Bachelorarbeit

A Geographical aware Routing Protocol in NDN-VANETs

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Abstract

During the last decades, networking experienced a shift from a host bound 'where' to a content centric 'what', where content dissemination is in the centre of communication. Additionally, the amount of network users and the amount of exchanged Data between those grows every day. TCP/IP and, therefore, host-to-host communication, where it is crucial to establish a well-known, secured path for Data exchange through IP addresses, is not suitable for the emerging patterns of content distribution. Furthermore, network devices are getting more and more mobile. These ongoing changes lead to the development of new robust schemes for efficient content dissemination. Named Data Networking (NDN), as a new network paradigm, suits the content dissemination purpose. Routing in NDN is based on content names and arises locally on each node. In a mobile environment like Vehicular Ad-hoc NETworks (VANETs), where paths to hosts can break due to moving nodes, there is a huge need for non end-to-end network architectures like NDN. Especially, because communication in NDN does not depend on host locations, NDN is suitable for VANETs.

This thesis aims to reduce network traffic in NDN VANETs. To achieve this, we extend an existing improved Multihop, Multipath and Multichannel Vehicular NDN forwarding protocol (iMMM-VNDN) for VANETs. We propose a Geographical aware Routing Protocol (**GaRP**), which uses four directional antenna devices to limit the dissemination spreading area of messages. With the help of directional antennas, every vehicle in **GaRP** sends messages towards a designated direction. Thus, less traffic should be generated in areas where nodes do not need to communicate with each other. Therefore, less collisions occur, and overall network communication improves. Furthermore, the forwarding protocol is adapted to exploit future positions of nearby vehicles on the road. To obtain this information, a node estimates its future position with the help of a navigation device and adds it to every outgoing message. Intermediate nodes subsequently process this message and, it reaches its target node. The estimated future position of the message is extracted and added to the Pending Interest Table (PIT), or to the Forwarding Information Base (FIB) of every target node. When the messages containing this future position information propagates through the network, nodes are aware of the locations of surrounding vehicles. Afterwards, the information about the future position is used to target a node by using an on-board directional antenna. To this end, **GaRP**-nodes use only one designated directional antenna, to unicast messages on defined routes between consumer and producer nodes. We evaluate the performance of **GaRP** compared with iMMM-VNDN and some standard routing protocols. This thesis presents the Data Delivery rate, the produced traffic of every node as well as the message retransmissions of the requester node.

The simulation results of **GaRP** show that paths are formed on which messages are exchanged. Therefore, the approach reduces network traffic on areas where no paths are formed. This leads to fewer packet losses due to collisions. Due to better packet delivery, also a higher Data/Interest delivery rate is achieved within a given time period, leading to an improvement of the underlying protocol, iMMM-VNDN.

1. Introduction

This chapter presents the motivation of the work performed in this thesis. Subsequent, the research contribution is shown, followed by a brief outline of the succeeding chapters.

1.1 Motivation

The leading principles of today’s commonly used Internet architecture were created several decades ago. Back then, the purpose of networking aimed to solve problems for resource sharing e.g., tape drives between two machines, one demanding the resource and the other providing it. Since then, several technical improvements lead to cheaper devices, providing Internet access to a variety of people. Nowadays, global networking of mobile, household, cars and other networked devices on the Internet of Things (IoT) massively increases the generation of network traffic year by year [1]. During 2016 the global traffic amount was already greater by a factor of thousand than in 2008 and reached 16 zettabytes. A prognosis shows that until 2025 the generated Data will reach 200 zettabytes. With this exponential increase in traffic, the manner how the Internet is used changed [2]. Today’s networks rely on the traditional resource sharing paradigm of the host-to-host-based TCP/IP model [3]. However, it is now most needed to diffuse multimedial content [4]. This leads to a paradigm shift where the key point in the network is the content. Therefore, new network architectures emerged. Named Data Networking (NDN) [5], [6] is one of the most prominent among them. NDN focuses on content distribution, based on content names [6]. By decoupling the content from a certain host, NDN is highly suitable for network environments where the original content producer is not anymore reachable. Therefore, in an architecture like NDN, with a decentralized cache-based Interest/Data message model, every node that previously cached the requested content can fulfil a request with the corresponding Data. In a mobile environment like Vehicular Ad-hoc NETworks (VANETs), where paths to hosts can break due to moving nodes, there is a huge need for non end-to-end network architectures like NDN [7].

This work focuses on content distribution in VANETs. In recent years VANETs are witnessing a rapid development for mobile content dissemination techniques. VANETs contain highly mobile vehicles. Because such vehicles nowadays are mostly equipped with communication devices, they have the possibility to access or create on the fly wireless networks to exchange information. Vehicles, for example, ask for information to avoid traffic or retrieve surrounding gas prices, etc. [8]. These networks are prone to difficulties like constantly changing topologies, short connection times due to speed differences or various problems of signal propagation due to the wireless nature of the communication process itself. Therefore, the information dissemination in VANETs, which encounters different problems, leads to a lot of connection breaks and packet losses. The question arises on how to solve the traffic overhead problem that causes congestion, thus a decrease of delivered messages. To address signal interferences, especially due to network traffic overhead in VANETs, this work presents a Geographical aware Routing Protocol (**GaRP**), based on geographical directed message transmissions with the help of directional antennas. Directional antennas have a focused, narrow beam and do not spread their signal at full power in 360°. Every **GaRP** node is equipped with those directional antennas and can choose where to send messages. Therefore, **GaRP** can reduce traffic overhead in regions where no communication is needed and consequently, reducing network traffic in non-targeted areas of the network.

1.2 Research Contribution

This thesis extends an existing forwarding strategy, namely the improved Multihop, Multipath and Multichannel Vehicular NDN forwarding protocol (iMMM-VNDN) [9], developed in the network simulator ndnSIM [10]. The extension exploits the current and the future position of vehicles in the road network. With the help of this information, the extension allows transmission of messages to a direction by using directional antennas, according to the geographical location of each node that holds content or forwards it. To achieve this geographically directed message delivery, this thesis proposes the use of parabolic antennas. After the discovery of the surrounding network topology, each mobile device considers geographical information to send out messages. The main goal is to deliver content to a direction in order to reduce network overhead in VANETs. Therefore, the needed simulation scenarios are based on stationary as well as on moving nodes. The extension is done in ndnSIM, an open source network simulator, based on ns-3 [11]. Finally, the proposed Geographical aware Routing Protocol (**GaRP**) is compared with existing routing protocols in ndnSIM.

1.3 Outline

This thesis is structured as follows. By looking at related work on the topic of NDN and VANETs, *Chapter 2* shortly explains the NDN architecture in detail and how the Information Centric Networking (ICN) paradigm is ported to VANETs in case of NDN. *Chapter 3* introduces the ndnSIM simulation environment by looking at the most important components for this thesis. In *Chapter 4* the design and implementation of the

Geographical aware Routing Protocol in NDN-VANETs is introduced. Therefore, the modifications done to the ndnSIM simulation environment are presented. *Chapter 5* summarizes the simulation results. *Chapter 6* concludes the work of this thesis.

2 Related Work

When the Internet was created, only a few resources and computers existed, so knowing the location of a client and a server was crucial. Nowadays, due to changes in networking towards content dissemination and the huge growth of network users, better fitting solutions, as the TCP/IP model, are needed. One main reason is, that the TCP/IP model with its host-to-host architecture needs a connection between two endpoints during the entire process of communication. If the same resource or information is requested from two different clients, a connection must be established, secured, and maintained twice. Furthermore, long distance connections from a server to a client need to be provided for every requesting entity, even if clients are located close to each other. The Data, then, needs to be transmitted along the entire path from the server to every client, instead of being shared among neighbouring devices. Therefore, TCP/IP is no longer seen as the best choice for contemporary networking requirements, which shifted from a resource sharing to a content distribution purpose. This is where the Named Data Networking (NDN) architecture takes effect [12]. Further, Section 2.1 presents the NDN architecture and its key structures.

Network devices are getting more and more mobile these days. Mobile Ad-hoc NETworks (MANETs) create Ad-hoc connections on the fly in areas without infrastructure. Consequently, networking has become more and more independent. Vehicular Ad-hoc NETworks (VANETs) as a highly mobile special case of MANETs are getting more and more involved in everyday life [13]. Therefore, as part of the study subject of this thesis, NDN in connection with VANETs and the related work in this context are shown in Section 2.2. Afterwards, Section 2.3 presents the underlying improved Multihop, Multipath and Multichannel Vehicular NDN forwarding protocol for NDN-VANETs (iMMM-VNDN) for the Geographical aware Routing Protocol (**GaRP**) introduced in this thesis.

2.1 Named Data Networking

Named Data Networking (NDN) [4] is an implementation of the Information Centric Networking (ICN). This section describes various parts of NDN, and concepts also introduced with ICN. Key architectural components of NDN, such as the Pending Interest Table (PIT), the Content Store (CS) and the Forwarding Interest Base (FIB) are introduced. Further, their interaction with NDN message packets within the NDN protocol stack is shown. To better illustrate the overall picture, also name-based transport and routing of the individually secured NDN messages is introduced.

2.1.1 NDN Protocol Stack

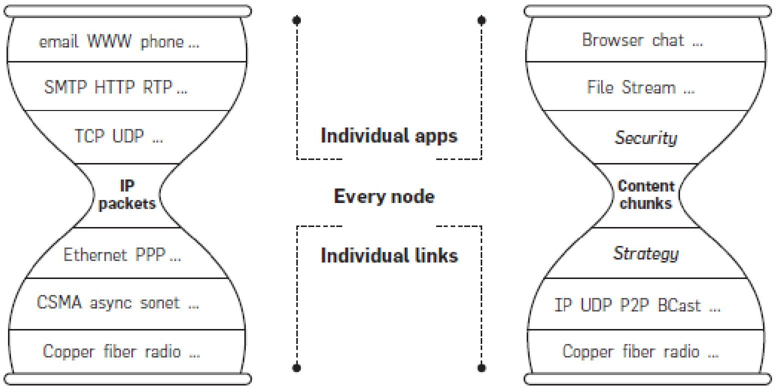


Figure 1 : Hourglass Shape of IP and NDN Protocol Stack [4]

Fig. 1 shows the thin waist hourglass shape of the IP protocol stack on the left and the NDN stack on the right. NDN reforms the limitations of the current Internet architecture while keeping this thin waist architecture. Thus, a minimal functionality necessary for connectivity is implemented in a universal network layer. This allows lower and upper layers to innovate without forcing unnecessary constraints. Furthermore, NDN is a universal overlay. That means that it is capable to run over everything. Therefore, it can be deployed directly on top of the IP model. This permits to use existing infrastructure services for IP packet routing, such as Domain Name Services. The nature of the IP protocol is embodied in its Datagram format, the IP address as an endpoint qualifier. This restriction is now removed in NDN by changing the use of IP packets with named Content Chunks, as shown in Fig. 1. Therefore, a node asks directly for the 'what' instead of the 'where'. Every content chunk is individually named (Section 2.1.3). Instead of addressing hosts, the content is now directly addressable and routable by its name, making the Data independent from where it arrived. Lower layers in NDN protocol stack are used for encoding, decoding, and routing of the content. Bottom-up, the first layer manages physical links like copper fiber. The second layer, the link layer, embodies everything that can forward NDN Datagram, like Wi-Fi, Bluetooth or TCP/IP. The third layer, the strategy layer, is responsible for message forwarding. It makes choices to best exploit multiple connections under changing conditions, discovers network problems and sends messages. On the other hand, the higher layers take the role of securing, signing and interpreting the content. Layer five, the security layer, signs and secures all named Data and, therefore, applies security to the content itself (Section 2.1.4). The two upper layers are the layers where application protocols and applications run. They are responsible for the naming of messages.

2.1.2 NDN Message Packets

This section presents a brief sketch of NDN's key message elements, the Interest packet and the Data packet, as shown in Fig. 2. When content requesters want to request content, they send out Interest packets. Fig. 2 shows the components of an Interest message on the left. The components are the crucial name, different selectors and some nonces. On the right side of Fig. 2, there is a Data packet. The Data packet is the response of a node to a received Interest from a Data requesting node. This Data packet contains the same name field as the Interest, some signatures and the requested content itself. In NDN it is important that the Data packet is signed, thus NDN has no need for further network security on the network [5] (Section 2.1.4).

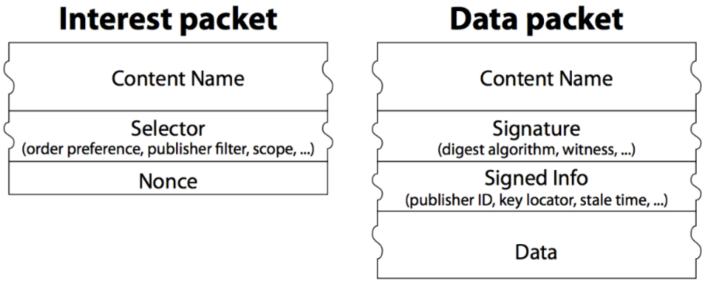


Figure 2 : NDN Message Packets [5]

2.1.3 Content Name

Fig. 3 shows an exemplary name of an NDN message packet. This name is part of every Interest and Data packet as shown in Fig. 2. Names are constituted in a hierarchical way, like IP uses the hierarchical structure of net, subnet, etc. In NDN, a node requests content by sending Interests towards the network. These Interests request pieces of Data that are called Content Chunks. Moreover, many nodes may share the same Chunks or even different versions of the requested content. This leads to the problem of properly identifying Data segments. In this case, a simple segment number like in TCP is enough (Fig. 3, Fig. 4). To identify the correct content version, the naming of an NDN packet contains a version mark '_v' followed by a number, specifying the version and a segmentation mark '_s' followed by a segment number, for correct reassembly of the content.

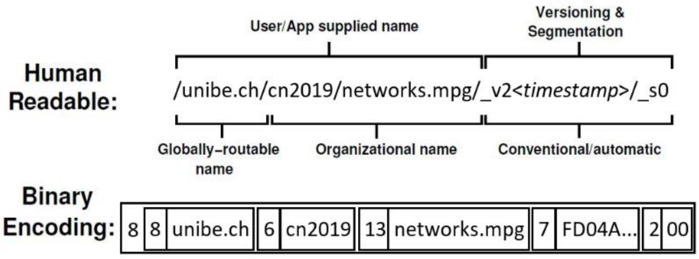


Figure 3 : Example Content Name

To request content, like a course video of University of Bern, the request can have this structure: /unibe.ch/cn2019/networks.mpg/_v2/_s0. The slash ('/') is not part of the name itself but indicates boundaries between name components. As shown in the binary example in Fig. 3, the slash is not encoded in the naming itself and is, therefore, only used for human reading purposes. Naming schemes can evolve by the international or national convention. As an example, the naming of a local application, like a projector in a room, can have the conventional prefix /local/. If the naming of content is not known to a requester, it can be specified in a deterministic way by using conventions and relative specifications to the known names. This is possible because NDN name trees (Fig. 4) are totally ordered and relations, such as 'next' and 'previous' can be clearly interpreted. In order to get the second part of an mpg file, the node can simply specify the old content (segment one) with a 'next' flag. Interests in this manner provide a form of restricted

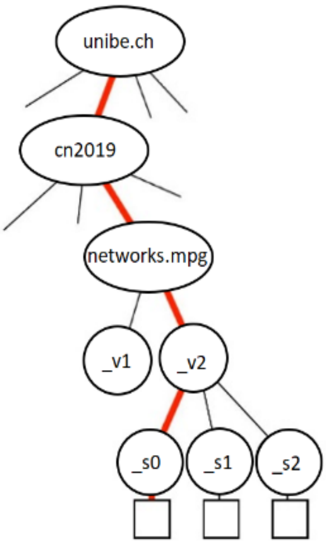


Figure 4 : Content Name Tree, Traversal to Segment 0 of Version 2

query mechanism over accessible content collection in the network [4]. Name-based routing, moreover, improves the scalability problem of IP's finite address space [5].

2.1.4 Security

NDN uses the following building blocks to build up the NDN security mechanism: Digital keys, trust policies, and NDN certificates. NDN uses a private and public key cryptography mechanism to sign and encrypt Data. The keys are distributed by so called NDN certificates, which are Data packets carrying public keys. They can be fetched in the network using normal Interests. These packets are signed by a certificate signer that can be a node or an external certificate signer. A trusted certificate signer, the so-called trust anchor, like a root certification authority in a certificate chain, is needed to start the certification chain. This trust anchor can be pre-configured or securely obtained by other operations. In the end, the decision is left to the consumer to choose why to trust a key.

NDN Data packets are immutable and, therefore, if a content object in a Data packet must be changed, the whole packet must be regenerated. Every newly generated or modified packet must be signed with a Digital key within the producer's namespace, following the public-key cryptography principles [14]. Also, every Data packet must be signed and optionally encrypted by its producer's application key. This enables every consumer application to ensure the authenticity and integrity of the received Data packet. This can be done by verifying the signature of the producer. In connection with the in-network storage mechanisms of NDN, the fact that Data is secured by the original producer leads to the possibility that Data can be safely reused, regardless of its location and the trustworthiness of the storage system.

