

Article

Challenges and Opportunities of Named Data Networking in Vehicle-To-Everything Communication: A Review

Benjamin Rainer *  and Stefan Petscharnig 

Center for Safety and Communication Technologies, Austrian Institute of Technology, 1210 Vienna, Austria; stefan.petscharnig@ait.ac.at

* Correspondence: benjamin.rainer@ait.ac.at

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Abstract: Many car manufacturers have recently proposed to release autonomous self-driving cars within the next few years. Information gathered by sensors (e.g., cameras, GPS, lidar, radar, ultrasonic) enable cars to drive autonomously on roads. However, in urban or high-speed traffic scenarios the information gathered by mounted sensors may not be sufficient to guarantee a smooth and safe traffic flow. Thus, information received from infrastructure and other cars or vehicles on the road is vital. Key aspects in Vehicle-To-Everything (V2X) communication are security, authenticity, and integrity which are inherently provided by Information Centric Networking (ICN). In this paper, we identify advantages and drawbacks of ICN for V2X communication. We specifically review forwarding, caching, as well as simulation aspects for V2X communication with a focus on ICN. Furthermore, we investigate existing solutions for V2X and discuss their applicability. Based on these investigations, we suggest directions for further work in context of ICN (in particular Named Data Networking) to enable V2X communication providing a secure and efficient transport platform.

Keywords: Information Centric Networking; Named Data Networking; V2X; secure communication

1. Introduction

In near future, autonomously driving and driving assistance systems may unlock the potential to increase safety for road users and persons indirectly involved in road traffic. This will not only be achieved by better sensing of the current traffic and environment situation alone, but also by using information of other vehicles or existing fixed infrastructure. A key technology for exchanging control information and other data between autonomous and/or assisted driving vehicles is Vehicle-To-Vehicle and Vehicle-To-Infrastructure (or Vehicle-To-Everything, V2X) communication. This includes a vast amount of sub-technologies such as dynamic caching strategies, (un)reliable transport protocols, dynamic routing and/or forwarding strategies and new network architectures (e.g., Information Centric Networking). Due to mobility of vehicles, the aforementioned technologies shall be able to cope with highly varying transmission channel(s). Increasing road traffic safety by utilizing V2X communication has been and still is a hot topic in current literature [1]. Currently, it cannot be foreseen that this topic will be fully resolved in near future.

With the maturing technological advance in the field of autonomous vehicles and novel driving assistance systems, cars are required to collect much information about the current traffic situation. The benefit of exchanging such information has been investigated for different traffic scenarios. For instance, Le et al. [2] have investigated how safety at intersections can be improved by V2X communication. They have evaluated their use cases on several dimensions, the most prominent are traffic efficiency, prevention of rear-end collisions and prevention of traffic light violation (see also [1]).

The conclusion is that, V2X bears tremendous potential with respect to road and intersection safety. Industry recently also emphasized that road safety via V2X is a very important topic and that they are eager to pursue an inter-operable data specification [3].

In this work, we focus on the technologies enabling V2X communication. We aim at addressing how specific data is requested, found, and delivered within V2X scenarios. In detail, we are going to investigate how suitable Information Centric Networking (ICN) [4,5] is for V2X communication scenarios by reviewing the existing literature. We focus on Named Data Networking (NDN), which is one of the most elaborated implementations of ICN [6]. The benefits of NDN in V2X scenarios, especially for data offloading, has been shown in [7]. For V2X communication, the advantages of NDN over IP-based networking are its adaptive forwarding plane, inherent security concepts, and the seamless ad-hoc nature of the hardware to software coupling of interfaces. We are not going to propose completely new approaches in this work. Rather, we want to highlight and motivate research in NDN that is specific to V2X scenarios. We will discuss research trying to tackle issues of NDN in V2X scenarios. Furthermore, we will review single features of NDN and discuss how V2X communication can benefit from them. We also highlight which aspects of NDN need more attention of the research community in future.

Thus, this work discusses research and problems of NDN in V2X scenarios covering following areas:

- dynamic forwarding,
- caching of content,
- security, authenticity and integrity, and
- simulation of wireless NDN communication.

