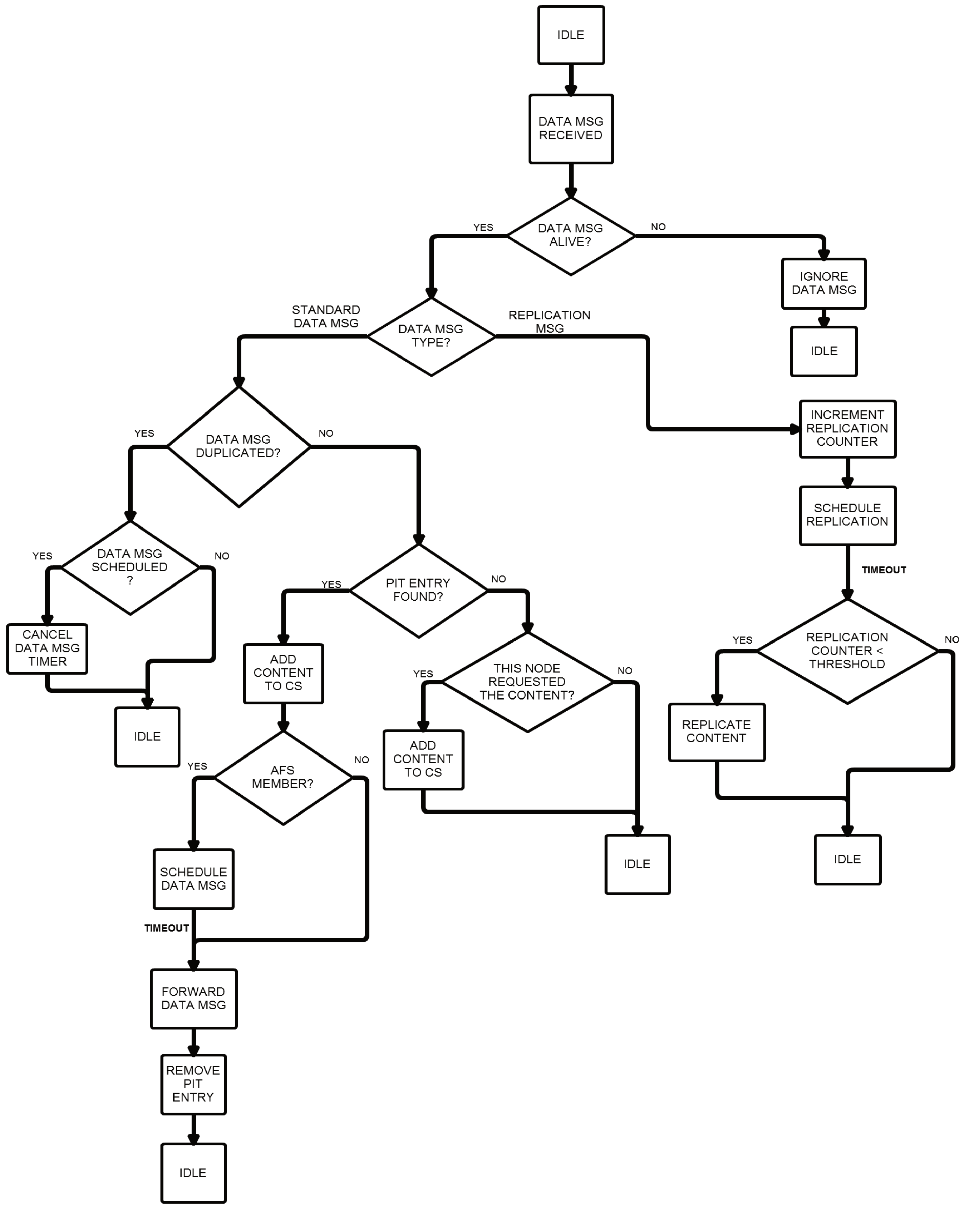


Figure 7.3: MobiVNDN Data message processing

The MobiVNDN mechanism for Data messages processing is similar to the mechanism described in Section 6.2 for the content source mobility problem. As it can be observed the MobiVNDN routing schemes are built on top of the routing schemes from the previous Chapters and integrate all the solutions proposed on these Chapters in a single framework.