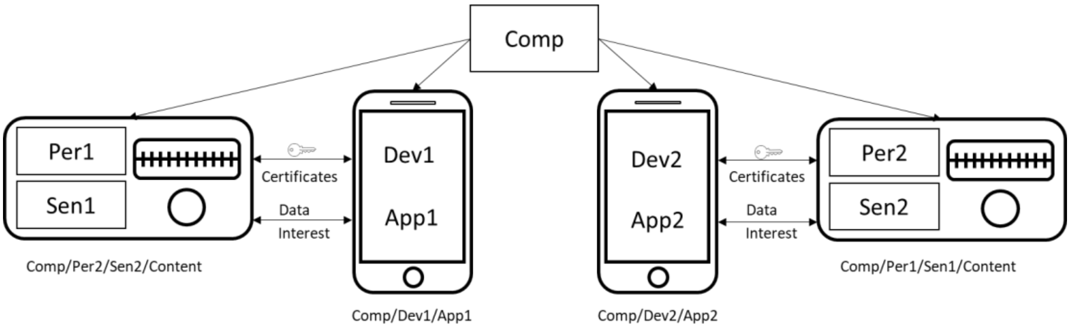


Figure 5 : Application Pairing in NDN

To show up the above made explanations, consider two applications (App1, App2) running on two different devices (Dev1, Dev2) and communicating with two different peripheral devices (Per1, Per2) each. Dev1 communicates with Per1 and Dev2 with Per2. The two applications are consumers of Data generated from two sensors (Sen1, Sen2), each in one peripheral device. This setup is depicted in Fig. 5. Considering that the applications are identical and belong to the same company (Comp) as also the peripherals do, following NDN naming semantics, packets of the two applications can have different name prefixes as follows: "…comp/dev1/app1…" and "…comp/dev2/app2…". On the other hand, Data packet names from the sensors can look as follows: "…comp/per1/sen1/content…" and "…comp/per2/sen2/content…". In a first stage the Dev1 pairs to the Per1 allowing App1 and Sen1 to interchange messages. During this pairing, a priori key and certificate distribution occur. Afterwards, Sen1 only accepts messages, keys, and certificates under the prefix "…comp/dev1/app1…", belonging to the paired device and application. On the other hand, App1 only accepts messages, keys, and certificates under the prefix "…comp/per1/sen1…", belonging to the desired peripheral sensor. Also, Sen2 and App2 accept only messages under the needed prefixes. By this, the two systems (App1, Sen1) and (App2, Sen2) are paired, allowing each application to communicate with the appropriate sensor [14].

2.1.5 NDN Architecture

The NDN architecture consists of three main Data structures for the management of the ongoing traffic. These three structures are the Pending Interest Table (PIT) (Section 2.1.5.1), the Content Store (CS) (Section 2.1.5.2), and the Forwarding Information Base (FIB) (Section 2.1.5.3). Together PIT, CS, and FIB are responsible for requesting content through Interest messages, as well as for managing and delivering the Data packet from a content provider to the Interest source. In the following, these key Data structures are introduced.

2.1.5.1 Pending Interest Table (PIT)

Every node in NDN has a table called the Pending Interest Table (PIT) (Fig. 6). This Data structure maintains accounting of all forwarded Interest messages that entered a node and are waiting for returning Data. The PIT keeps track of all incoming and outgoing faces for a specific Interest. The term incoming face is used for the network device where the Interest was received, and the term outgoing face is used for the network device through which an Interest packet is forwarded to the network. If multiple Interests for the same content request are received from downstream, only the first one is sent upstream to a potential content source. Therefore, subsequent Interests are aggregated to the corresponding PIT entry. Thus, every PIT entry contains the name of the requested Interest and a set of interfaces, from which the Interest with the same content request has been received. In this way, multiple Interest requests are stored and managed by one PIT entry.

To avoid Interest loops in NDN, the PIT, with the help of some randomly set nonces, achieves regulatory loop control. The tuple of content name and the randomly set nonce are globally unique. Therefore, this tuple is used to identify looping Interests when they are compared against every PIT entry.

When a forwarded Interest packet gets to a node that holds the content, the Data is sent back according to the stored information in the PIT of each node. Every time a Data packet reaches a node that has a pending Interest request for this Data, it is forwarded according to the PIT entry. Because the Data follows the entries in the PIT, on the way downstream, it does not loop. When a pending Interest message then has been fulfilled, by the transmission of the corresponding Data downstream, the PIT entry that the Data message followed is deleted. Each traversed node will then cache the traversing Data packet in the Content Store (CS), according to a defined caching strategy.

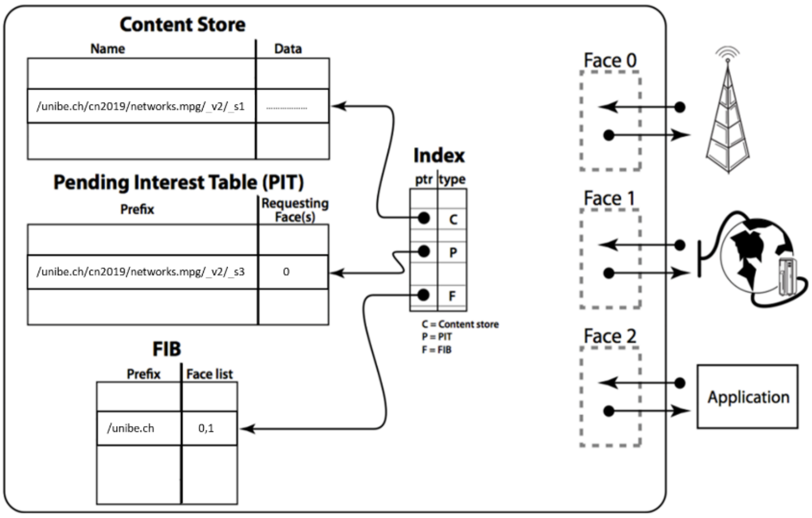


Figure 6 : Key Data Structures in NDN Nodes [5]

2.1.5.2 Content Store (CS)

The Content Store (CS) (Fig. 6) is the second key Data structure located in each node. The CS serves as a cache for transient Data packets. The CS is basically a buffer memory in today's routers. A difference of NDN's CS against buffers of IP routers is that an NDN node can reuse Data to serve different requesting devices. This is a main advantage that NDN has over the TCP/IP architecture, providing an all-time available, growing in-network storage. Because Data is identified according to their name and do not belong to a specific requester, it is reusable for further needs. If an incoming Interest, demanding for a content, reaches a node with the appropriated cached Data, instead of being forwarded upstream to the network, it can be satisfied by the node’s CS. In this manner, NDN minimizes the demanded upstream bandwidth and the downstream latency. Fewer Interests are forwarded to the original content. To prevent cache overflows or growth at infinite, different replacement policies for cached Data exist. Current replacement strategies are focusing on Least Recently Used (LRU) or Least Frequently Used (LFU). Furthermore, not all the Data is cached, only solicited Data will be held for further use. This means that unsolicited Data packets that were not requested are not stored in the CS.

2.1.5.3 Forwarding Information Base (FIB)

The Forwarding Information Base (FIB) (Fig. 6) is the third key Data structure in an NDN node. The FIB table holds information about potential content holders in the network. A FIB entry consists of a prefix and a face list, corresponding to a received Data message. This information is subsequently used for Interest forwarding in the upstream process (Fig. 7). By performing longest prefix match, while comparing the requested Interest name with the FIB entries’ name, a node can determine where the Interest must be forwarded to reach a possible content source. The FIB is always checked after no PIT entry has been found. If the prefix is not found in the FIB, then the Interest is treated according to the implemented strategy. Therefore, it can be dropped or, likewise, forwarded. If there is an entry with a prefix match in the FIB, the PIT is updated, and the Interest is forwarded upstream through the specified outgoing face to reach a previously known content holder.

2.1.6 Interaction among PIT, CS and FIB

Fig. 6 shows the interaction of the mentioned three key Data structures (PIT, CS, FIB). On the right-hand side, some network interfaces are displayed. In NDN, these network interfaces are abstracted as faces. Applications of a node usually also have additional faces for forwarding, generating or requesting Data. The three key Data structures have their own incoming and outgoing faces. Incoming faces and outgoing faces represent source and destination of the respective messages. In Fig. 6 an Interest is received through an incoming face and a corresponding PIT entry is created. In this example, the prefixes of CS, FIB and PIT entries are all related to each other. The FIB contains the forwarding destination for content belonging to unibe.ch. Every new Interest that matches this prefix is, therefore, forwarded through a FIB's outgoing face. In the example, there is a FIB entry containing the requested prefix and the affiliated faces "0" and "1". The PIT contains an entry for segment "s3" of an mpg file, which cannot be fulfilled by the CS that contains segment "s1" of the same content. This means that the Interest is forwarded according to the FIB and is pending for a Data to return. When the Data comes back it is sent to the requesting PIT face "0" and stored for further requests to the CS. Now, the CS also contains segment "s3" for further requests.

2.1.7 Forwarding Interest and Data

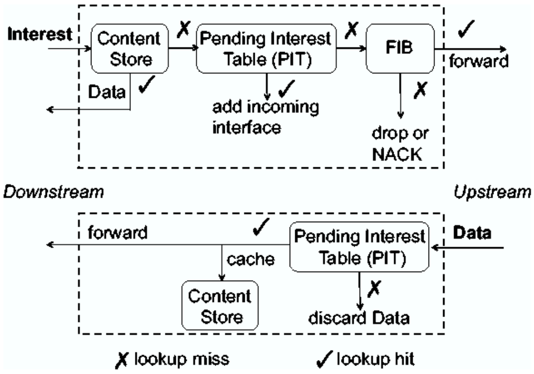


Figure 7 : Forwarding Plane in NDN [12]

Fig. 7 gives an overview of Interest and Data forwarding. Two directions for message forwarding are considered, the upstream and the downstream way. During the upstream way, which is the way from a requester to a content holder, an Interest message is forwarded through different intermediary nodes until it reaches a content source. Generally, an Interest is created from a consumer application in a requester node, and then it is forwarded to the network. When an Interest enters a node, the CS, PIT and FIB entries are checked, as shown in Section 2.1.6. When no CS entry has been found, and there is a match in the FIB table, the Interest is forward upstream towards a known destination. In this case, the PIT must be updated with the information of the newly pending Interest that was forwarded through the FIB's information. If an Interest remains unsatisfied within a certain period, it is not retransmitted from intermediate nodes. The requester is, therefore, responsible for re-expressing the unsatisfied Interest request. This way a requester node can control its traffic by not sending out all the Interests at once.

When a Data packet finally arrives at a node, it is sent out the downstream way to the original requester. This happens according to the already stored faces, left back in the PIT table. In this manner, incoming faces of the previously processed Interests become outgoing faces for the Data message on the way back to the requester. Only solicited Data is forwarded. If the PIT does not contain the corresponding prefix, the Data is discarded after entering the node. Traversing Data packets are cached in the intermediate node's CS, for further reuse, before being sent out. Therefore, also VANETs benefit from in network decentralized Data caching and replication mechanisms of the NDN architecture [8].

2.2 NDN in VANETs

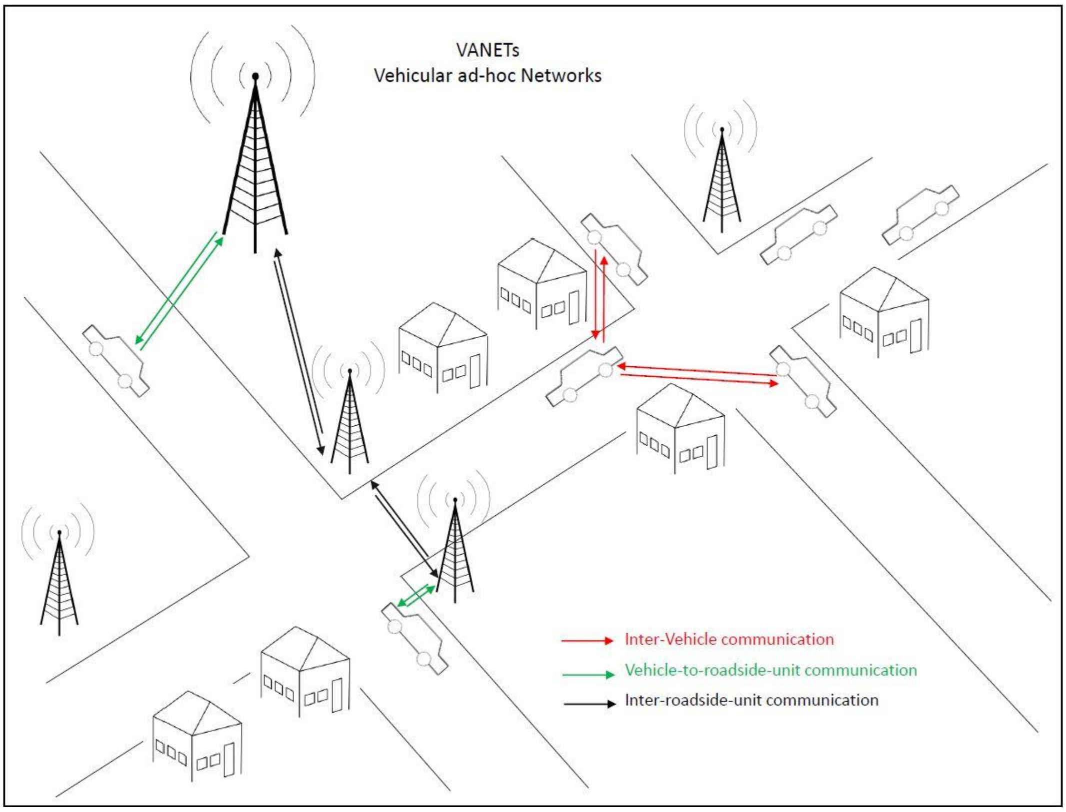


Figure 8 : VANETs Example

Vehicular Ad-hoc NETworks (VANETs) are networks with highly mobile network devices. These network devices can be cars, motorcycles or others. They are all part of a dynamic network system (Fig. 8). In some cases, static devices, like RoadSide Units (RSU), are embedded in the topology of these mobile environments. A large variety of applications, like safety warnings in case of accidents, information dissemination e.g., parking lots availability, traffic/weather conditions, fuel prices or even bus times can be spread over

VANETs. More and more, VANETs can and should additionally offer commercial, informative and entertainment services like file sharing, web browsing and video streaming [15].

The TCP/IP model originally designed for static network topologies [4] addresses a host-to-host based routing where secured paths are maintained during the whole communication period. In such highly mobile environments like VANETs, paths may break. In this case, communication can stop under the use of the end-to-end principle of TCP/IP. If paths to new content sources providing the same content are discovered, TCP/IP is not capable to seamlessly resume, due to various handover mechanisms. Host based communication may also overload servers if popular content is requested simultaneously by many users. NDN, as an alternative, addresses these problems. NDN in-network caching suits vehicles that can store information and move. In this manner, they carry information within and beyond network areas. Providing the content to other different requesters or allowing vehicles to seamlessly resume their previously broken content retrieval. Content, therefore, is clearly identifiable and routed in a one-hop manner. Hence the TPC/IP problem is eliminated [16].

VANETs are prone to very dynamic topologies. Vehicles can move at different speeds towards various locations. In case of vehicles traveling on roads, the maximum speed can be indicated by speed limits and the road management can control the directional propagation leading to a sort of predictable flow of moving vehicles. This does not guarantee at all a stable network topology. Due to vehicles moving at different speeds, or having different transmission ranges, connections can break before the Data reaches the content requester or subsequent Interest requests reach the producer. Receiver mobility in VANETs is addressed by [17] proposing an Auxiliary Forwarding Set (AFS) that takes additional factors into account, like expected content delay, average speed and distance to next forwarder. If then partitioning is probable, eligible vehicles are selected, towards which Data messages are forwarded. In addition to the original forwarder, these can serve as intermediate nodes and fulfil the forwarding of the Data.

On the other hand, also Source Mobility must be addressed to guarantee a good Interest Satisfaction Ratio. For this problem, a zonal model is proposed in [18], in which nodes leaving a certain area must forward their content before leaving it. In this manner, content remains in this area. Therefore, a fixed home router can be used as a static storage point in the area. To be able to address the general problem of low vehicle density, a delegation to RSUs allows the forwarding of Interest and Data.

Another zonal approach is Navigo [19], which steers Interests towards specific locations where Data resides. Data messages and their name are coupled with so called ''Geographic Faces'', which are mappings to geographic cluster on the map, where the Data originally is coming from. Therefore, with the help of a specialized Dijkstra algorithm, which has the street topology as underlying graph, Interest messages are steered towards these geographic clusters. On the other hand, the presented Geographical aware Routing Protocol (**GaRP**), sends Interest and Data messages directly to moving vehicles according to their location.

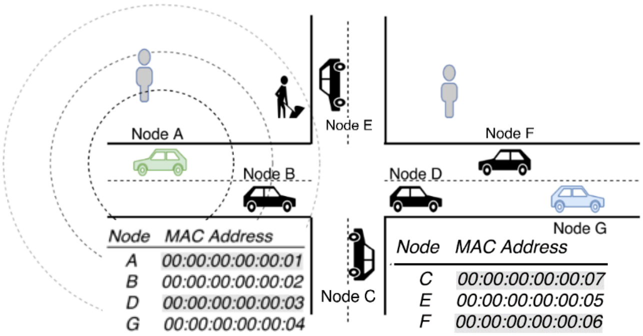
Further, to guarantee faster Data delivery and address a bad usage of network resources due to message retransmissions an improved Multihop, Multipath and Multichannel Vehicular NDN forwarding protocol (iMMM-VNDN) for VANETs, based on [20] is proposed in [9]. This protocol is the underlying protocol for this thesis, and is presented in the next section.