2. NDN Principles

NDN in general follows the opposite principle of IP, namely it builds upon the idea of addressing content instead of hosts. This fundamental change leads to a completely new view on the network architecture because routers and other nodes in the network aren't anymore the center of the communication. In order to allow such drastic change in the communication principle one needs a completely new network and transport plane. We will discuss all the benefits and disadvantages of this *new* communication principle (for the sake of simplicity one may think of resource identifiers in the sense of HTTP URLs but without the actual host part). In this section, we elaborate on the reasons why NDN is well applicable for ad-hoc networking. Specifically, we review basic NDN principles, such as the NDN packet format, and discuss potential uses for V2X communication.

In packet format version 0.3 for Interest and Data packets [8], the structure of the respective packet types is described. For Interest packets, the only mandatory field is the name in form of a Uniform Resource Identifier (URI). In case of Data packets, name and signature are mandatory. However, in terms of necessity, one may also regard the nonce (randomly generated four octet byte string) as mandatory, because it is used to detect looping interests. Other fields which were not present in earlier versions of the packet format specification are *CanBePrefix*, *HopLimit* and *Parameters*. If *CanBePrefix* is present it indicates that the name is a prefix, exact, or full name of the request content. The *HopLimit* indicates the maximum number of allowed hops before the Interest is discarded. The *Parameters* field can carry any arbitrary data. A field that is currently not used by forwarding strategies is the *ForwardingHint*. This field allows to specify which path the Interest should take. This particular field could prove very useful in V2X communication, we will pick up this field and discuss its possible use later. Furthermore, data is fragmented by NDN into so-called content chunks (with respect to the corresponding Maximum Transmission Unit (MTU)) and the number of the chunk is indicated in the name of the Data packet. Figure 1 depicts the packet format for Interests and Data packets, respectively.

Interest Packet Format
Name
<i>CanBePrefix</i>
<i>MustBeFresh</i>
<i>ForwardingHint</i>
<i>Nonce</i>
<i>InterestLifetime</i>
<i>HopLimit</i>
<i>Parameters</i>

Data Packet Format
Name
<i>MetalInfo</i>
<i>Content</i>
Signature

Figure 1. The packet format for Interest and Data packets in NDN showing the mandatory (**bold**) and optional (*italic*) fields.

Essential NDN features yielding benefits for ad-hoc networking are inherent caching and dynamic forwarding. Routing plays a supporting role for forwarding by providing a starting point for the Forwarding Information Base (FIB). Figure 2 depicts the basic architecture of a NDN node. The ordering in the index plays an important role because upon reception of an Interest, the node checks whether it can satisfy the Interest by returning a cached copy (if *MustBeFresh* is not set) of the requested content. If not, it enters the Interest into the Pending Interest Table (storing the face from which the Interest was received) and forwards it based on longest prefix matching using the entries in the FIB. Data packets traverse the path of the matching Interest in reverse order and clears its corresponding pending Interests in NDN nodes on this path. Whether a node caches data seen on the reverse path depends on the employed caching strategy (e.g., Least Recently Used (LRU), Least Frequently Used (LFU), First In First Out (FIFO), Most Recently Used (MRU)).

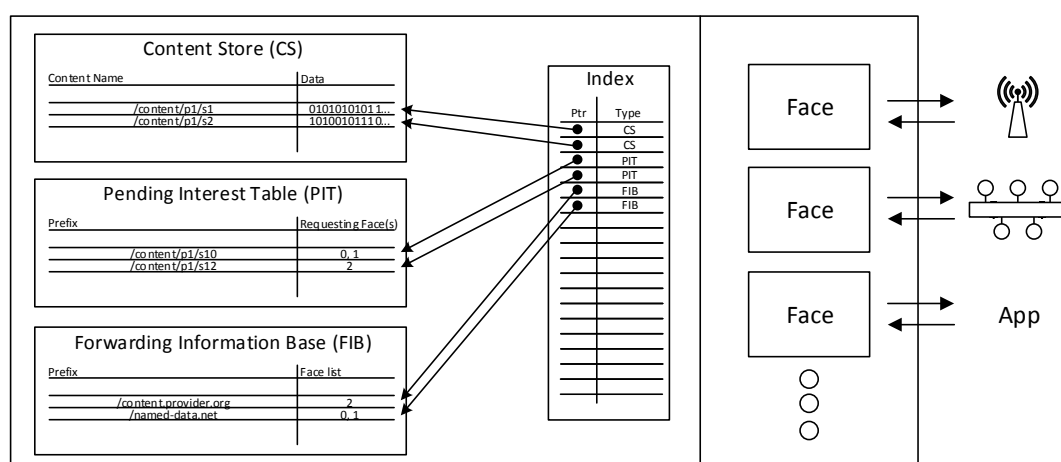


Figure 2. The architecture of a NDN node. It maintains a list of faces used for sending/forwarding and receiving packets and the tables such as an index, Content Store (CS), Pending Interest Table (PIT), Forwarding Information Base (FIB), and Routing Information Base (RIB) which is not shown in [6].