7.2 Performance Evaluation

This Section evaluates the performance of MobiVNDN compared to plain VNDN, as described in Chapter 3, and the message routing approach presented in V-NDN [22], a VNDN architecture from the literature. It also lists the simulation tools and parameters, it describes the simulation scenarios as well as the performance metrics and finally discusses the obtained results.

7.2.1 Simulation Tools Scenarios and Performance Metrics

Similar to the previous Chapters, the simulations were performed using the Omnet++ network simulator [51], SUMO [52] for road traffic simulation and Veins [53] for inter-vehicular communication described in Chapter 4.

Two different VNDN communication scenarios were used for simulations.

1. *Advertised content (Urban case):* In this scenarios content requesters only request content objects previously advertised by existing content sources;

2. *On-demand content (Highway case):* In this scenario content requesters request content objects that do not exist yet to be produced according to their interests;

To show the feasibility of the MobiVNDN framework under different network topologies the simulations where performed in both urban and highway traffic scenarios. For the urban case, a grid traffic scenario corresponding to an area of $25km^2$ was used. For the highway case, the E45 Route in the city of Erlangen, Germany described in Section 4.3 was used. Table 7.1 shows the main simulation parameters for the urban case.

Table 7.1: MobiVNDN - Simulation parameters for the urban case

Parameters	**Values**
Density of vehicles	100-600 Vehicles/km^2
Vehicles speeds	0-50 km/h
Number of content requesters	60
Number of content producers	10
Number of content objects	10
Carrier frequency	5.9GHz
WAVE channel type	Service Channel
Size of Interest messages	1024bytes
Size of Data messages	4096bytes
Number of chunks per content	25
Communication technology	IEEE802.11p
Communication types	V2V
Maximum vehicle transmission range	200m

Table 7.2 shows the main simulation parameters for the highway case.

The performance of MobiVNDN is assessed according to Interest Satisfaction Ratio, Delay per Interest Satisfied, and the number of Data Messages Forwarded.

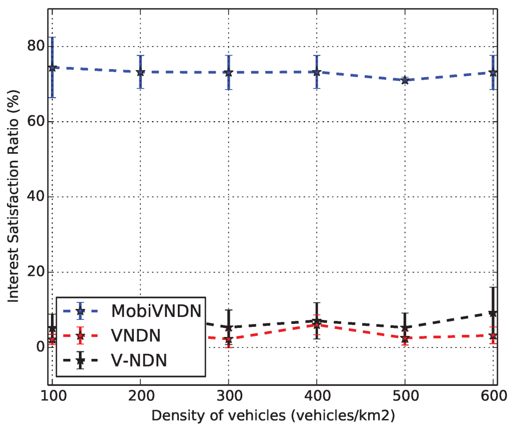
7.2.2 Performance Results

This Subsection describes the simulation results. These results correspond to the average of 33 simulation runs with a confidence interval of 95%.

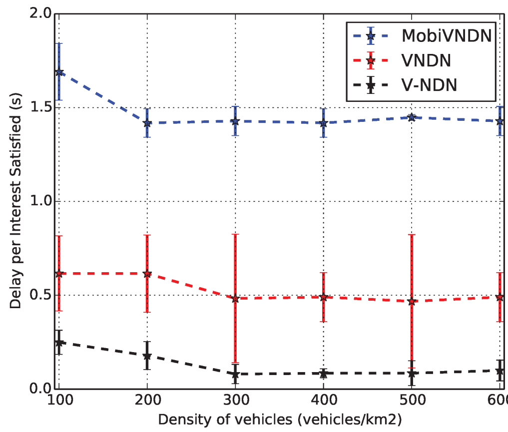
Considering the advertised content scenario, which was simulated in the urban case, Figures 7.4(a) and 7.4(b) show that MobiVNDN achieves higher ISR, which is its main

Table 7.2: MobiVNDN - Simulation parameters for the highway case

Parameters	**Values**
Number of vehicles	600
Vehicles speeds	0-100 km/h
Number of content requesters	60
Number of content producers	10
Number of content objects	10
Carrier frequency	5.9GHz
WAVE channel type	Service Channel
Size of Interest messages	1024bytes
Size of Data messages	4096bytes
Number of chunks per content	25
Communication technology	IEEE802.11p
Communication types	V2V
Maximum vehicle transmission range	200m