2.3 Improved Multihop, Multipath and Multichannel Vehicular NDN Forwarding Protocol

The improved Multihop, Multipath and Multichannel Vehicular NDN forwarding protocol for NDN-VANETs (iMMM-VNDN) aims to release network resources by minimizing the possible transmissions in nodes. IMMM-VNDN exploits several paths to achieve faster content retrieval [9]. Therefore, messages are distributed according to information that these paths provide. Those paths are discovered in a network flooding phase by using newly introduced unique identifiers, the target, and origin MAC address. In a second phase, these known paths are used for message interchange.

One new field used for iMMM-VNDN, the Target MAC Address (TMA), shows the MAC address to which Interest and Data messages will be forwarded (next hop). Another new field, the Origin MAC Address (OMA), represents the network device address of the Interest or Data forwarder (previous hop). The TMA and OMA, during iMMM-VNDN, are directly extracted from the strategy layer at the time of incoming messages, and then stored to the respective FIB and PIT entries. The forwarding mechanism of iMMM-VNDN is explained in the next two Sections (2.3.1 and 2.3.2).

2.3.1 Flooding Phase

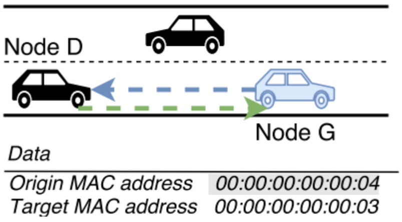


Node	MAC Address
A	00:00:00:00:00:01
B	00:00:00:00:00:02
D	00:00:00:00:00:03
G	00:00:00:00:00:04

Node	MAC Address
C	00:00:00:00:00:07
E	00:00:00:00:00:05
F	00:00:00:00:00:06

Figure 9 : Flooding, iMMM-VNDN [9]

In the beginning, nodes do not know where content sources are located in the network. Therefore, also the FIB tables of the nodes are empty. In order to populate the FIB with information about next hops towards possible content sources, the flooding phase is initiated. Now, the consumer broadcast an Interest towards the network. Fig. 9 illustrates the flooding phase, initiated from node A requesting a content and, therefore, broadcasting an Interest. During the broadcast phase, no TMA is known. The nodes only know their own MAC address. Node A has the following MAC address [00:00:00:00:01]. Each time an Interest message arrives at a node, the OMA of the previous node that forwarded the Interest, is extracted from the strategy layer and stored in the node’s PIT entry. Subsequent, if nodes do not provide the content and have no entry in to their FIB, the Interest message is broadcast. At this point, only the OMAs are known from every forwarder of the Interest.



Data	
Origin MAC address	00:00:00:00:00:04
Target MAC address	00:00:00:00:00:03

Figure 10 : Message Sending with TMA and OMA, iMMM-VNDN [9]

When a content holder has been found, in Fig. 10 depicted by node G, the Data can be sent back downstream according to the breadcrumbs left in the PIT. The destination of such a Data message is the OMA of the node that sent the Interest. Fig. 10 shows that node G sends a Data message towards this address, for node G the TMA [00:00:00:00:03]. This TMA belongs to node D. Therefore, node D would not ignore the Data message. If a message is received by a node with TMA not matching its own MAC, the message is dropped. On the way downstream, every intermediate node check if a PIT entry for the Data exists and if the TMA matches its own MAC address. Otherwise, as mentioned before, the Data message is discarded. Afterwards, the node extracts the OMA of the Data forwarder and adds it to the corresponding FIB entry. This entry then represents the TMA for subsequent Interest requests. The Data message is then forwarded downstream according to PIT. This process is repeated until the content reaches the original requester, for example in Fig. 9, node A. After the flooding phase finishes, the nodes' FIB entries look as shown in Table 1. Supposing that node E and F also received the Interest and forwarded it towards the producer node G, therefore, they also received the Data message from node G and sent it back towards node A. Therefore, the Data is sent via multiple nodes back to node A. This is also evident in the FIB of node A that received the Data message from Node B and E.

Table 1 : FIB after Flooding, iMMM-VNDN

Node ID	Own Mac	FIB next hops (TMA)
A	[00:00:00:00:01]	[00:00:00:00:02] [00:00:00:00:05]
B	[00:00:00:00:02]	[00:00:00:00:07]
C	[00:00:00:00:07]	[00:00:00:00:03]
D	[00:00:00:00:03]	[00:00:00:00:04]
E	[00:00:00:00:05]	[00:00:00:00:06]
F	[00:00:00:00:06]	[00:00:00:00:04]
G	[00:00:00:00:04]	-

2.3.2 Forwarding According to the FIB

When the first Data has reached the initial content requester, routes to content holders are already discovered. Now the requester can send out a second Interest. Therefore, Node A checks its FIB entries. The FIB at this moment can possibly contain multiple next hop entries for a given content request. The FIB of node A contains two possible next hops for further Interest sending. Thus, iMMM-VNDN combines the subsequent two approaches to select one route (TMA). To ensure homogenous traffic distribution, the least used TMA is selected first. To know which TMA was last used, a counter field is added to the FIB. On the other hand, to ensure fast transmission rates, the TMA with the lowest latency is used. The latency is, therefore, also stored in the FIB as shown in Table 2. If there are multiple FIB entries with the same counter, the FIB entry with the lowest latency is selected. Once the designated TMA is selected, the Interest messages are sent out. No broadcasting of messages occurs during this phase. Subsequently, every node receiving the new Interest, updates its PIT, selects the appropriate TMA from the FIB, and forwards the Interest message by unicast. Forwarding of Interest and Data now occurs according to the green and blue arrows in Fig. 11.

Table 2 : FIB Additional Fields, iMMM-VNDN

Node ID	FIB next hops (TMA)	Latency(ms)	Counter
A	[00:00:00:00:02] [00:00:00:00:05]	700 350	0 0

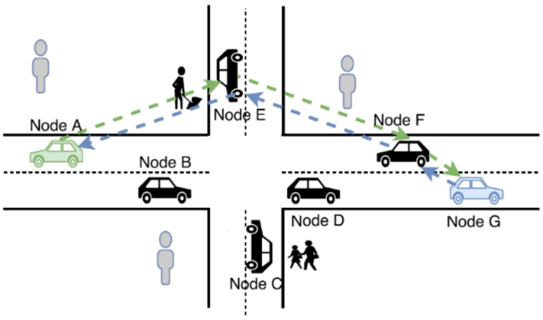


Figure 11 : Path, iMMM-VNDN [9]

Since the topology in VANETs is constantly changing as shown in the preceding Section 2.2, these established paths can easily break. To discover new paths or to discover better paths, iMMM-VNDN repeats the flooding phase every 10 seconds. In this manner, the FIB entries are regularly populated with new and active connections.

3 NDN Simulation Environment

Named Data Networking (NDN) requires extensive evaluation through experimentation. Therefore, adequate simulation tools are needed that enable experimentation at scale, in a short reproducible and cheap accessible way. In this thesis, the GNU GPLv2 licensed, ns-3 discrete-event network simulator platform (ns-3) is used. The ns-3 core infrastructure enables research on IP and non-IP based networks. On top of this ns-3 platform an open source NDN simulator, ndnSIM is used. The first version, ndnSIM v1 was released in 2012, and the second version in 2015, ndnSIM v2 [21]. NdnSIM 2.4 is the latest available version at the moment of this thesis. The subsequent sections describe the ns-3 antenna abstraction and the ndnSIM simulator design with its key elements.

3.1 Antenna Abstraction

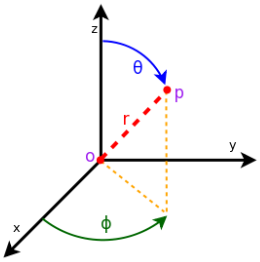


Figure 12 : Antenna Model Coordinate System [22]

The antenna module that is used during the simulations for this thesis in ndnSIM, is part of ns-3. It provides a base class interface, the AntennaModel. This interface provides a radiation pattern open for modelling of different antenna types. Fig. 12 shows the coordinate system of the AntennaModel obtained by translating Cartesian coordinates to the new origin 'o', representing the position of the antenna. Every point 'P' is transformed from the Cartesian $[x, y, z]$ coordinate system to spherical $[r, \theta, \phi]$ coordinates. The coordinate r denotes the radial component, which is neglected in the ns-3 antenna model. The angle θ is the polar angle and the azimuth is the angle ϕ. The ns-3 antenna model neglects the r component and only considers the two angle components $[\theta, \phi]$. An antenna radiation pattern is then expressed as a mathematical function $g(\theta, \phi) \rightarrow R$ that returns the gain (in dB) for each possible direction of transmission/reception (Equation 1). All angles are expressed in radians. Three different radiation patterns have already been implemented in ns-3 at the moment of this thesis. These three patterns are the

IsotropicAntennaModel, the CosineAntennaModel, and the ParabolicAntennaModel. This thesis uses the ParabolicAntennaModel. This model is based on the parabolic approximation of the main lobe radiation pattern. The antenna gain in dB is determined as in Equation 1:

$$g_{dB}(\phi, \theta) = -\min\left(12\left(\frac{\phi - \phi_0}{\phi_{3dB}}\right)^2, A_{max}\right)$$

Equation 1 : Antenna gain in dB in ndnSIM (ParabolicAntennaModel)

In Equation 1, the azimuth orientation of the antenna is denoted by $'\phi_0'$, and the 3 dB beamwidth by $'\phi_{3dB}'$. The maximum attenuation in dB of the antenna is denoted by A_{max}. As shown in Equation 1, the inclination angle $'\theta'$ is not used, therefore, the radiation pattern is independent of the inclination angle $'\theta'$ [22].

3.2 NdnSIM Design Overview

Fig. 13 shows the basic components of ndnSIM 2.4. The ndnSIM core consists of the ndn::L3Protocol, which is an abstraction of the NDN stack implementation. This protocol starts the NDN Forwarding Daemon (NFD) and links it to the ndnSIM specific application layer. The NFD itself links other abstractions, for instance, the nfd::Face performs best effort delivery for NDN network layer packets. The three key NDN Data structures are the Pending Interest Table (Section 2.1.5.1) nfd::PIT, an abstraction for logging and receiving Interests. The Content Store (Section 2.1.5.2) nfd::Cs that serves as an in-network cache. The Forwarding Information Base (Section 2.1.5.3) nfd::FIB, is responsible to forward the Interest towards known content sources. The Forwarding Strategy nfd::fw::* is a collection of several helper algorithms. These algorithms determine the way of forwarding an Interest message [23].

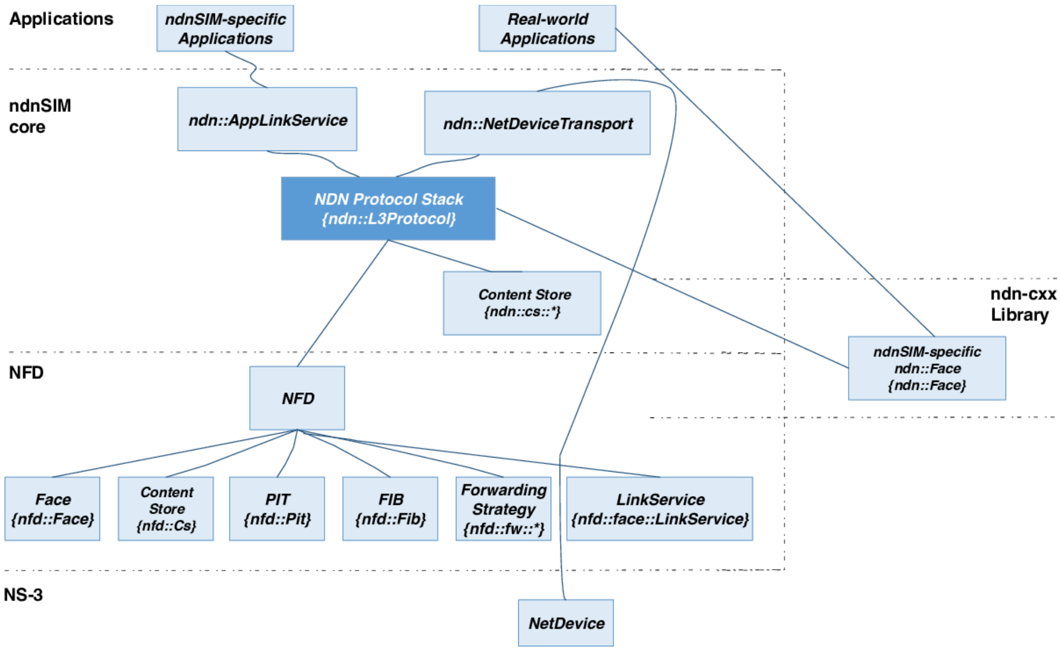


Figure 13 : Design Overview of ndnSIM [24]

3.2.1 Pending Interest Table (PIT) Abstraction

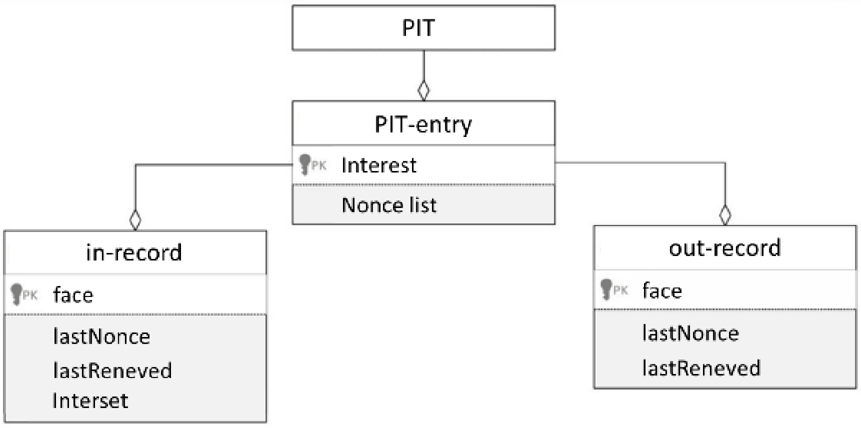


Figure 14 : PIT Abstraction [24]

As shown in Section 2.1, the Pending Interest Table (PIT) (Fig. 14) contains references to Interests that were forwarded upstream towards the network. Every PIT entry represents a uniquely, by its content name identifiable, forwarded Interest. Interests having the same name prefix share the same PIT entry. The incoming or outgoing face of the Interest are added to the PIT in- and out-record. The lastNonce field is a randomly generated integer number that helps to prevent loops. In addition to the nonce field, the in- and out-record fields contain an expiration timer that triggers if an Interest is resent or if it is dropped according to the prevailing policy.

3.2.2 Forwarding Information Base (FIB) Abstraction

The Forwarding Information Base (FIB) (Fig. 15) is a lookup table to determine the best forwarding choice for upstream outgoing Interests. FIB entries represent previously discovered content sources. Each of those entries store a name prefix corresponding to the solicited Data packet. Subentries of a FIB entry are called next hop records. These records specify a forwarding destination route for Interests. For every Data from a different content source, corresponding to the same Interest request, a next hop entry is added to the FIB entry. The best next hop outgoing face (there can be multiple) is, therefore, selected according to a metric, here the cost field. The selected next hop's face is then used as the outgoing face for subsequent upstream Interest forwarding.

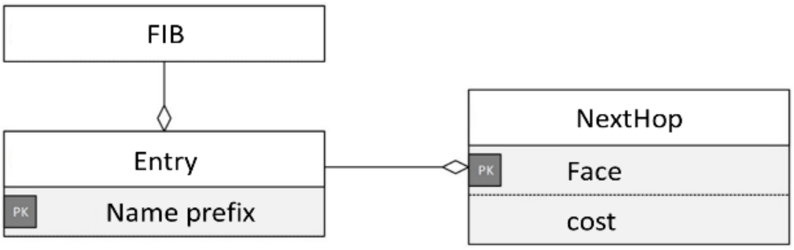


Figure 15 : FIB Abstraction [24]

3.2.3 Content Store (CS) Abstraction

As shown in Section 2.1, the Content Store (CS) is a key element of the NDN architecture that allows transient Data to be stored in the node itself for further use. It serves, therefore, as an in-network Data cache. The CS provides distinct cache replacement policies for different invocation moments like after insert or before erase. At the moment, there are two policies implemented in ns-3: Last Recently Used (LRU) and Last Frequently Used (LFU) [24].

3.2.4 Forwarding Abstraction

The forwarding abstraction implements decisions regarding the Interest forwarding strategies. It decides if, when, and how an Interest should be forwarded to a given destination. In ndnSIM, the forwarding abstraction features an interface, the strategy API, that provides a clean, modular implementation for strategies. Then, the implemented strategy, as a decision maker, steers the mechanisms of the forwarder class and has an impact on the entire process of Interest and Data dissemination.

3.3 NDN Forwarding Daemon (NFD)

The NDN Forwarding Daemon (NFD) implements the NDN protocol. All the formerly mentioned abstractions, as described in Section 3.2, are coordinated and implemented within the NFD. The NFD evolved with the NDN platform and became one of its crucial core components [25]. The forwarding daemon is responsible for the correct processing of packets within the ndnSIM. With this responsibility, the NFD is directly involved in the forwarding process of Interest and Data packets as well as the maintenance of the PIT, FIB and CS. The NFD packet processing consists of forwarding mechanisms, the so-called pipelines, which are a series of steps and operations triggered by a specific event. These events can be, for instance, a reception of an Interest packet or others. When such an event is triggered, it is then passed to the forwarding strategy that is attached on the incoming and outgoing side of each pipeline. The strategy then makes decisions whether, when and where to forward messages [24].