A Face is an abstraction of physical and virtual interfaces. In NDN, every entity that wants to communicate creates a Face. For instance, this can be physical interfaces, logical interfaces, and applications. Figure 3 depicts the architecture of an NDN Face. A Face consists of a link service and a transport mechanism. The link service is split into two types: generic and vehicular. Whereas the vehicular link service is currently neither implemented nor specified, the generic link service is available. As already mentioned, each Face can be an abstraction of a physical interface or a virtual or logical one. It supports different transport mechanisms, depending on the interface it hides. This level of abstraction allows NDN to be used as overlay network on existing networking technologies (e.g., IP).

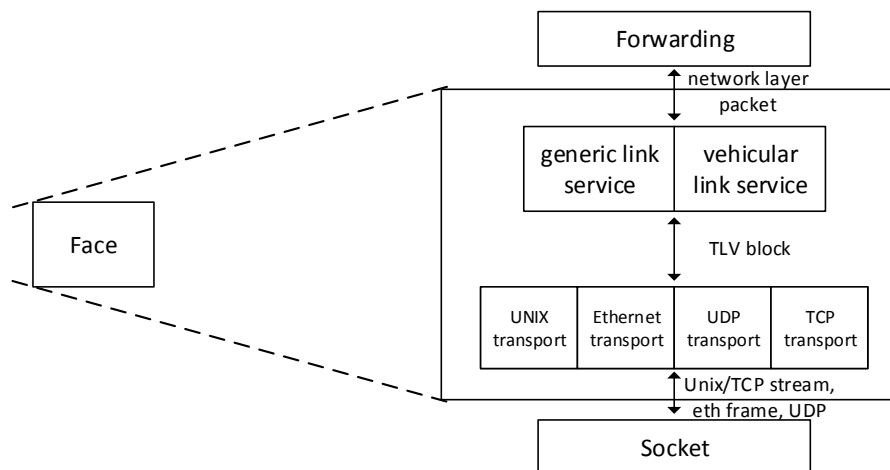


Figure 3. The architecture of a NDN Face. A Face consists of two mechanisms: link service and transport.

3. NDN Enabled Communication and Transport Research in V2X

In this section, we review mechanisms and research essential for efficient and secure communication in V2X scenarios.

3.1. Dynamic Forwarding

In recent literature, a plethora of forwarding strategies for NDN were proposed. Examples include, but are not limited to (ideal) Nearest Replica Routing ([i]NRR) [9], adaptive hop-by-hop forwarding strategy using reinforcement learning inspired by the Q-routing framework (INFORM) [10], Request Forwarding Algorithm (RFA) [11], Stochastic Adaptive Forwarding (SAF) [12]. Yacub et al. [13] give a comprehensive overview on existing forwarding strategies for NDN in a general context. However, this survey does not cover forwarding strategies designed for vehicular networks. Grassi et al. [14] provided an implementation of NDN for vehicular networks (V-NDN). Their forwarding implementation forwards each Interest to all available interfaces. Following work describes Navigo [15], a forwarding strategy using the geolocation of vehicles. Another forwarding strategy leveraging trajectories of vehicles in addition to geolocation is proposed by Liu et al. [16]. Controlled data propagation in vehicular named data networking (CODIE), a forwarding strategy is presented in [17]. CODIE features a data dissemination limit which allows to limit the hops a Data packet travels back. A forwarding strategy based on the link stability (LISIC) for V-NDN is provided in [18]. A density-aware and delay tolerant forwarding strategy is introduced by Kuai et al. [19]. Their approach proposes a two phase forwarding strategy (rebroadcast and retransmissions). Density-awareness is achieved by utilization of a neighborhood list which is updated whenever the vehicle observes a packet in-the-air. A multi-hop and multi-path routing approach for fast content retrieval in VANETs is proposed in [20].