(a) Interest Satisfaction Ratio

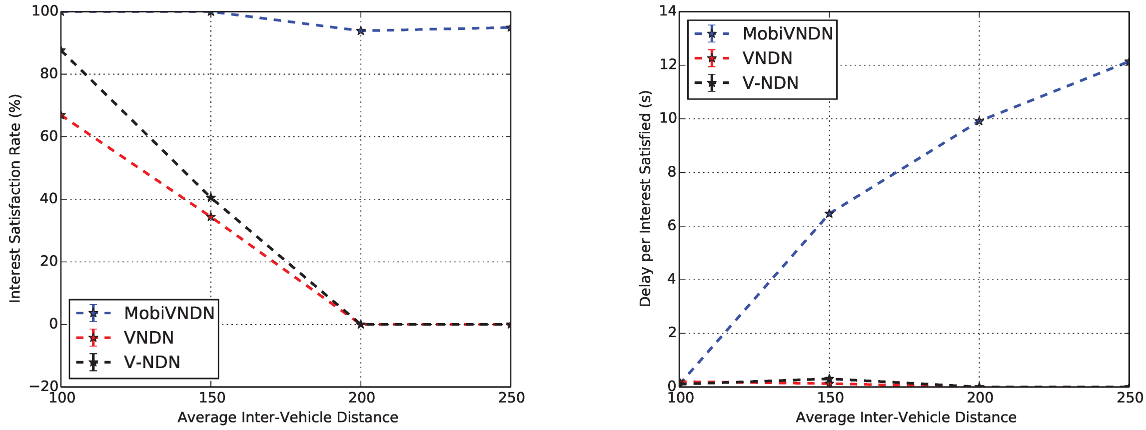


(b) Delay

Figure 7.4: MobiVNDN Results Scenario I

goal, at the cost of increasing the delay. However, this increase in delay is not significant as the values are still low (i.e., lower than two seconds). This increase is due to the store carry forward, replication and auxiliary forwarding set mechanisms, which unlike in VNDN and V-NDN, allows MobiVNDN to deliver content under partitioned and highly mobile scenarios. The results show that for large traffic scenarios, such as the one used in this case (i.e., $25km^2$ of area) where content requesters and content source vehicles are likely to be located farther away from each other, the advantages of MobiVNDN are obvious when compared to other solutions that do not address the effects of reverse path partitioning, network partition, and content source mobility. In the specific case of this simulation, content objects are requested by vehicles located at approximately 3km from the locations where the requested content objects were advertised. In this case the performance of the other solutions regarding ISR almost drop to zero while MobiVNDN still provide high ISR.

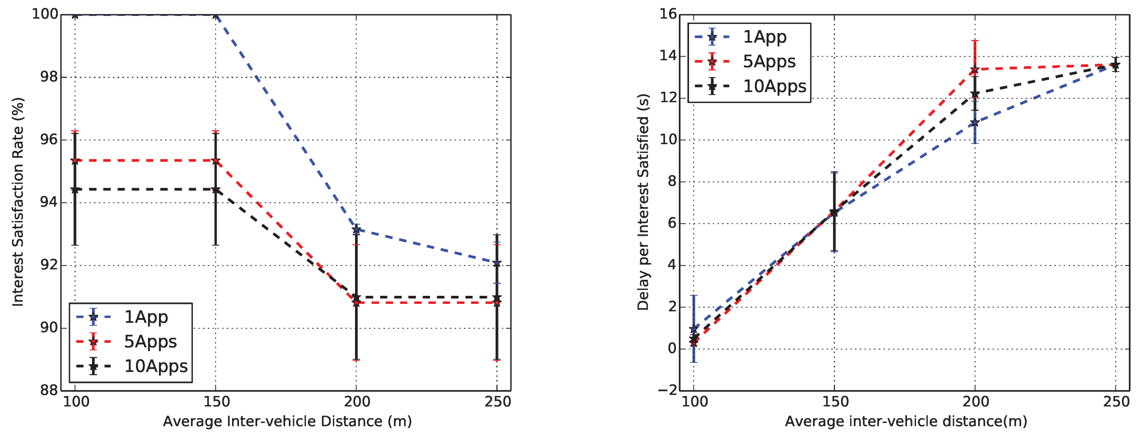
Considering the on-demand content scenario, which was simulated in the highway case, Figures 7.5(a) and 7.5(b) show that MobiVNDN also provides higher ISR, which also comes at the cost of increasing delay. This increase in delay happens because in



(a) Interest Satisfaction Ratio (b) Delay

Figure 7.5: MobiVNDN Results Scenario II

highways, vehicles reach higher speeds, and as the average distance between vehicles increases the effects of network partitions, reverse path partitioning, and source mobility become more significant. Therefore, the performances of VNDN and V-NDN are also affected in this case.