Fig. 16 shows an overview of all forwarding pipelines managed by the NFD. The white boxes describe decision points for the selected strategy and the blue ones represent different pipelines that are triggered during the diverse forwarding steps. Pipelines manage Data, Interest and NACK packets coming from the underlying network layer or the overlying applications. Each packet is passed from one pipeline to another according to the implemented strategy. There are two timers available during the message processing, the straggler and the unsatisfy timer that manage the lifetime of Interests in the PIT. For example, the straggler timer keeps alive a PIT entry for a brief time period after it has been satisfied or rejected. This mechanism helps for further loop control. On the other hand, the unsatisfy timer can expire and trigger the *Interest Unsatisfied pipeline*. Processing Interest, Data, and NACK differs, leading to various main processing paths each. Those paths are briefly explained in this section.

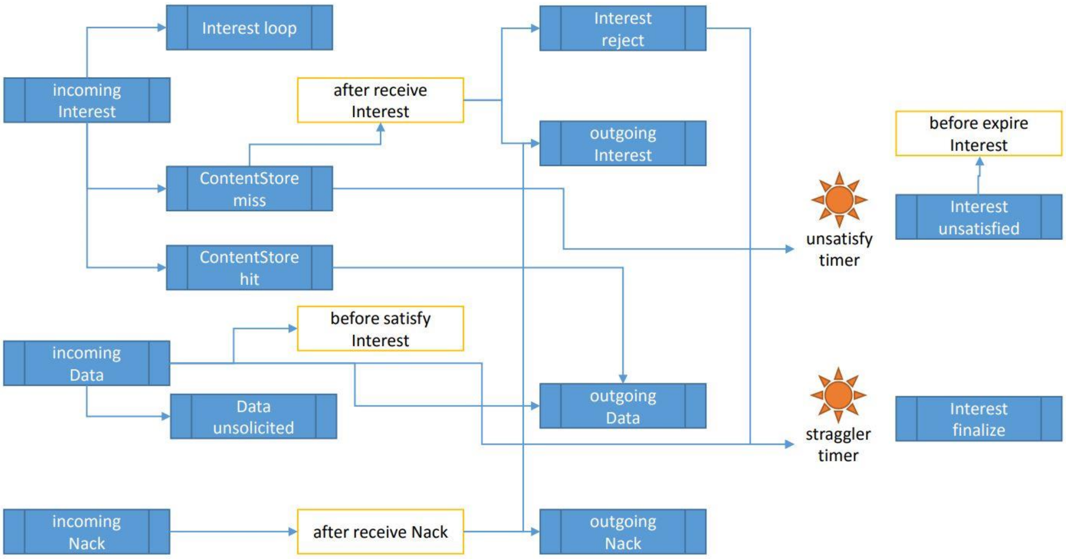


Figure 16 : Forwarding Pipelines in NFD ndnSIM [24]

The Interest Processing Path is split up in the following forwarding pipelines, each triggered by its own event:

- *Incoming Interest pipeline*, when an Interest reaches a node. The Interest enters the node through a face ready to be processed.
- *Interest Loop pipeline*, when an incoming looped Interest is detected.
- *Content Store Miss pipeline*, when an incoming Interest cannot be satisfied by a CS match.
- *Content Store Hit pipeline*, when a prefix match refers to Data in the CS and, therefore, the Interest message does not need to be forwarded.
- *Outgoing Interest pipeline*, when an Interest is prepared to be sent out to the network.
- *Interest Reject pipeline*, when an Interest is rejected by the strategy.
- *Interest Unsatisfied pipeline*, when an Interest unsatisfy timer runs out and the Interest is prepared to be deleted.
- *Interest Finalize pipeline,* when the Interest is deleted from the PIT.

On the other hand, the Data Processing Path*,* the Data messages are sent back through intermediate nodes to the original consumer that produced the Interest. The Data packets follow the breadcrumbs downstream left in the PIT during the forehand mentioned Interest Processing Path*.*

The following pipelines can be triggered and traversed by a Data packet during the Data Processing Path.

- The *Incoming Data pipeline* is triggered through an incoming Data packet that needs to be processed. This pipeline then also triggers the following three pipelines.
    - The *Unsolicited Data pipeline* processes Data not intended for the node.
    - The *Outgoing Data pipeline* processes Data for each pending downstream.
    - The *Interest Finalize pipeline* removes Interest from the PIT.

4 Geographical aware Routing Protocol

The goal of this thesis is to extend the existing improved Multihop, Multipath and Multichannel Vehicular NDN forwarding protocol (iMMM-VNDN) for vehicle-to-vehicle communication in NDN-VANETs, introduced in [9]. The contribution of this work consists in the addition of location information into the main NDN Data structures, to further lower the network traffic in particular regions. Therefore, the Geographical aware Routing Protocol (**GaRP**) sends messages towards designated geographical locations, with the help of parabolic antennas. The changes made to the various Data structures and the Interest and Data messages to implement the Geographical aware Routing Protocol are shown during the following sections of this chapter. An overview of the interaction of these Data structures is provided in Section 4.3.6.

4.1 Problem Description

The underlying iMMM-VNDN routing protocol cares about the destination of the forwarded messages, in terms of the 'who' but not the 'where'. The iMMM-VNDN protocol uses MAC addresses of every node in the network to uniquely identify surrounding vehicles. In addition, by the broadcast nature of Wi-Fi itself, the problem of having network traffic in particular regions, where no traffic is needed, persists. With the help of parabolic antennas and the usage of geographical position information, **GaRP** tries to minimize this traffic created through the flooding of information in a radial way. Therefore, **GaRP** sends out messages only to regions where receivers are located. Once this is achieved, fewer collisions will occur, and the overall network traffic should lower.

4.2 Design of GaRP

This section shows up some design decisions made for **GaRP**. It is explained how geographical directed message sending is achieved. Therefore, the NS-2-Trace-file as the underlying moving mechanism of ndnSIM nodes is introduced. Then, with the help of those, the design for the future position estimation and propagation is explained.

4.2.1 Mobility Prediction

In real life, cars are mostly equipped with GPS modules. With their help, vehicles can know their own position at any time. Also, we assume, that navigation systems can estimate future locations of vehicles according to a set route. In this work, this fact is simulated. This is done by means of specially arranged and statically available sequences of commands, according to which nodes move in the system. These movement sequences are special files, the NS-2-Tracefiles. An NS-2-Tracefile is a text file that describes initial Cartesian coordinates and further positions of the simulated nodes. A trace file entry specifies where a node will be at a given time. This leads to the fact, that a node position can be predicted with 100% accuracy by just reading out its coordinates from the NS-2-Tracefile at a given time. The ns-3 network simulator also provides the possibility to set up a desired static and moving topology given the preformatted NS-2-Tracefiles. Because of the simplicity in their structure, we use the NS-2-Tracefiles in this thesis [26].

4.2.2 Parabolic Antennas

In order to overcome the inherently 360° radial broadcast nature of the wireless communication, **GaRP** uses parabolic antennas to achieve high directivity of message sending towards designated network areas. Thus, **GaRP** sends messages only towards a given direction with limited radiation. A trade-off between the beamwidth, representing the main opening lobe of the parabolic antenna and the gain level, exists. The higher the achieved gain is, the narrower is the beam of the antenna and thus, its coverage area. In a realistic scenario, placing 36 or even more antennas on a vehicle seems unrealistic, because something like that would create huge interferences in the node. Another possibility would be to use MIMO antennas to adapt to particular angles. But in this thesis we choose to install directional antennas in vehicles. Therefore, every **GaRP** node is equipped with four network devices, each. In every network device, there is one parabolic antenna installed. These parabolic antenna devices are then arranged in a fixed radial way to cover 360°.

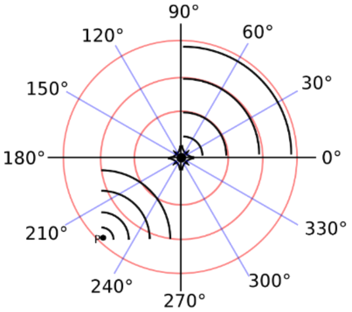


Figure 17 : Exemplary Parabolic Beam 90°

Each of the four parabolic antennas uses a beamwidth of 90° to cover a quarter of the possible reachable area (Fig. 17). With this beamwidth of 90°, and a power of 20 dBm approximately 100m transmission distance is achieved, which seemed a good middle course for the used one-hop vehicle-to-vehicle communication. Only one of the four antennas at a time transmits a message towards the network. This is shown by the circular segments going away from the centre. Thus, permitting the others to sense the ongoing network traffic, like the traffic from the point ‘P’. The right antenna that points towards the destination is chosen as shown in Equation 2, according to a trigonometric calculation. The calculation considers the target and source two-dimensional Cartesian coordinates of vehicles on the map.

$$Target\ direction\ in\ degrees = toDegrees\left(arcTan\left(\frac{x_{source} - x_{futureTarget}}{y_{source} - y_{futureTarget}} \right) \right)$$

Equation 2 : Angle Calculation Parabolic Antenna

The variables x_{source} and y_{source} in Equation 2 indicate the actual [x, y] two-dimensional Cartesian coordinates of the sending node. This information is read out directly from the simulation map with the help of the ns-3 network simulator. In real life, that can be done by the help of the GPS navigation system in a car. On the other hand, the variables $x_{futureTarget}$ and $y_{futureTarget}$ describe the target node’s [x, y] two-dimensional Cartesian coordinates on the map at a future time. This ‘futureTarget’ coordinates are both directly read out at runtime from the NS-2-Tracefile before every message sent. Therefore, sending nodes can read out the information from obtained Interest and Data messages. With the help of this ‘futureTarget’ information, it is possible to know where a message receiver is situated in a later moment.

Once calculated, the target direction in degrees indicates the angle to the destination node, related to the position and orientation of the sending source node. When a message sender is ready to send a packet towards a designated destination, this sender chooses the appropriated antenna covering the desired angle of the target direction in degrees. Every outgoing message then contains a future location information of the sending node, also directly obtained from the trace file. The mentioned 'futureTarget' coordinates must be sent over the network from one node to another. Therefore, Interest and Data messages, as well as the FIB and the PIT tables, are manipulated as it is described in Section 4.3.

4.3 Implementation

To achieve **GaRP**'s geographical directional message sending, we made several changes on the provided ndnSIM simulation environment, as well as the underlying iMMM-VNDN. This section describes these changes made to the exchanged packets, the interacting data structures, and the used protocols. Finally, an example in Section 4.3.6 depicts the introduced work.

4.3.1 Additional Object in Data and Interest Packets

In order to transmit the retrieved position information during **GaRP**, a Future-Position Object is created. This object contains the future position information and is inserted in the Data and the Interest messages. Therefore, the Future-Position Object is added from every node to the respective message packets before they are sent out (Fig. 18). The location represents the future location of a vehicle one second ahead. This Future-Position Object has the following fields, all directly read out of the underlying NS-2-Tracefile:

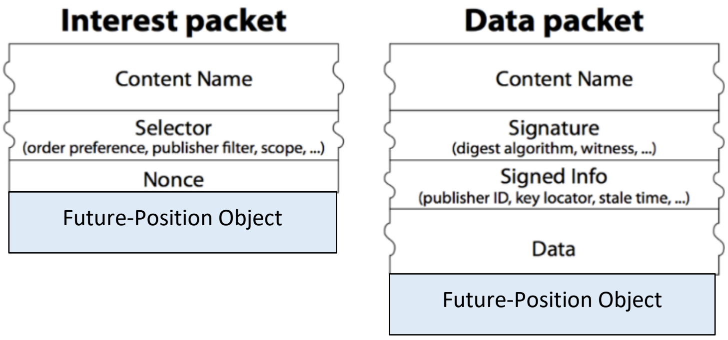


Figure 18 : Future-Position Object in NDN Messages

- (double) futurePosition_X
- (double) futurePosition_Y
- (double) speed
- (double) timeAtFuturePosition
- (double) isPositionSetFromFile

The futurePosition_X and futurePosition_Y fields indicate the two-dimensional Cartesian coordinates [x, y] of a point on the map, where the forwarder will be located at a given time frame. The speed of the vehicle is stored in the speed field. The field timeAtFuturePosition carries the expected arrival time at the future position. To ensure that this location information is set from the underlying trace file and does not contain the initialization values from the constructor method, the container carries the flag isPositionSetFromFile. Every time this container is filled up by reading out position information from a trace file, the flag is set to one, else it would be zero and signals that the position information was not set from a trace file. When a message then reaches a node, the Future-Position Object is read out to populate the FIB and/or the PIT. Therefore, once future location information is stored in these two tables it can be used for further processing and for forwarding of Data and Interest packets.

4.3.2 Changes to NDN Routers

The NDN consumer is an application installed in a node that requests content by generating Interest messages towards the network. In order to let surrounding nodes know, where the requester moves after it sends an Interest, the application adds the node’s own future position information to the Interest. The application, therefore, modifies the Interest before it is forwarded. Three steps are needed for this modification.

1. The NS-2-Tracefile is read out to get the future position at a requested time.
2. The position is written to a new Future-Position Object.
3. The Future-Position Object is added to the outgoing Interest.

The above steps are performed every time before an Interest is sent out by the application. Subsequently, when an Interest reaches any intermediate node, the above steps are repeated before the Interest is forwarded. Therefore, every node that sends out Interest messages adds its own future position information to the Interest message.

4.3.3 Forwarding Information Base (FIB) Extension

The FIB in NDN is the data structure that holds information about known potential content providers. It contains various entries that belong to a designated previously fulfilled content request. Every FIB entry has a name prefix that is associated with a list. This list is called next hops and contains information on the next node the Interest should be sent to find the corresponding Data. If an incoming Data packet contains a content name that matches a pending Interest in the PIT by longest prefix match, a next hop entry is created or updated for every subsequent incoming Data matching this prefix. In this manner, the next hop list provides an aggregation of all next hop nodes for one content prefix.

The underlying routing protocol for this thesis, iMMM-VNDN [9], extracts the MAC address from the previous node that forwarded the Data message, and adds it to the FIB. This MAC address is stored in the next hop list and represents the target address to which subsequent Interests are sent out. Therefore, the FIB provides the necessary information, like the MAC address to select the desired node to unicast the Interest. In this state, the next hop entry does not contain the necessary geographical position information to select one of the four parabolic antennas.

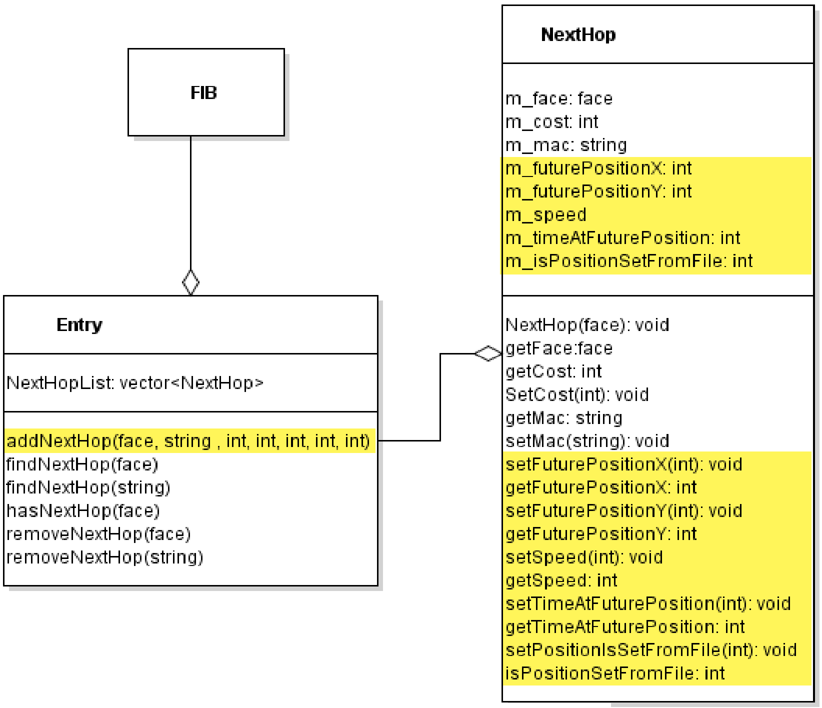


Figure 19 : FIB Extensions

Therefore, the change made in this thesis to the FIB, consists of an extension of the next hop fields. The FIB entry class now provides methods to add next hops with their respective future position information fields. Once set, the FIB-Next hop class allows accessing this position information, allowing **GaRP** to target geographical location with the selection of a respective parabolic antenna. Fig. 19 shows the new structure of the FIB table. Highlighted are the new fields that are added to the original FIB structure.

4.3.4 Pending Interest Table (PIT) Extension

The PIT, the Data structure that holds the basic information about where to send Data messages to nodes downstream to the network, is also extended to hold the future position of the targeted node. Every PIT entry is uniquely identified according to the longest prefix match of the incoming Interest. The underlying routing protocol for this thesis, iMMM-VNDN [9], extracts the MAC address of the incoming Interest previous hop and adds it to the corresponding PIT entry. This MAC address represents the target address to which subsequent Data messages are forwarded downstream to reach the content requester. Therefore, the PIT provides the necessary information like the MAC address to select the desired target node. In this state, the PIT in-record entry does not contain the necessary geographical position information to select one of the four parabolic antennas (Section 4.2.2).