The advantage of NDN over IP for vehicular ad-hoc networks is that content itself is addressed. This resolves a lot of issues of routing and forwarding. The principles of dynamic forwarding and a stateful data plane have tremendous advantages for V2X communication. For instance, forwarding strategies can exploit their neighborhood in order to find new *routes* to specific content. This somehow mimics protocols we know quite well from ad-hoc routing in IP networks (e.g., Ad-Hoc On-demand Vector routing [21]). However, the request response principle of NDN also introduces a problem that has not yet been extensively investigated in current literature. The Data packet (whether at the origin or in a cache) that matches an Interest, is sent along the reverse path of the matching Interest. When an intermediate node leaves communication range, the Data packet will be discarded.

Figure 4 illustrates the problem of discarded Data packet(s) in case that intermediate nodes become out of range after Interests have been forwarded to the origin or hit a cached copy. As vehicle E replaces vehicle D (position wise) the Data packet will be discarded by D because it has no corresponding PIT entries or by B due to the missing Face. This example sketches a problem that has a tremendous impact on the performance of NDN (throughput and delay wise) in medium to high velocity V2X scenarios. Even if the Interest was successfully forwarded to the origin, the corresponding Data packet cannot be delivered which would trigger retransmissions of Interests and consequentially increase delay. The implementation of the forwarding core of NDN (part of the NFD) does support dynamic hand over of Data packets which match a specific PIT entry but unsolicited data may only be cached or discarded. Therefore, we suggest to delegate the decision what happens with unsolicited Data to the forwarding strategy registered for the corresponding prefix. This would allow that Data may be even handed over to nodes without a corresponding PIT entry (or PIT entries are created on-demand) in such scenarios. An alternative suggestion for that scenario would be to estimate whether vehicle D will leave the communication range and, therefore, prepare Interests that register the corresponding PIT entry in vehicle E.

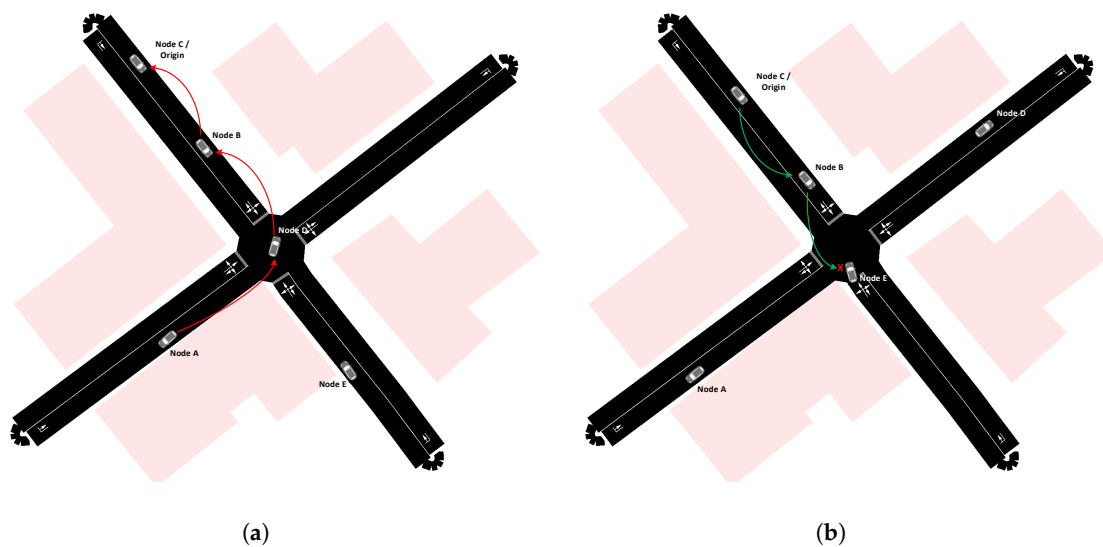


Figure 4. The problem of *unsolicited* Data packets in medium to high velocity V2X scenarios decreasing delivery ratio and increasing delay. (a) Vehicle A requests content that is located at vehicle C. The red arrows illustrate the Interests flow which are forwarded via vehicle D and B to C. We assume that the other vehicles are out of range. So, the only available path is the one shown by red arrows. (b) Vehicle C returns the Data packet(s), but vehicle D is already out of range and vehicle E may receive the Data packet(s) (vehicle E replaces D w.r.t. to the corresponding Face). In both cases the Data packet(s) are discarded (once because D moved out of range, and once because for E the received Data packet(s) are unsolicited).