(a) Interest Satisfaction Ratio (b) Delay

Figure 7.6: MobiVNDN Results - Multiple Applications

However, ISRs are still high (i.e., over 90%) and there is no major effects in delay, which shows the robustness of MobiVNDN.

To evaluate the effects of the shared communication channel in MobiVNDN, the highway traffic scenario was used to simulate the cases of MobiVNDN working along with one, five and ten (1,5, and 10) other applications. For these cases, one, five and ten vehicles respectively were selected to produce a set of content objects and send over the wireless communication medium every three seconds. Figures 7.6(a) and 7.6(b) show that due to higher traffic in the wireless communication medium and larger number content objects to cache the ISR slightly decreases.

7.3 Conclusions

This Chapter described the proposed MobiVNDN framework, a distributed framework designed to improve VNDN communication performance in scenarios with high mobility. To evaluate the performance of the MobiVNDN framework, a series of simulations were performed showing that it is an efficient solution to address the negative effects of mobility and the unreliability of the wireless communication medium in Vehicular Named-Data Networking.

Chapter 8

Final Remarks

According to the described in the previous Chapters, by applying the NDN communication model over VANETs, VNDN has the potential to overcome the main drawbacks of existing communication technologies such as the Internet protocol and the broadcast communication approach and improve application performance. However, to efficiently deploy VNDNs a set of problems caused by the high mobility of vehicles and the unreliability of the wireless communication medium, including receiver and source mobility, network partitions, broadcast storms, message redundancy, and transmission resynchronization shall be addressed. This thesis proposed a framework to simultaneously address the negative effects of each of these problems and provide high VNDN application performance.

8.1 Main Contributions

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 in a VNDN framework to provide high VNDN application performance. The main contributions of this thesis can be summarized in the following manner:

Message Routing in Vehicular-Named Data Networking

The first contribution of this thesis is a multi-hop routing mechanism for Interest and Data messages. This routing mechanism is designed with the goal of enabling content requesters to retrieve content objects from distant locations. Besides, this routing mechanism avoids unnecessary usage of the limited and shared wireless communication medium and prevent the occurrence of the broadcast storm, message redundancy, and transmission resynchronization problems.

As explained in detail in Chapter 3, in multi-hop scenarios this proposed routing mechanism minimizes the number of intermediate vehicles that forward Interest and Data messages and reduces the number of message collisions. Consequently, it avoids the broadcast storm problem, by selecting as message forwarders only the vehicles that allow more progress towards the message destination, among all vehicles that receive a message. The decision of whether to forward a received message is taken locally by each vehicle through the use of a delay/timer approach, set in a way that 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. In this way, this mechanism does not require the exchange of state information between neighbor vehicles to find the best message forwarders. Therefore, this routing mechanism is multi-hop, receiver-based and beacon-less. Similar to NDN, vehicles use the information stored in their PITs 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.

To prevent transmission resynchronizations, this routing mechanism is aware of channel switchings in the wireless access in vehicular environments (WAVE) standard, which is used for communications. When calculating the delay for forwarding Interest messages, vehicles take into account the WAVE channel switching time, and when required they add extra delays to prevent close vehicles from simultaneously transmitting messages into the wireless communication medium.

To identify message redundancies, vehicles extract from received Interest messages the locations of the vehicles from whom they received the Interest message. In this way, if a vehicle receives multiples copies of the same Interest message, it can distinguish a message that has been transmitted by a neighbor vehicle located closer to the message destination from a redundant message transmitted by another vehicle farther away from the message destination.

Content Receiver Mobility

The second contribution of this thesis proposes to increase ISR in VNDNs by addressing the effects of the reverse path partitioning (RPP) problem.