The new fields in the PIT table are as depicted in Fig. 20. Therefore, Fig. 20 shows in highlighted lines what is new to the original PIT Data structure. These additions allow entering or updating the Interest with the needed information to the respective PIT entry. The PIT now takes a Future-Position Object (Section 4.3.1) as input parameter, and adds it to the corresponding PIT entry. When a Data packet arrives from upstream for further forwarding these records are checked. Thus, there is a newly added Future-Position Object in the PIT entry, which represents the future position of the next node to forward a Data message to reach the content requester. At this point, the Data message is sent out downstream, according to this position, by selecting one of four parabolic antennas of the node. In order to do this, the forwarder node calculates the angle between the newly added destination’s future position (PIT in-record) relative to its own current position according to Equation 2 in Section 4.2.2. Then the node sends out the Data downstream through the respective antenna device covering this angle.

Figure 20 : PIT Extensions

4.3.5 Changes to the iMMM-VNDN Routing Strategy

iMMM-VNDN [9] makes decisions whether, how, and to whom to forward an Interest packet. After receiving an Interest message, it needs to be processed by adding the node's future position information. The iMMM-VNDN strategy operates in two phases, a flooding phase and a forwarding phase based on the FIB and the PIT. These two phases are illustrated in Section 2.3. During the flooding phase, the surrounding network topology is discovered. Therefore, Interest messages are broadcasted hop-to-hop until a content source is reached.

GaRP, throughout the flooding phase, the PIT is populated with the respective future position information of the node that forwarded the Interest. After a content source is discovered, the Data is sent back according to the previous populated PIT entries. During the traversing of Data messages, the FIB next hop entries are populated with the future position information of each previous node that forwarded the Data message. When the Data have reached the consumer node, paths have been established. The communication now uses **GaRP** to send further Interest messages to selected geographical target locations [x, y].

The following four changes are made to the underlying iMMM-VNDN forwarding strategy to support the above-explained communication mechanism. The relevant steps are illustrated in Fig. 21:

1. After receiving the Interest, the node modifies the received Interest by adding its own future position information. Then, the target MAC is checked.
2. If the Interest's target MAC is not broadcast, it has a designated destination. Therefore, there exists a target MAC entry in the Forwarding Information Base of the previous forwarder. This means that the Interest is sent intentionally to this node. In consequence, this node has the Data or the appropriate information for further processing the Interest. If the Data is not available at this node, the current node's and target node's coordinates are extracted from the mobility model and the FIB, respectively. Otherwise, the Interest is broadcast with the Future-Position Object containing the forwarder future geographical location.
3. This target node's coordinates information is processed, together with the actual position, to determine the designated antenna pointing to the Interest destination node according to Section 4.2.2.
4. Finally, the Interest is sent out through the chosen parabolic network device towards the geographical region of the potential content provider.

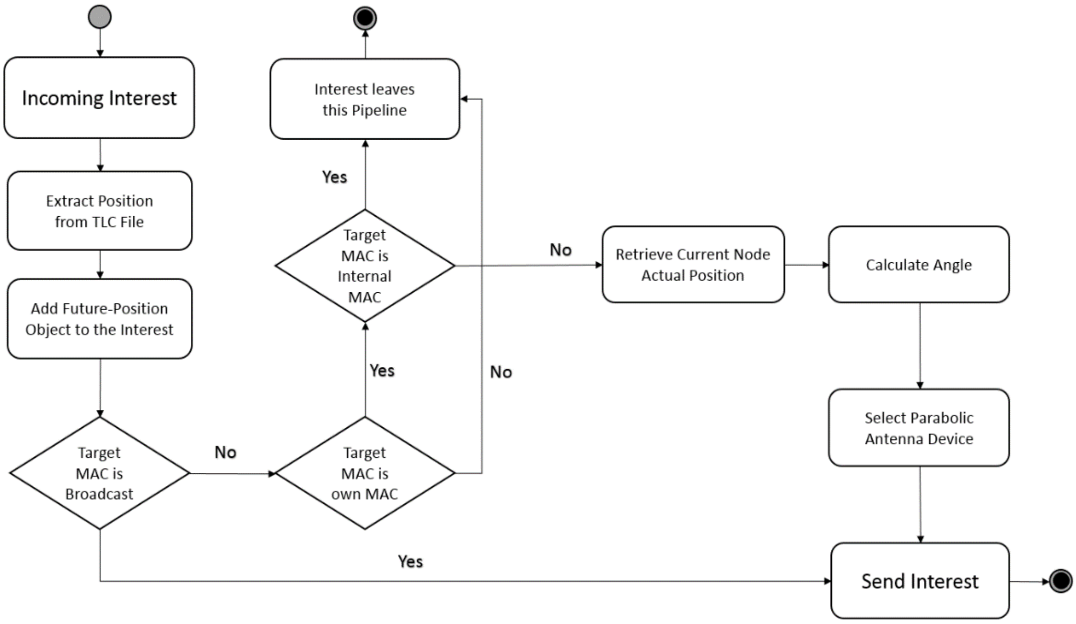


Figure 21 : GaRP Interest Forwarding

Once an Interest message arrives at a node that provides the appropriate Data, the Data must be sent back to the content requester. Therefore, the Data packet travels the way back according to the breadcrumbs left from upstream propagating Interest messages. Four main changes are made to the Data Forwarder class illustrated in Fig. 22:

1. When an incoming Data packet arrives, the origin MAC address is checked. If the origin MAC address is not an internal one and a PIT entry exists, the future position information is extracted from the Data, and for further upstream traffic, stored to the FIB next hop list. At this stage of **GaRP,** the Data should be forwarded to all pending downstream nodes, according to the existing PIT entries.
2. Otherwise, there is no existing previous Hop Future-Position Object in the Data packet, because the Data is original of the node itself. In this case, it is directly forwarded according to the PIT.
3. Before sending the Data out to a pending downstream, the correct parabolic antenna must be selected. Thus, the angle between the target future position, extracted from the PIT, relative to the current node's actual position is calculated according to Section 4.2.2.
4. To this end, Data receivers also want to update their FIB's with the location of the content provider. Therefore, the Data forwarder adds its own future position information to the Data message and sends it out through the selected parabolic network device.

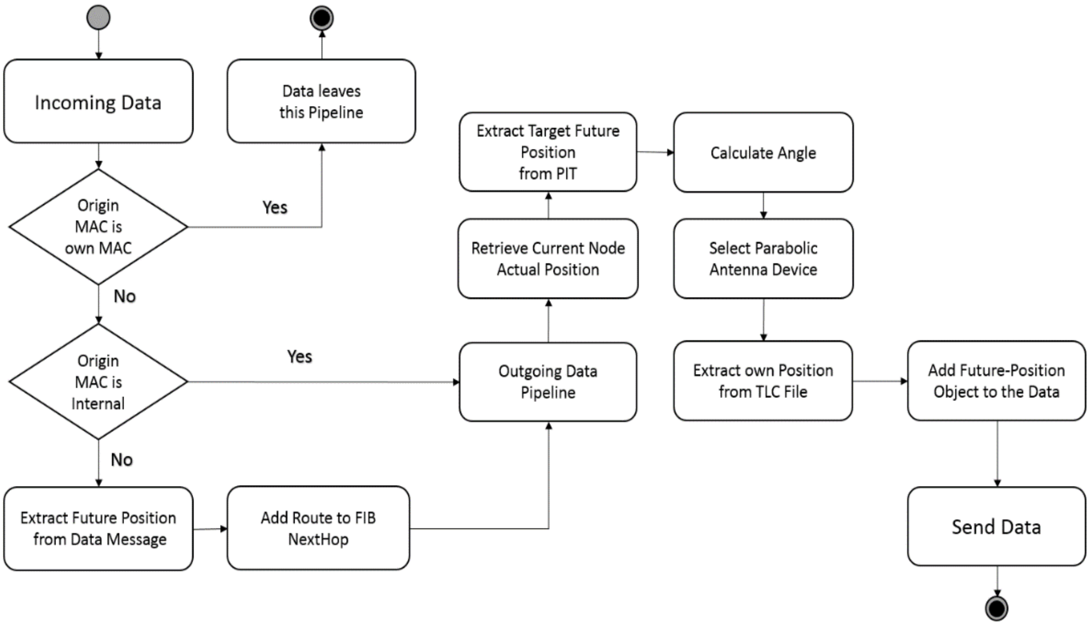


Figure 22 : GaRP Data Forwarding

4.3.6 Example of the Geographical aware Routing Protocol in NDN-VANETs

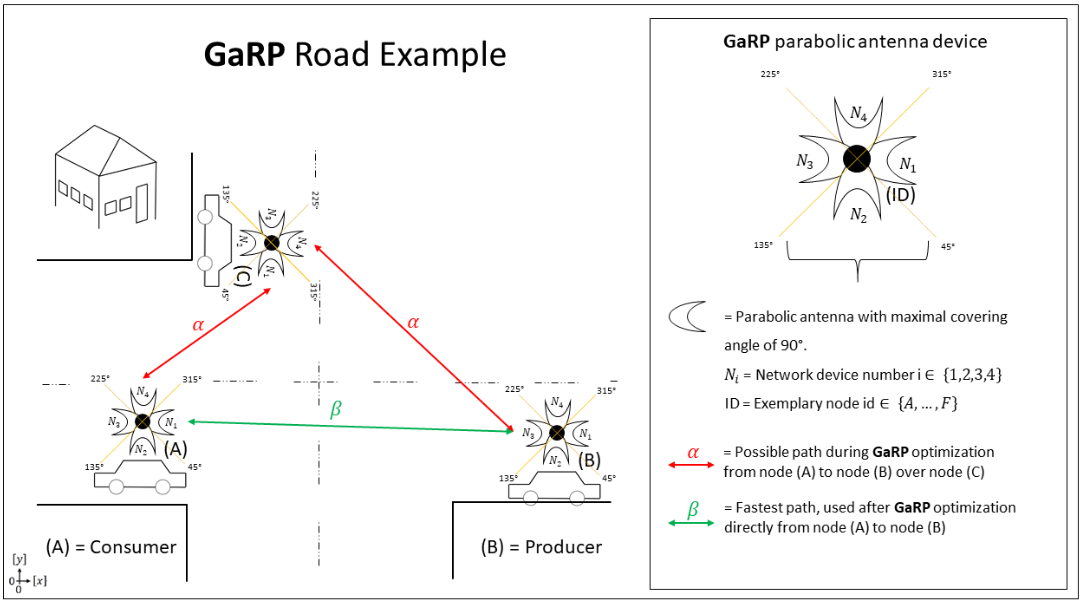


Figure 23 : GaRP Road Example Overview

Fig. 23 shows an example of the Geographical aware Routing Protocol (**GaRP**) in NDN VANETs. This figure shows a very simplified topology with 3 vehicles. The functioning of **GaRP** would be the same for topologies with any number of nodes. Every vehicle carries four parabolic antenna network devices illustrated by the crescents (N_1-N_4). Each of those antenna devices has its own network interface device. The main lobe of each antenna is set to cover an angle of 90°. Therefore, every node is capable to send and sense traffic within a radius of 360°. In this example node (A) has installed the consumer application and acts as the content requester, depicted on the left. On the right, node (B) is the producer that provides the content. However, node (C) is neither consumer nor producer but acts as an intermediary node between node (A) and node (B).

For simplicity, during the next explanations, the MAC addresses of the network devices are replaced as follows. For example, the MAC address 00:00:00:00:01 belonging to node (A)'s network device N_1 is replaced with (A) N_1.

In a first stage of the communication, the nodes must learn their surrounding one-hop topology. This is equivalent to the flooding phase of the underlying iMMM-VNDN strategy mentioned in Section 2.3. Therefore, the requester node (A) broadcasts an Interest to the network. All traversing intermediate nodes subsequently broadcast the Interest. Before an Interest is sent out, every node adds the own future position information to the

Future-Position Object (Section 4.3.1) of the Interest. At this moment all the nodes are broadcasting the Interest on all the network devices as shown in Table 3.

Table 3 : Interest Broadcast

Node ID	Interest Target MAC
(A)	FF:FF:FF:FF:FF
(C)	FF:FF:FF:FF:FF

Whenever an Interest message reaches a node, the information in the Interest packet is extracted and stored to the PIT (Section 4.3.4). These PIT entries now also contain the future location from the Future-Position Object carried in the Interest message. This future location information shows where the downstream requesting node will be in one second. The underlying iMMM-VNDN uses target and origin MAC addresses of network devices, to identify the forwarder of Interest or Data packets. Therefore, the PIT entries do not only contain a future position but also the network device of the incoming Interest forwarder.

The point [X,Y = 0,0] of the Cartesian coordinate system in Fig. 23 is situated in the lower left corner. Coordinates of nodes, like node (A), has the form [x_A, y_A]. In this example, we assume, that Node (A) moves towards position [x_A, y_A]. Node (A), therefore, inserts these coordinates [x_A, y_A] to the Interest message that is broadcasted. Node (B) receives this Interest message. Then, it extracts the [x_A, y_A] coordinates and enters them into the PIT. Additionally, Node (B) updates the PIT with the respective origin MAC. Also, node (C) receives the same Interest from node (A) and updates its PIT table. Node (C) does not have the content and inserts its own future position coordinates [x_C, y_C] into the forwarded Interest message. Node (B), therefore, receives the same Interest request twice. Therefore, during this stage, the PIT of the nodes (B) and (C) look as shown in Table 4.

Table 4 : GaRP, PIT after Flooding

Node ID	Incoming MAC / Origin MAC / Origin future Location
(B)	(B) N_3 / (A) N_1 / [x_A, y_A] (B) N_3 / (C) N_4 / [x_C, y_C]
(C)	(C) N_1 / (A) N_4 / [x_A, y_A]

Table 4 shows that during the flooding phase of **GaRP** a node can have multiple pending destinations for a same content request. Node (B) at this moment has pending Interests towards node (A) and (C). As a content holder, node (B) initiates the next phase of **GaRP**.

After the flooding phase, if the content is discovered in the network, it must be forwarded downstream to the content requester. At this point, the content holder and every node that previously forwarded the Interest has enough information to forward Data downstream, according to its PIT entries. Now the producer node (B) wants to fulfil the Interest request with the associated Data. Therefore, the producer calculates the relative angle to the Data target nodes (A) and (C). This is done according to Section 4.2.2, with the help of its own actual position and the Interest origin future locations [x_A, y_A] of node (A) and respectively [x_C, y_C] of node (C). When the angle has been calculated, the producer can determine which one of its network devices points towards the origin future locations [x_A, y_A] and [x_C, y_C]. Further, a Data packet containing location information of a node is written as follows: Data([x_B, y_B]), for a Data packet containing future location information of Node (B). Before the producer Node (B) can send out the Data packet, it has to modify it to contain its future location, obtaining Data([x_B, y_B]). Producer (B) sends out the Data([x_B, y_B]) towards (A) N_1 and (C) N_4 according to its PIT entry (Table 4). The downstream cascade of the Data packet has started.

When the Data packet arrives at a downstream node, the location information is extracted from the Data, and stored to the FIB table together with the forwarder MAC. Subsequently, every node with a pending Interest, according to Table 4, updates its FIB at incoming Data and computes the outgoing network device towards the successive forwarding destination of the modified Data packet. Finally, the Data packet arrives at the original content requester (A). At this point, the FIB tables of the nodes (A) and (C) look as shown in Table 5.

Table 5 : GaRP, FIB after Data Downstream

Node ID	Outgoing MAC / Target MAC / Target future Location
(A)	(A) N_4 / (C) N_1 / [x_C, y_C] (A) N_1 / (B) N_3 / [x_B, y_B]
(C)	(C) N_4 / (B) N_3 / [x_B, y_B]

Table 5 represents the FIB of nodes (A) and (C). Node (A) received the Data packet from two different nodes, once from node (C) and once from node (B). This leads to two possible paths (α, β), as shown in Fig.23, for Data and Interest propagation from the content requester to the Data source.

GaRP routing does not use all possible routes. To select a designated route, different metrics are used. The underlying iMMM-VNDN chooses the best route according to the newest connection and the latency, a number representing the elapsed time from the outgoing of an Interest, to its fulfilment by an incoming Data packet. We assume that in Fig. 23 the path (α) containing the route over the nodes (A), (C) and (B) has a higher latency as the path (β) using the direct route over the nodes (A) and (B). Therefore, in a second phase, in which only one designated path is used, **GaRP** selects the path (β) for subsequent Interest and Data forwarding.

During the second phase of the protocol, all included nodes in the communication know the best path for message forwarding. Communication between two nodes, therefore, only occurs through designated antennas along the path (β). At this stage of **GaRP**, the relevant PIT and FIB tables entries look like in Table 6 and Table 7.

Table 6 : PIT during GaRP

Node ID	Incoming MAC / Origin MAC / Origin future Location
(B)	(B) N_3 / (A) N_1 / [x_A, y_A]

Table 7 : FIB during GaRP

Node ID	Outgoing MAC / Target MAC / Target future Location
(A)	(A) N_1 / (B) N_3 / [x_B, y_B]

Node (C), now, is excluded from the best path (β) and, therefore, does not receive or produce traffic. This way **GaRP** reduces the traffic overhead in regions where no traffic is needed, namely the geographical regions near node (C).