Another convenient feature of NDN is the field *ForwardingHint* (cf. Figure 1). This Interest packet field enables to store information about where the Interest may be forwarded. This can ease forwarding

if the forwarding strategy already discovered paths for Interests with the same prefix (of course this may underlie some constraints). Utilization of the ForwardingHint potentially decreases the effort of searching new paths at intermediate nodes, similar to dynamic source routing in mobile ad-hoc networks for IPv4 [22]. However, forwarding strategies do not utilize this feature which may become relevant in V2X communication, because the pre-coding of a path may prove to become useful for certain applications.

The assumption of *available routing information* is a further point of interest regarding forwarding strategies. Many of the listed forwarding strategies rely on a priori routing information or even rely on the knowledge of the overall topology or global vehicle information. This means that they are not able to discover new paths by themselves leading to the fact that they are not suitable for building the foundation of ad-hoc V2X communication.

A further issue in dynamic forwarding is *Interest flooding* of V2X forwarding strategies. On the one hand, this increases the satisfaction ratio, but on the other hand, Interest flooding can quickly escalate to broadcast storms preventing other network traffic, such as traffic information updates, from being properly delivered.

In highly changing environments such as V2X scenarios, forwarding strategies must be able to react and find/reveal new paths within a short amount of time. However, development of V-NDN has introduced mechanisms which overtake some of the functionalities of a forwarding strategy (in V-NDN first the FIB was removed and broadcasting of Interests was implemented, later the FIB was re-introduced). We think the architecture of NDN should not vary depending its area of application and its applicability should be seamless. Since NDN allows to use different forwarding strategies for different prefixes, we think that it is the duty of forwarding strategies to find new paths and to maximize or minimize certain metrics (i.e., satisfaction ratio, delay) in V2X scenarios.

3.2. Caching of Content

Caching is a very prominent research field in ICN/NDN. Zhang et al. provide a comprehensive overview on available caching strategies in ICN [23]. However, caching in vehicular networks is quite different from caching in conventional networks because

- Data is twofold** This means that data can be divided into a category of data which hardly becomes stale (e.g., multimedia data) and data with a short lifetime (e.g., situational data from other vehicles) or a short time span until they are useless.
- Vehicles move** Therefore, data may become stale in terms of that it is no longer relevant to vehicles in communication range.

Current literature provides multiple mobility-aware caching strategies for V2X scenarios. For instance, [24] propose a proactive caching policy taking content popularity and mobility of vehicles into account. However, the mobility prediction is based on the exhaustive availability of base stations and considers the probability of entering and leaving communication range of base stations. Mauri et al. [25] present an optimal content prefetching mechanism for NDN in vehicle to infrastructure scenarios. The authors present a binary optimization problem whose solution provides an optimal prefetching of content for known topologies (which in mobile scenario is only valid for a very short period of time, if at all). Zhao et al. [26] propose a community similarity and population-based cache policy for vehicle-to-vehicle scenarios. Their approach reduces cache redundancy based on content popularity and lowers cache replacement overhead by predicting content popularity over time. Recently, Modesto et al. [27] investigate ICN caching strategies for vehicular environments (Leave Copy Down (LCD), Move Copy down (MCD), copy with probability (Prob) and distance based probability caching (DProb)) using simulation studies.

The discussed caching strategies do not consider vehicle mobility as well as data category to full extent. Some of them try to predict the mobility of the vehicles, the connection duration to other vehicles, and take into account whether the content received or stored content is still *popular*. However,

none of the caching strategies separates the incoming data into data vital for (safety) assistance systems or relevant for autonomous driving and (conventional) data which is relevant for passengers, i.e., multimedia content. We suggest that data vital for vehicles must be cached differently than conventional data, as it becomes irrelevant quickly.

3.3. Security, Authenticity and Integrity

The concept of security is inherent to ICN and its implementations like NDN. That is because the location independence of data. If data is cached on its path to the consumer on untrusted nodes in the network, the actual data has to be protected.

Security. Basically, NDN's security builds upon public-key cryptography [28] and relies on security bootstrapping (exchanging public keys). However, this concept has one crucial issue, namely caching (which is a major advantage of NDN). Using traditional public-key cryptography enforces that content chunks are encrypted for each consumer which obviously leads to a bad cache hit ratio [29]. The approach of clustering consumers and using re-encryption proxies, provides a feasible solution from a caching point of view but raises the problem of required processing resources of those re-encryption proxies. Another approach is to use Broadcast Encryption which provides a better cache affinity. The work of Posch et al. [29] provides an investigation of Broadcast Encryption applied to multimedia (video and audio) streaming.