In this thesis, a reverse path partitioning 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. In a VNDN scenario very often vehicles travel at different speeds making inter-vehicle distances very dynamic. In VNDN vehicles closer to a message destination (i.e., vehicles farther away from the previous sender/forwarder of the message) are selected as next forwarders for that Interest message, in order to allow more progress towards the message destination. Therefore, consecutive Interest message forwarders tend to be located distant from each other, contributing to increase the probability of RPP. To address the effects of RPP, this thesis proposds 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 and determines the probability of RPP occurrence between any two 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 any of the original Data forwarders, among the members of the AFS group that received the message, the one closer to it retransmits the Data message. The Data message is then received by the original forwarder and the reverse path is reconnected. Simulation results showed that AFS is efficient and scalable since it is able to provide high VNDN application performance without excessive load on the communication channel regardless of receivers mobility and the number of content requests.

Network Partitions

The third contribution of this thesis addresses the problem of network partitions in VNDN.

The network partition problem occurs when 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 can significantly degrade VNDN application performance leading to low ISR and high delays. Network partitions might temporarily occur in VNDN scenarios with high vehicle densities due to signal attenuations caused by obstacles and other disturbances in the wireless communication medium. However, network partitions are more frequent and harmful in sparse VNDN scenarios where the density of vehicles is low, and often vehicles get out of the transmission range of each other for significant periods of time.

To address the network partitions problem, this thesis proposes two different solutions. The first proposed solution targets scenarios with infrastructure support and applies the idea of VNDN agent delegation. The VNDN agent delegation communication approach inspires on the concept of agent delegation [20]. The main idea is that in sparse networks when nodes are unable to connect to content sources to request content objects, content requests can be delegated to other nodes that due to their trajectories will be able to communicate with a content source and again with the content requester in the future to deliver the requested content object. Since the agent delegation approach was designed for scenarios with low mobility, as opposed to this thesis that focuses on VNDNs with high vehicle mobility, a new communication model for the agents was required. In this sense, a new VNDN communication mechanism specifically designed for road side units (RSUs) was developed and deployed in RSUs along roads. In case of network partitions, content retrieval is delegated to these VNDN enabled RSUs. Since the VNDN RSUs form a network of static and connected nodes, they are immune to the problems of mobility, and as shown in the simulation results the VNDN agent delegation approach can efficiently retrieve requested content objects from distant locations with short delays and provide high application performance.

Despite the efficiency of the VNDN agent delegation approach in retrieving content objects from distant locations, the high costs associated with the deployment and maintenance of networks of RUSs along roads represent a great obstacle for the deployment of RSU networks and currently, such networks are still scarce around the world. In this context, this thesis recognizes the need for an alternative solution to the problem of network partitions in VNDN scenarios without infrastructure support. For such cases, this thesis proposes the VNDN store carry forward mechanism (VNDN-SCF). The intuition behind VNDN-SCF is that 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. Vehicles use the messages forwarded by their neighbors as implicit acknowledgments of message delivery. When a vehicle sending or forwarding a message perceives that the message was not forwarded by any neighbor vehicle, it concludes that a network partition has occurred. In such a case, 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.

Simulation results showed that the VNDN Agent Delegation and the VNDN-SCF mechanisms are scalable and able to efficiently address the negative effects caused by network partitions and improve VNDN application performance in scenarios with and without infrastructure support respectively.

Content Source Mobility

The fourth contribution of this thesis proposed a solution to the problem of content source mobility. NDN assumes that content sources might advertise the content objects that they can provide, to inform the remaining nodes about available content objects within the network. After understanding about the availability of a given content object, vehicles can decide whether they are interested or not in receiving such a content object. If a vehicle is interested in an existing content object it can request it, either immediately or after a certain time interval, by sending an Interest message with the content name towards the location announced in the Advertisement message. However, due to the high mobility of vehicles in VNDN, vehicles usually only stay for short time periods in particular locations. Considering this, the probability of Interest messages sent towards the location where a given content object was advertised reaching the vehicle that advertised the content object (i.e., the content producer) decreases proportionally with mobility and time as the content producer vehicle moves away from the location indicated in the Advertisement message. For the cases of popular content objects that might be requested by a large number of vehicles, several content requests might be satisfied by vehicles other than the content producer, if they previously requested the content object and have a cached copy of it. Nevertheless, in the case of unpopular content objects that are requested by few vehicles, the probability of finding a copy of the content object in the caches of neighbor vehicles is low, leading to a large number of unsatisfied content requests and significantly decreasing application performance.