5 Evaluation and Results

To evaluate the performance of the Geographical aware Routing Protocol (**GaRP**), simulations are executed for static and moving network topologies. Generally, in Wi-Fi networks the overhead creates several problems [27]. Because of this, the Interest Satisfaction Rate (ISR) can decrease significantly. The implemented **GaRP** exploits positions of network forwarders to send messages towards designated topology regions. By this, the protocol addresses network overhead problems in areas where no data traffic is needed. The messages are sent according to the predicted future location of the receiving device and, therefore, do not spread over the entire network. To demonstrate this behaviour, this section presents the evaluated scenarios of **GaRP**.

5.1 Evaluation Metrics and Scenarios Parameters

The metrics that are used to evaluate **GaRP** are:

1. The ISR, the percentage of satisfied Interest messages at a given time.
2. The number of delivered Data messages to the consumer at a given time.
3. The Interest retransmissions as the number of Interest messages the consumer node expressed.
4. The traffic as the total number of sent and received messages by a node.

All tests run with the same simulation parameters listed as follows in Table 8:

Table 8 : Scenarios Parameters

Parameter	**Value**
Phy Model	Wi-Fi 802.11a
Transmission Power	20 mW
Speed Propagation Delay Model	ConstantSpeedPropagationDelayModel
Distance Propagation Loss Model	TeeLogDistancePropagationLossModel
Propagation Loss Model	NakamiPropagationLossModel

Data Payload Size	1200 kb
Content Store Replacement Strategy	Least Recently Used
Content Store Size	10’000 packets
Interest Transmission Rate	10 packets/sec
Interest Lifetime	4 seconds
Number of Antennas per Node	4
Future Position After	1 second
GPS Accuracy	+/- 0m
Path Reconfiguration After	10 seconds

All nodes, in all presented strategies, have four network devices. The reason is to guarantee fairness with respect to the following tests presented in chapter 5. As mentioned in the previous chapter, each **GaRP** node has also four network interfaces equipped with a parabolic antenna each, all four together covering 360°.

5.2 Simulation

This section presents the simulation scenarios. Three different scenarios are used to evaluate the performance of **GaRP**. These scenarios consist of a nine node moving and static topology, and a 40 nodes moving Manhattan topology. Finally, the results of **GaRP** are compared against iMMM-VNDN, the Multicast, and the Best-Route routing protocol.

5.2.1 Topology with Nine Static Nodes

For our first topology, we choose a static scenario with nine static nodes to evaluate the performance of **GaRP**. The simulation runs for 100 seconds. The initial topology with nine static nodes is shown in Fig. 24. This is the initial position of the nodes before the simulation starts. It shows various vehicles not moving because of a traffic accident. We call the presented topology as shown in Fig. 24 as the static nine node scenario.

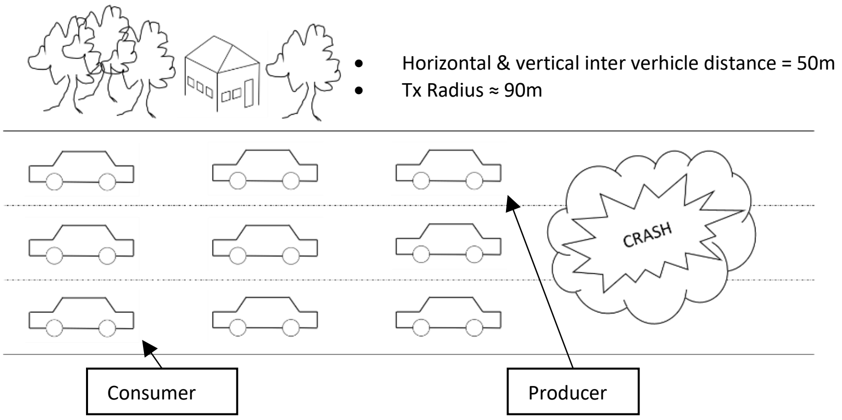


Figure 24 : Static Nine Node Scenario, Initial Topology

This scenario consists of nine nodes, uniformly arranged, on a three-lane street. The producer is in front of the upper lane, and the requester is at the end of the lower driving lane. The requester runs the consumer application. The other nodes serve as intermediate nodes for the Interest and Data propagation in the requester-producer interaction.

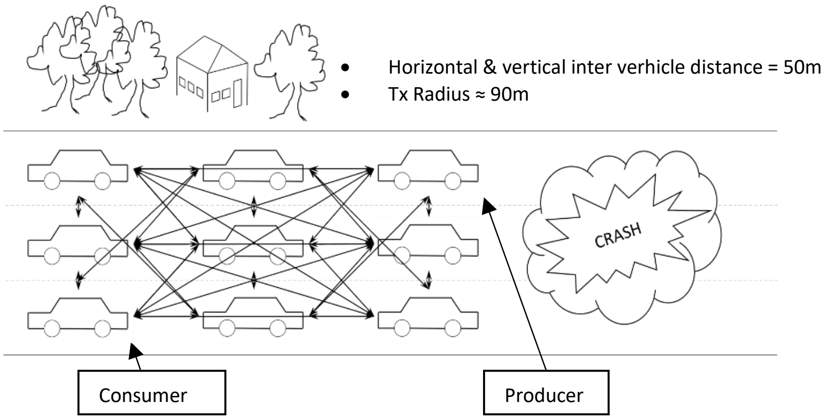


Figure 25 : Static Nine Node Scenario, No GaRP Path

Fig. 25 and Fig. 26 show the two different states of the static nine node scenario. During **GaRP**'s flooding phase (Fig. 25), the requester broadcasts an Interest into the network. Intermediate nodes also broadcast the Interest (arrows). At this point, the FIB entries do not contain any information. When the FIB and the PIT are populated with the according up- and downstream position information, the network traffic changes its state from Fig. 25 to Fig. 26. Therefore, Fig. 26 shows that paths are learned (arrows), and the designated parabolic antennas are used. Nodes that are part of the learned path no longer broadcast messages. They send their messages by unicast and with the help of the parabolic antenna towards the desired vehicle at a geographical location. Furthermore, nodes in regions near the path do not produce network traffic.

In addition, Fig. 25 is an example for the network state during Multicast and Best-Route routing strategy. For these two routing protocols, all the states between the simulation start (at zero seconds) until the simulation finish (at 100 seconds) are the same. This is the case, since these two protocols always send messages by broadcast. Therefore, all the vehicles are constantly involved, and produce traffic.

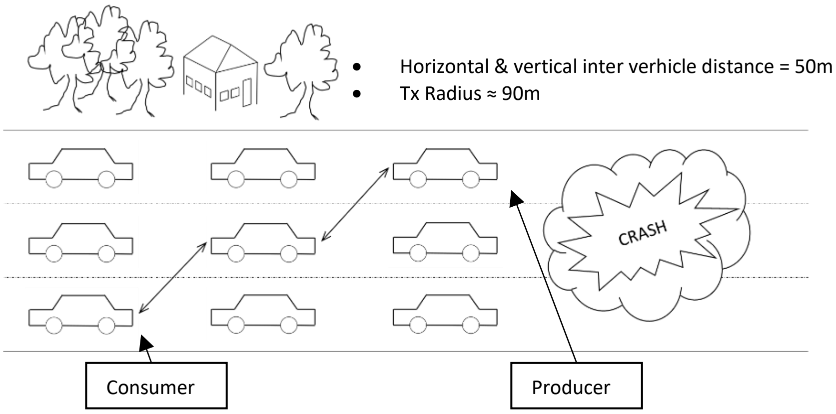


Figure 26 : Static Nine Node Scenario, GaRP Path

5.2.2 Topology with Nine Moving Nodes

To evaluate **GaRP** under a mobile environment, also a scenario with nine moving nodes is simulated. We refer this scenario as the moving nine node scenario. Fig. 27 shows the initial topology before the simulation starts. A traffic jam inspires this topology, where vehicles want to know about the state of traffic. The vehicles in the lanes move at different speeds. In the lowest lane, the vehicles have a constant speed of 20 m/s. In the middle lane, they move with speed 15m/s and in the upper lane, they drive at 10 m/s. The requester in this scenario is the first node from the left in the lowest lane. During the entire simulation, all vehicles move from left to right direction. The requester sends out Interests that are satisfied by the producer, located in a position in front of the upper lane. The other nodes serve as intermediate nodes for the Interest and Data propagation in the requester-producer interaction. During the 100s simulation, the requester node will surpass the producer node. During the simulation of this scenario, the **GaRP** path from the requester to the producer node must change, as shown during the evaluation.

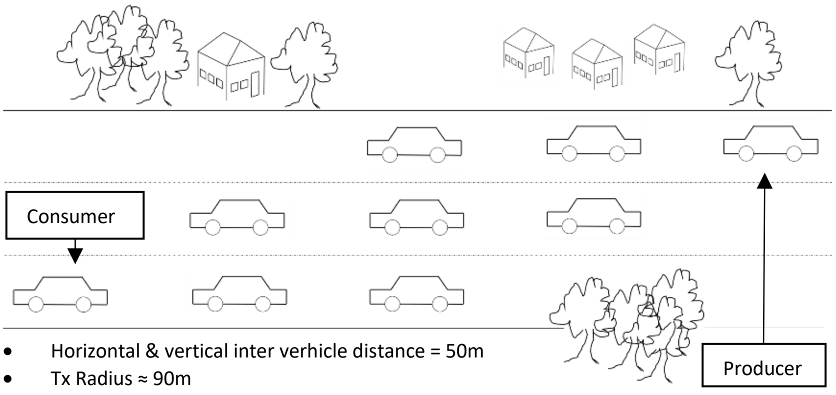


Figure 27 : Moving Nine Node Scenario, Initial Topology

At the beginning of the simulation in the flooding phase, in order to learn the paths, the nodes broadcast an Interest to populate the FIBs and the PITs with the needed future position information of the surrounding one-hop nodes. Fig. 28 and Fig. 29 illustrate the change of the path during the simulation of **GaRP**.

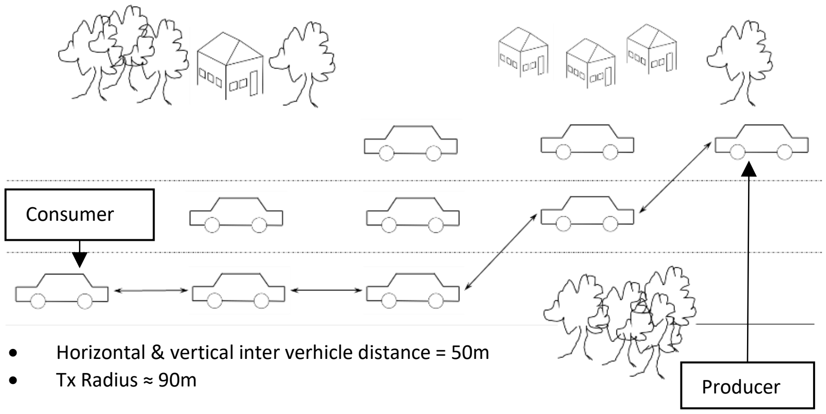


Figure 28 : Moving Nine Node Scenario, GaRP Path

Fig. 28 shows the established path between the producer and the requester nodes after the flooding phase. These two are now communicating through designated intermediate nodes without forwarding the message to nodes that are outside the established route. On the other hand, Fig. 29 shows that the path changes (arrows) when the vehicles move to various positions.

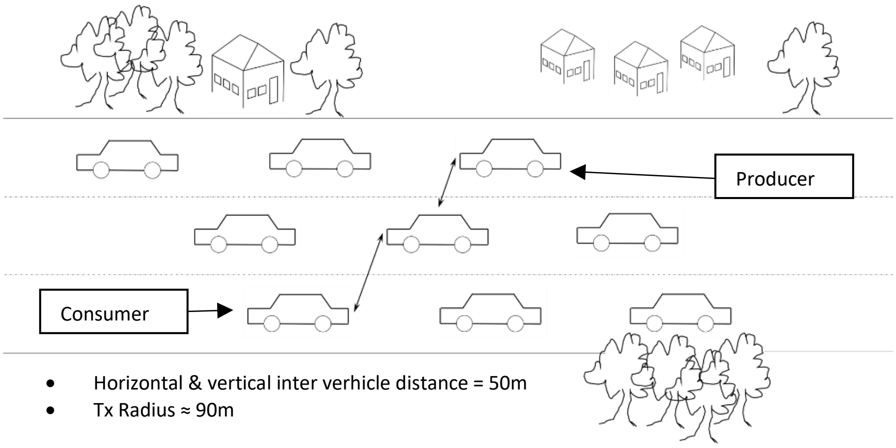


Figure 29 : Moving Nine Node Scenario, GaRP Path Change

5.2.3 Manhattan Topology

To evaluate **GaRP** against iMMM-VNDN in a more complex mobile scenario, we use the Manhattan topology. The Manhattan topology is based on nodes moving across horizontal and vertical streets, like in an urban area. The used Manhattan topology consists of 1km x 1km grid with 40 nodes. We call the presented topology as shown in Fig. 30 as the Manhattan scenario. The left side of Fig. 30 depicts the initial position of vehicles in the Manhattan scenario. Therefore, the vehicles are shown as dots on the grid and the grey lines depict vertically arranged streets. On the right of Fig. 30 an enlarged detail of the framed intersection is shown. During the simulation, vehicles move according to the roads and start and stop at various intersections.

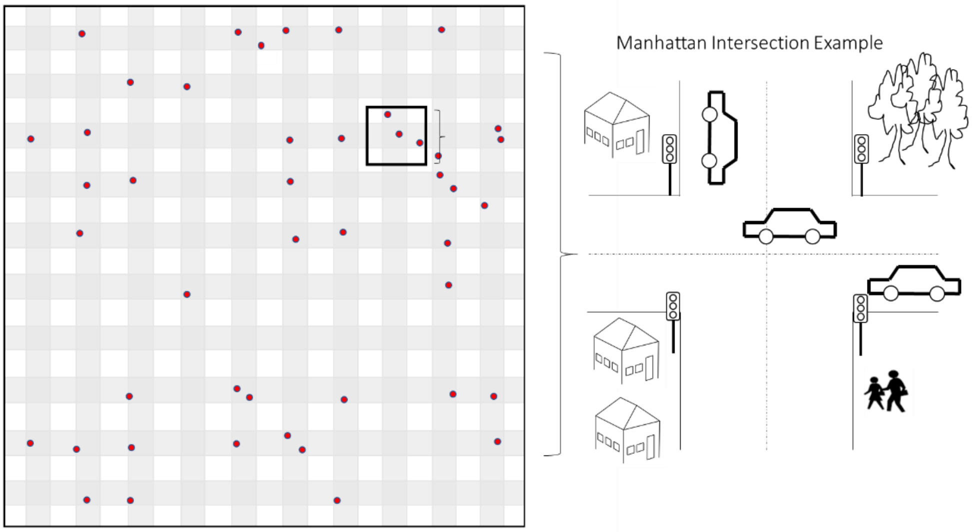


Figure 30 : Manhattan Scenario, Initial Topology and Intersection Example

5.3 Simulation Results

GaRP decreases the number of overall network connections by building up paths with the help of parabolic antennas. This section presents the results of the simulations. Every simulation lasts 100s and is repeated 25 times for each different routing protocol and scenario. **GaRP** is the routing protocol introduced in this thesis. It is compared against Best-Route and Multicast (former Broadcast) routing protocols in a non-modified ndnSIM 2.4. Furthermore, **GaRP** is also compared against iMMM-VNDN protocol (Section 2.3) that underlies it. The first two protocols are not used to compare the results of **GaRP** during the Manhattan scenario. This is the case, because the underlying protocol iMMM-VNDN and **GaRP** are protocols designed for Vehicular Ad-hoc NETworks (VANETs), therefore, only those two are also compared against each other in a more complex scenario. To illustrate the range of fluctuations in the measured results, the diagrams are presented with 95% confidence interval.

5.3.1 Static 9 Node Topology

This chapter presents the results of the static nine node scenario. Therefore, **GaRP** is compared against other in ndnSIM 2.4 implemented routing protocols, the Best-Route and the Multicast (former Broadcast) protocol, as well as, iMMM-VNDN.

5.3.1.1 Interest Satisfaction Ratio (ISR) in the Static Nine Node Scenario

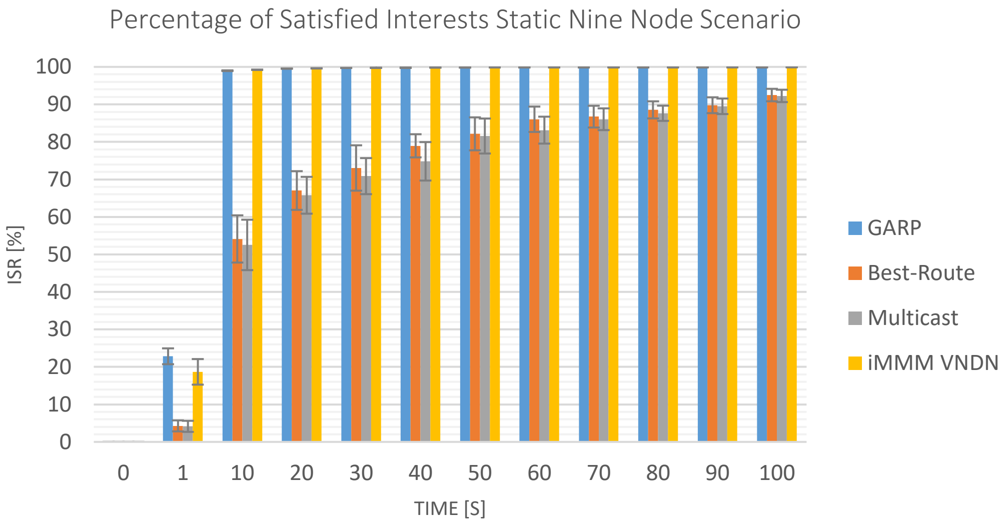


Figure 31 : Static Nine Node Scenario, ISR

Fig. 31 shows the Interest Satisfaction Rate (ISR) in the static nine node scenario. The ISR is the percentage of satisfied Interest messages at a given time. On the X-axis there is the simulation time from 0 seconds to 100 seconds, and on the Y-axis the ISR at the requester node for the given time frame. The standard routing implementations of ndnSIM 2.4 take about half of the simulation time to set up a high stable percentage value. **GaRP** reaches its peak of satisfaction within the first few seconds. Also, iMMM-VNDN performs as well as **GaRP**. The standard routing protocols do never reach the performance of **GaRP** and iMMM-VNDN. Once set up Best-Route and Multicast do not even reach 100% of satisfaction rate and stay at 90%. On the other hand, **GaRP** and iMMM-VNDN achieve and hold 100% ISR from the beginning of the simulations.

5.3.1.2 Number of Delivered Data Messages at the Consumer Node in the Static Nine Node Scenario

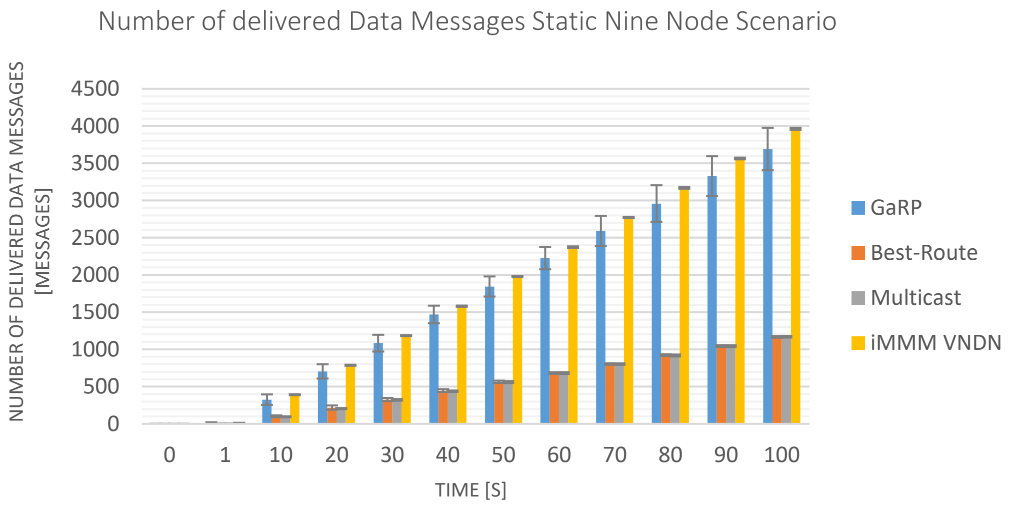


Figure 32 : Static Nine Node Scenario, Data Delivery

Fig. 32 depicts the number of total delivered Data messages, at the consumer node, during the static nine node scenario. The X-axis shows the time in seconds from 0 to 100, and the Y-axis the total number of delivered Data messages at the given timeframe. During the static nine node scenario, **GaRP** and iMMM-VNDN achieve three times more the number of delivered Data, compared to Best-Route and Multicast. **GaRP** performs slightly worse than iMMM-VNDN, it looses on average about 5% of delivered Data. This is the case, but considering the ISR of the two protocols that is depicted in Fig. 31, we see that **GaRP** satisfies all of the Interests of the requester. Thus, the 5% of Delivered Data that **GaRP** looses, do not affect the application performance. The new routing protocol and iMMM-VNDN outperform the standard routing implementations of ndnSIM 2.4, from the beginning.

5.3.1.3 Interest Retransmissions in the Static Nine Node Scenario

Fig. 33 depicts the number of total retransmitted Interest messages during the static nine node scenario. The X-axis shows the time in seconds from 0 to 100, and the Y-axis is the total number of Interest messages the consumer node expressed. Compared to Best-

Route and Multicast, **GaRP** has almost 80% less retransmissions and, simultaneously, it performs better in terms of ISR and total number of delivered Data messages, as shown in the previous two sections. The new routing protocol outperforms the standard routing implementations of ndnSIM 2.4, from the beginning. On the other hand, **GaRP** needs three times more retransmissions than iMMM-VNDN. This happens because **GaRP** sends messages to a known position of a node, even if the node already changed its position. Therefore, if a node did not receive position updates of the next target node that wants to send the message, the node will send and retransmit Interest messages to the next target node's old position until the path reconfiguration happens. Even the fact, that **GaRP** uses more retransmissions than iMMM-VNDN, it achieves almost the same high ISR and Data delivery rates.

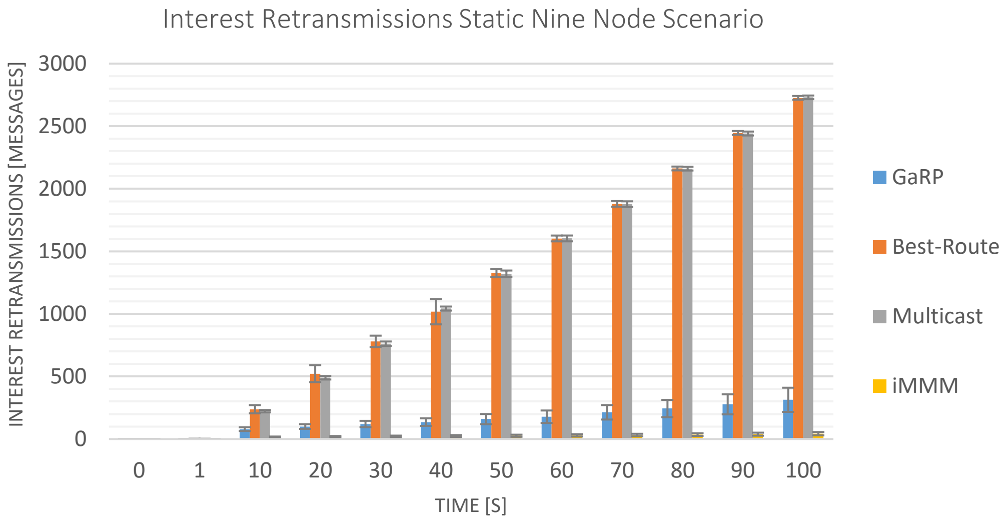


Figure 33 : Static Nine Node Scenario, Interest Retransmissions

5.3.1.4 Traffic Comparison in the Static Nine Node Scenario

Fig. 34 shows the number of total packets sent per node for the static nine node scenario. The X-axis indicates the node ID, and the Y-axis depicts the total traffic per node. The traffic here is the sum over all the received and sent messages of all the network devices for each node. In the static scenario in Fig. 34, node 8 runs the consumer application and requests Data from the network. On the other hand, node 0 has the producer application installed and produces the Data. A **GaRP** node sends less packets than a node using Best-Route or Multicast routing protocol. This is due to the fact, that **GaRP** selects a designated network device to send out Data and does not use all the four network devices simultaneously. Additionally, as shown in Fig. 33, nodes need many Interest retransmissions that flood the network and produce a large amount of traffic for the iMMM, multicast and broadcast strategies. This leads to a higher number of packets sent. In addition, Fig. 34 depicts that node 0 and node 8 are most heavily used by **GaRP,** because these nodes produce Data and request Data. Compared to them, other nodes which are not permanently in the designated **GaRP** route produce less traffic. Compared against iMMM-VNDN, **GaRP** produces less traffic in those nodes not included in the designated path.

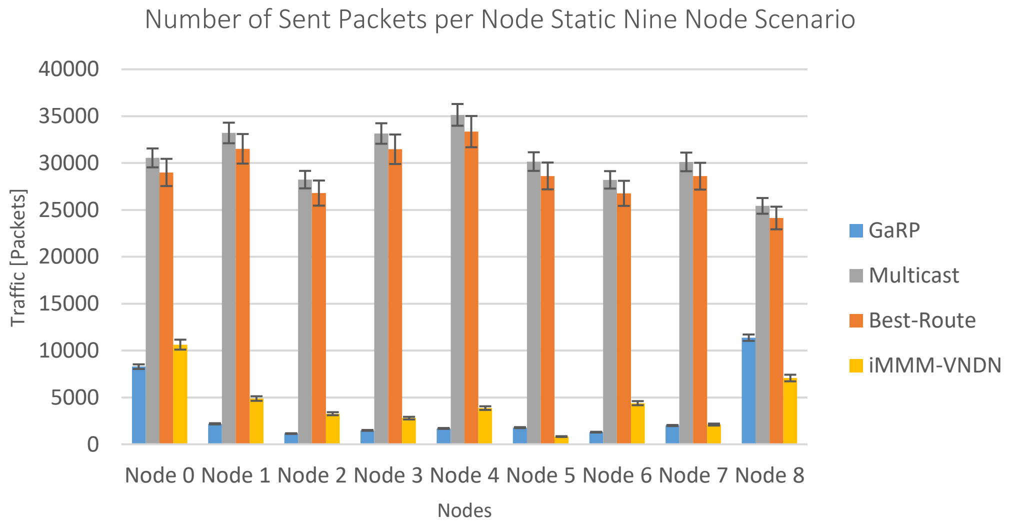


Figure 34 : Static Nine Node Scenario, Packets Sent

5.3.2 Moving 9 Node Topology

GaRP and the underlying iMMM-VNDN are designed for Vehicular Ad-hoc NETworks (VANETs). Therefore, this chapter presents the results of the moving nine node scenario. These protocols are also compared against other standard ndnSIM 2.4 routing protocols, the Best-Route and the Multicast (former Broadcast) protocol.

5.3.2.1 Interest Satisfaction Ratio (ISR) in the Moving Nine Node Scenario

Fig. 35 shows the Interest Satisfaction Rate (ISR) in the moving nine node scenario. The X-axis shows the simulation time from 0 seconds to 100, whereas the Y-axis shows the ISR at the requester node for the given time frame. The standard routing implementations of ndnSIM 2.4, Best-Route and Multicast, perform worse than in the static scenario, as shown in Fig. 31. Best-Route and Multicast only reach 50% of ISR after 70s of simulation time. On the other hand, **GaRP** and iMMM-VNDN reach 100% of ISR after the very first seconds of simulation.

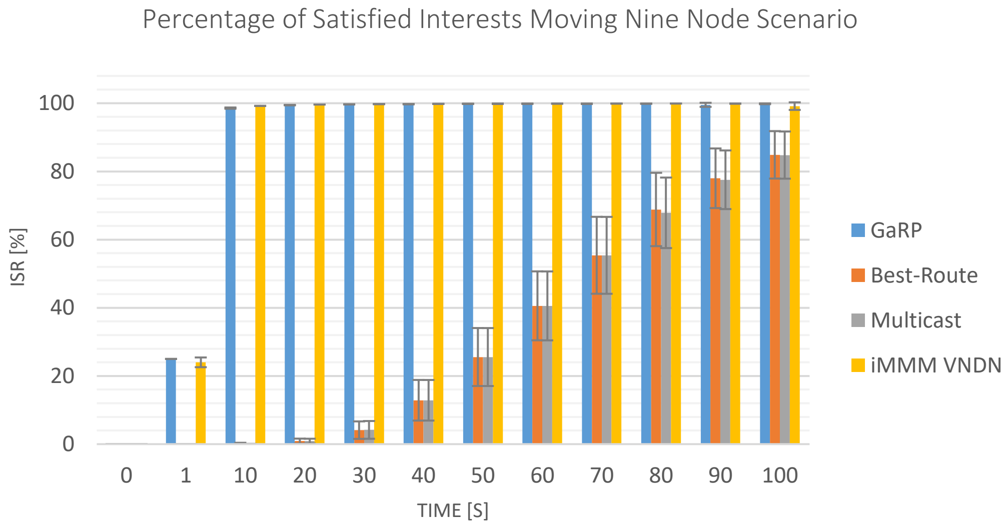


Figure 35 : Moving Nine Node Scenario, ISR

5.3.2.2 Number of Delivered Data Messages at the Consumer Node in the Moving Nine Node Scenario

Fig. 36 shows the number of total delivered Data packets, at the consumer node, in the moving nine node scenario. The X-axis shows the time from 0 to 100 seconds and on the Y-axis shows the total number of delivered Data packets to the requester at the given time frame. For the delivered Data Messages in this moving scenario, the results are similar to the static scenario. **GaRP** achieves three times more the number of delivered Data, compared to the other two standard routing protocols. The Best-Route and the Multicast strategy deteriorated noticeably compared to the static nine node scenario in

Fig. 32. The first Data packet is delivered only after 30 seconds. On the other hand, **GaRP** performs slightly worse than iMMM-VNDN, it looses on average about 5% of delivered Data, like in the static nine node scenario. This is the case, since paths are periodically renewed during **GaRP** to prevent malfunctioning of the protocol. The protocols designed for VANETs reach 400% of delivered Data messages as compared against Best-Route and Multicast. **GaRP** and iMMM-VNDN outperform the standard routing implementations of ndnSIM 2.4, from the beginning of the simulation.

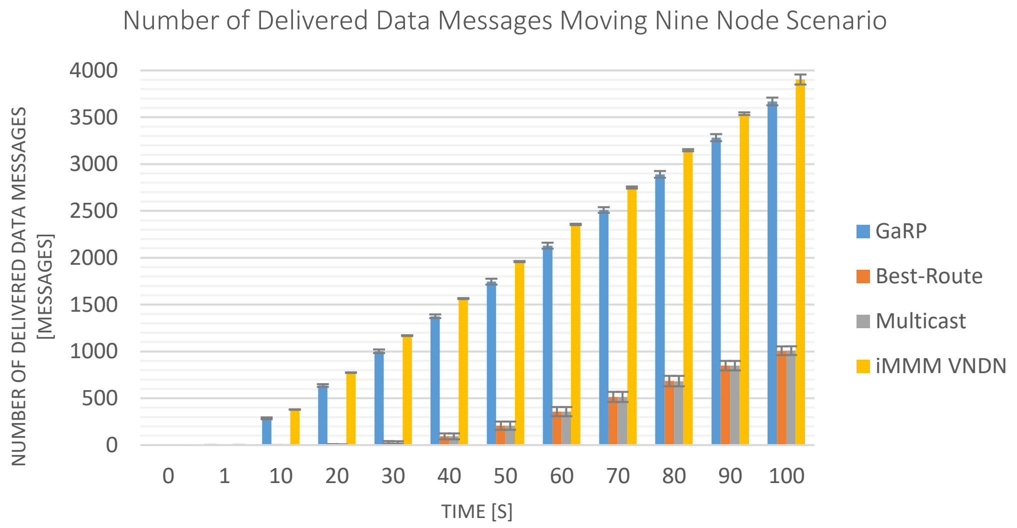


Figure 36 : Moving Nine Node Scenario, Data Delivery

5.3.2.3 Interest Retransmissions in the Moving Nine Node Scenario

Fig. 37 depicts the number of total retransmitted Interest messages during the moving nine node scenario. The X-axis shows the time in seconds from 0 to 100, and the Y-axis is the total number of Interest messages the consumer node expressed. Fig. 37 shows similar results as shown during the nine node static scenario (Fig. 33). Multicast and Best-Route are outperformed by the two protocols designed for VANETs. On the other hand, iMMM-VNDN performs again slightly better than **GaRP**, as also shown during the static nine node scenario. Even the fact, that **GaRP** uses more Retransmissions than iMMM-VNDN, it achieves almost the same high ISR and Data delivery rates.

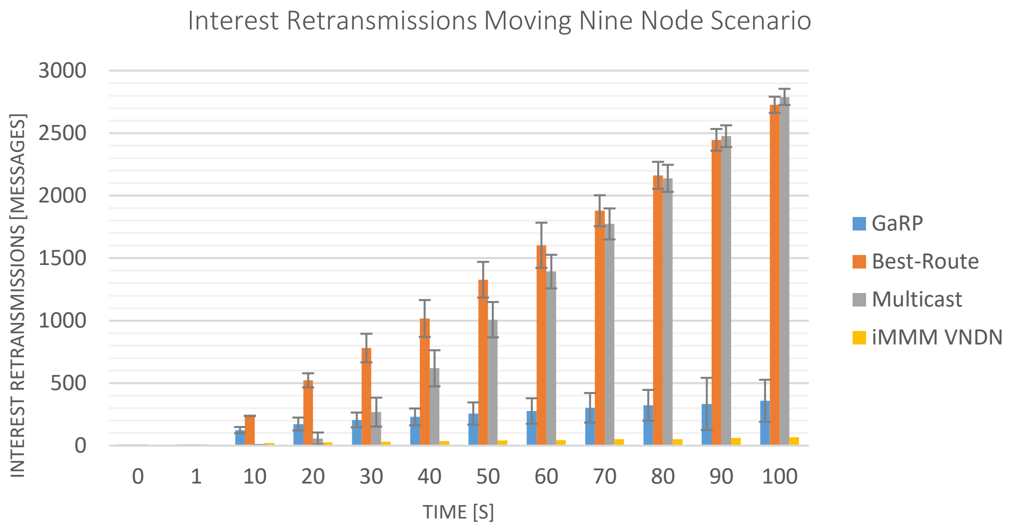


Figure 37 : Moving Nine Node Scenario, Interest Retransmissions

5.3.2.4 Traffic Comparison in the Moving Nine Node Scenario

Fig. 38 and Fig. 39 depict several aspects of the traffic, as total number of packets, during the moving nine node scenario. Fig. 38 shows of all network devices of the node that requests content. For the standard ndnSIM 2.4 routing protocols like Best-Route and Multicast, the total traffic is almost equal for all the network devices. This is the case, since no distinct device is targeted or selected for message transfer. Messages are sent equally on all network devices. The traffic for the Multicast protocol is five to six times bigger as the Best-Route traffic. Since iMMM-VNDN uses Target MAC Address (TMA) and Origin MAC Address (OMA) for message transfer it already performs a lot better than the Best-Route protocol.