This thesis proposed VNDN-FC as solution to the problem of content source mobility based on the combination of NDN in-network caching and the concept of floating content (FC). FC is a communication scheme, which supports infrastructure-less distributed content sharing over a given geographic area (i.e., the anchor zone). Whenever a node possessing a content object moves out of the spatio-temporal limits of its anchor zone (AZ), it replicates the content object to the remaining nodes within the AZ and deletes it. In this way, the content object may be available on a set of nodes and moves over time within the AZ and after the node that initially generated the content left the AZ, the content object still available within the AZ. In this thesis the AZ is defined by a center (i.e., the geographic location where the content object was produced) and a radius (i.e., 200m coinciding with the maximum transmission range of vehicles). When receiving a replica of a content object (i.e., Data message of type R) vehicles check whether they are within the AZ for that particular content object. If that is the case, they cache the content and become content sources for that specific content objects. When leaving the AZ they also replicate the content to the other vehicles within the AZ and delete the content object. In this way, Interest messages sent towards the location where the content object was advertised can still be satisfied over the time regardless of the mobility of the original content producer, leading to improved application performance compared to the cases where the problem of source mobility is not handled. Simulation results show that VNDN-FC is efficient to address the problems caused by content source mobility in VNDN and improve VNDN application performance.

Mobility Support for Vehicular Named-Data Networking

The last contribution of this thesis is MobiVNDN, a distributed framework designed to enhance VNDN communications and improve application performance in both highway and urban scenarios. The MobiVNDN framework integrates all the solutions described in the previous contributions. Summarizing, MobiVNDN simultaneously prevents the occurrence of the broadcast storm, message redundancy, and transmission resynchronization problems by applying the routing mechanisms for Advertisement, Interest, and Data messages described in the first contribution of this thesis and addresses the effects of reverse path partitioning, source mobility, and network partitions by applying the concepts of AFS, VNDN-SCF, and FC. Simulation results show that the MobiVNDN framework is able to address the effects of mobility and the unreliability of the wireless communication in highly mobile urban and highway VNDN scenarios and provide high application performance.

8.2 Future Work

This thesis proposed a framework to support vehicle mobility and provide high VNDN application performance. While this is a significant contribution for the deployment of VNDN other opportunities for extending the scope of this thesis remain since in addition to mobility the VNDN challenges encompass other aspects. Between this aspects we can highlight the following examples:

- Data structures management: Since the size of CS, PIT, and FIB in vehicles is limited, efficient ways for managing these data structures are required. Even if storage is not a major problem in vehicles, the lookup delay increases as the number of stored entries in each of these data structures increase, potentially leading to increased delay. Therefore data structure management mechanism should provide the optimal trade-off between hit rate and delay.

- Naming: In VNDN each content object is represented by a unique name. Hierarchical name structures have been the most common name structure applied in VNDN so far. However naming techniques is still an open research problem and contributions that enhance the VNDN naming schemes are still required.

- Caching techniques: In-network caching is a fundamental feature of VNDN. Therefore, cache discovery and cache replacement mechanism specifically designed for VNDNs can contribute to improving application performance.

List of Publications

- Duarte, Joao M., Eirini Kalogeiton, Ridha Soua, Gaetano Manzo, Maria Rita Palattella, Antonio Di Maio, Torsten Braun, Thomas Engel, Leandro A. Villas, and Gianluca A. Rizzo. "A multi-pronged approach to adaptive and context aware content dissemination in VANETs." Mobile Networks and Applications (2017): 1-13.

- Duarte, Joao M., Torsten Braun, and Leandro A. Villas. "Receiver Mobility in Vehicular Named Data Networking." In Proceedings of the Workshop on Mobility in the Evolving Internet Architecture, pp. 43-48. ACM, 2017.

- Duarte, Joao M., Torsten Braun, and Leandro A. Villas. Source Mobility in Vehicular Named-Data Networking: An Overview. In Proceedings of the 9th EAI International Conference on Ad Hoc Networks. Niagara Falls, Canada. 28.-29.09.2017.

- Duarte, Joao M., Torsten Braun, and Leandro A. Villas. "Addressing the Effects of Low Vehicle Densities in Highly Mobile Vehicular Named-Data Networks (accepted)." The 20th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. Miami, USA. 21.-25.11.2017. (2017).

- 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, João MG 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.

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