During the moving scenario, the consumer is always situated on the lowest lane of the simulation. Therefore, never having other nodes on one side. Because of that, one of the consumer network devices never points towards the other nodes on the topology. This network device with the MAC address [00:00:00:00:24] only produce traffic during the flooding phase of **GaRP** and, thus, in Fig. 38 the difference between **GaRP** and iMMM-VNDN is clear. Despite that fact that during iMMM-VNDN the traffic a requester node produces, is almost 70% less than the Best-Route strategy, **GaRP** reduces the traffic in particular interfaces e.g. [00:00:00:00:24]. This interface is not needed for communication and, therefore, it has 75% less traffic compared to iMMM-VNDN. On the other hand, **GaRP** increases the traffic in interfaces that are used for Data retrieval, like the network device [00:00:00:00:21].

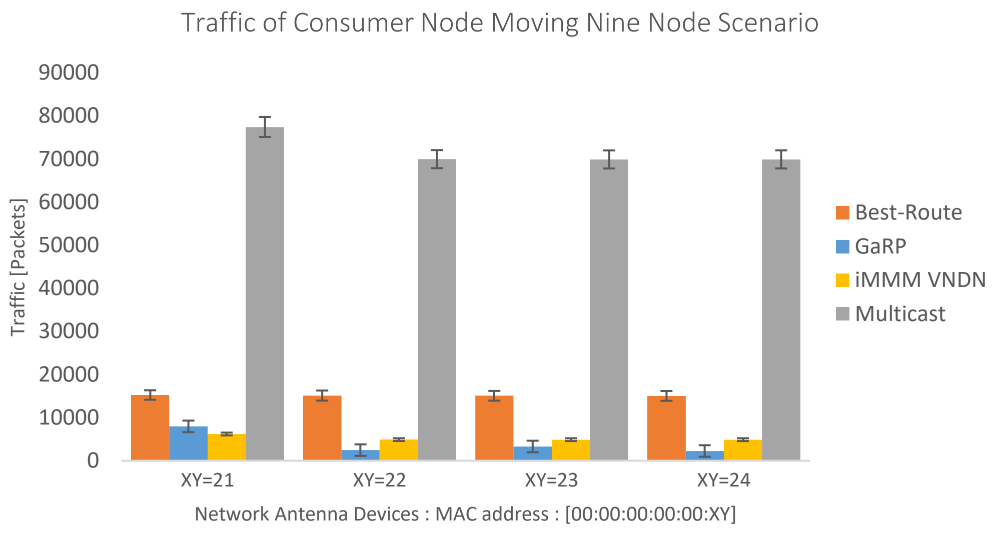


Figure 38 : Moving Nine Node Scenario, Traffic of Consumer Node

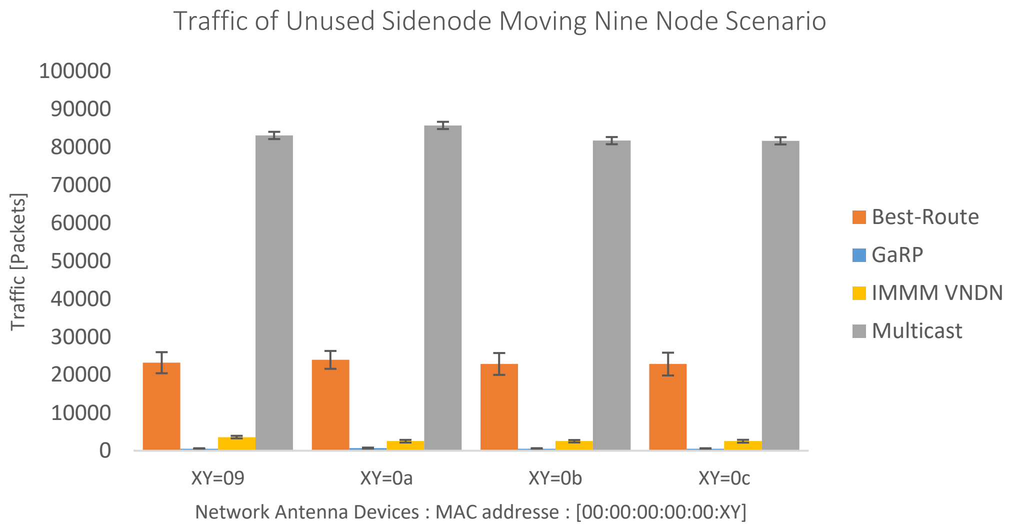


Figure 39 : Moving Nine Node Scenario, Traffic of Side Node

In contrast to Fig. 38, Fig. 39 depicts all network devices of a node that is never included in the route of **GaRP**. With the same reasoning as in the Fig. 37 the Best-Route protocol has equal traffic for all the network devices. In Fig. 39 **GaRP** has the lowest traffic for all four network devices. All **GaRP** network devices are only used during the flooding phase of the algorithm and do not produce further traffic.

5.3.3 Manhattan Topology

This chapter presents the results of the Manhattan scenario with 40 moving nodes. This scenario is a more complex scenario, than the static and moving nine node scenarios. Therefore, **GaRP** is only compared against the iMMM-VNDN. As before the evaluations show a comparison for the ISR, the Data delivery, the interest retransmissions, and the packets traffic.

5.3.3.1 Interest Satisfaction Ratio (ISR) in the Manhattan Scenario

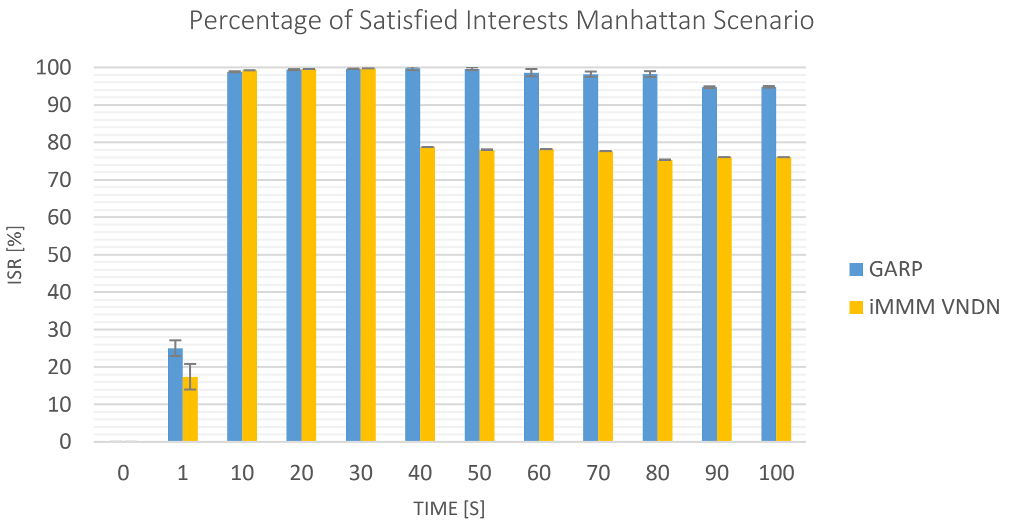


Figure 40 : Manhattan Scenario, ISR

Fig. 40 shows the Interest Satisfaction Rate (ISR) in the Manhattan scenario. The X-axis shows the simulation time from 0 seconds to 100, whereas the Y-axis shows the ISR at the requester node for the given time frame. Fig. 40 shows an average of 25 different simulations. **GaRP** and iMMM-VNDN perform the same until second 40 of the simulation. Both, iMMM-VNDN and **GaRP** loose performance after second 40 of the simulation. In all 25 runned simulations, iMMM-VNDN struggles. No Data message is received and the maximal number of Interests that will be sent out without waiting for Data is reached. Afterwards, only a few Data messages are received, and few new Interests are generated. Therefore, the ISR does not worsen. **GaRP**, on the other hand, continues receiving Data and sending Interests. But, also **GaRP** looses performance and the ISR starts dropping at the end of the simulation.

5.3.3.2 Number of Delivered Data Messages at the Consumer Node in the Manhattan Scenario

Fig. 41 depicts the number of total delivered Data messages, at the consumer node, during the Manhattan scenario. The X-axis shows the time in seconds from 0 to 100, and the Y-axis is the total number of delivered Data messages to the requester at the given timeframe. As shown in Fig. 40 the ISR of iMMM-VNDN drops at second 40. At this time, it is clearly shown that iMMM-VNDN does not receive any further Data messages. On the other hand, **GaRP** continues receiving Data.

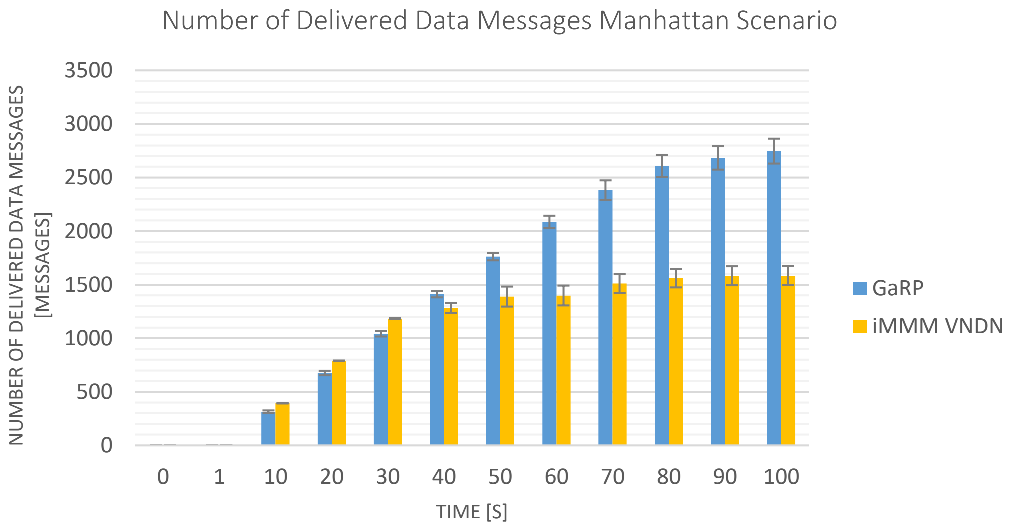


Figure 41 : Manhattan Scenario, Data Delivery

5.3.3.3 Interest Retransmissions in the Manhattan Scenario

Fig. 42 depicts the Interest retransmissions during the Manhattan scenario. The X-axis shows the time in seconds from 0 to 100, and the Y-axis is the total number of Interest messages the consumer node expressed. Both, **GaRP** and iMMM-VNDN have increasing over all Interest retransmissions during the Manhattan scenario. As shown in Fig. 40 and Fig. 41 iMMM-VNDN looses performance after second 40 of the simulation. Here we can see, that iMMM-VNDN Interest retransmission increases after second 70. This is a direct consequence of the missing Data reception after second 40. Because, the Data messages do not arrive at the consumer node, unsatisfied Interests are retransmitted. In contrast to iMMM-VNDN, **GaRP** does not stop suddenly receiving Data messages, as shown in Fig. 41. Therefore, the Interest retransmissions do not increase abruptly.

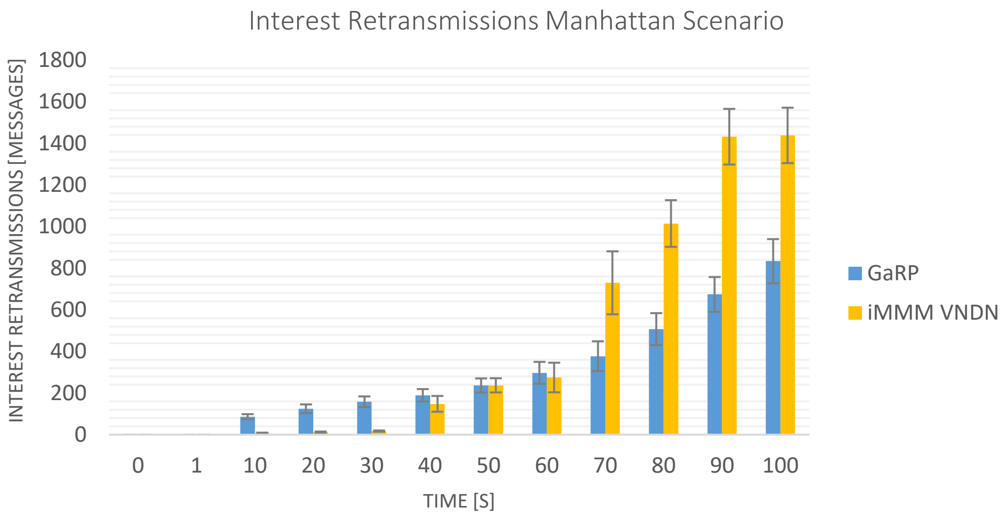


Figure 42 : Manhattan Scenario, Interest Retransmissions

5.3.3.4 Overall Traffic in the Manhattan Scenario

Fig. 43 depicts the overall traffic during the Manhattan scenario. The X-axis shows the node numbers. Node 0 runs the consumer application and node 4 the producer application. On the other hand, the Y-axis is the total number of traffic packets for every node. **GaRP** consumer and producer nodes produce more traffic than respective iMMM-VNDN nodes, due to the fact, that **GaRP** interchanges 40% more Data messages than iMMM-VNDN. **GaRP** reconfigures the best path by broadcasting Interest messages every 10 seconds, therefore, every **GaRP** node produces traffic. Nevertheless, 50% of **GaRP** nodes produce less traffic than iMMM-VNDN nodes. In total, **GaRP** generates 10% less traffic compared to iMMM-VNDN. Thus, the network experiences less collisions, due to traffic overhead.

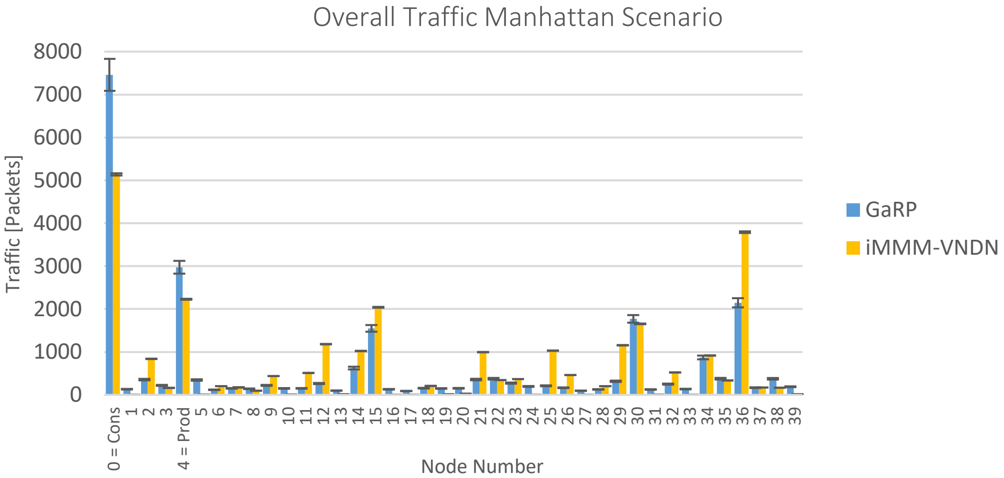


Figure 43 : Manhattan Scenario, All Nodes Total Traffic

6 Conclusions

In this thesis, a Geographical aware Routing Protocol for VANETs in NDN (**GaRP**) has been developed and evaluated in the ndnSIM ns-3-Network simulator. The goal was to achieve less network overhead by reducing the traffic in regions where no traffic is needed. To accomplish this goal, the proposed routing protocol for NDN VANETs exploits the geographical future position information of each node. This position information is transmitted within Data and Interest messages and then stored to the PIT and the FIB of every node involved in the communication. Simulation experiments showed that **GaRP** manages to create distinct paths from a requester to a producer node. This is achieved by installing in every node four network interfaces, and in each network interface card a directional antenna. Thus, by exploiting the appropriate antenna and unicasting messages towards future positions of target vehicles, **GaRP** manages to reduce the traffic at unnecessary areas, as shown in Section 5.3. The results of this thesis show that a high Interest Satisfaction Ratio is achieved. **GaRP** manages to deliver more requested Data messages with less total transmissions and a lower Interest retransmission rate than the compared protocols.

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