Authenticity. Again, a public-key infrastructure can be utilized to provide/issue certificates through a trusted instance. The content producer signs the data chunks and the consumer can easily verify whether the received data is authentic (in the sense of generated by the (real) content origin) [28]. This is easily implementable for V2X scenarios with base stations. Vehicles will regularly pass by base stations and retrieve the necessary certificates. NDN inherently supports the possibility to schematize trust. The possibility of abstract validation based on the structure of the namespace allows applications to define rules for trust or adopt pre-defined templates (provided by experts). Furthermore, the name structure of NDN allows to bundle keys, i.e., /example/KEY/ter-3 which is the *trust anchor* refers via a given policy to intermediate keys, i.e., /example/user/KEY/ter-4 (providing a trust hierarchy).

Currently, one of the biggest problems for a real deployment of ICN (and its implementation NDN) is content poisoning. Here, a content (not the real origin) provider issues malicious content under the same name as another registered provider. The content may be signed with a faked signature, or not signed at all (just padded with random bits). The problem of content poisoning originates in the circumstance that routers do not have the resources to verify each (Data) packet. An in-depth analysis and investigation on the impact of content poisoning attacks in NDN is given in [30]. The authors also address the drawbacks of current solutions to content poisoning attacks which involve verification of content in intermediate routers (i.e., [31]). The root cause of content poisoning is *prefix hijacking* [32]. In order to tackle this attack vector, Compagno et al. [33] introduce and investigate the *prefix attestation protocol* which builds on top of tracing-based mobility protocols [34]. The results indicate that their solution based on hash-chaining is order of magnitudes better than signature verification but introduces the possibility of denial of service attacks exploiting the introduced protocol. Despite of recent efforts, there currently exists no practically feasible solution to these problems.

Integrity. Data integrity can be interpreted in many different ways depending on the application area. Generally speaking, integrity guarantees that data is reliable, accurate and consistent. In V2X scenarios data integrity of transmitted sensor data is essential. e.g., if an autonomously driving vehicle trusts sensor data from another vehicle, the consequences of unreliable, inaccurate, or inconsistent data may be tremendous. The importance of data integrity for autonomously driving vehicles and in general V2X scenarios, as well as how integrity can be verified by internal (i.e., sensors) and external (i.e., map data) means is briefly discussed in [35].

In this work we want to discuss another case which we think is important for V2X scenarios. Imagine, a vehicle is approaching an area of interest, e.g., a critical (highway) passage, or an intersection. However, due to circumstances, such as high distance, weather conditions, or obstacles, it is not yet able

to analyze (sense) this area of interest. This vehicle requests information, e.g., in form of sensor data or traffic information, from all vehicles approaching or leaving ($n \in \mathbb{N}$) this area of interest. Assume, that the vehicle has to make certain decisions based on the gathered information. The previously discussed mechanisms can help integrity but may not be sufficient. One more vehicles ($f \in \mathbb{N} : f \leq n$) could act faulty (overtaken by an adversary) and will send incorrect information. The sent messages, however, are secured and authentic. In this context we want to introduce the term **byzantine vehicles**. This example raises the following question:

- How can the requesting vehicle retrieve consistent information?

A possible answer can be found in literature of distributed systems implementing byzantine fault tolerance: practical byzantine fault tolerance (PBFT) [36] and improvements thereof, such as Q/U [37], HQ [38], Zyzzyva [39] and Aardvark [40]. Some of the named improvements to PBFT address its performance (Q/U, HQ, Zyzzyva) whereas others (Aardvark) deal with its robustness. However, the protocol to mitigate byzantine faults needs at least $3f + 1$ non-byzantine vehicles or conversely if we have n vehicles we are able to tolerate at most $f \leq \lfloor \frac{n-1}{3} \rfloor$ faulty vehicles. However, these protocols generate a lot of messages leading to unnecessary delays. Furthermore, they assume that each vehicle is holding the same information. For the V2X scenario, this assumption does not apply due to different sensors, angle of arrival/departure, or other circumstances. Therefore, before checking consistency, a preprocessing step has to be introduced which transforms the information to a comparable representation. How this is done in detail is subject to future research and will highly depend on the available information. Thus, solutions that aim on allowing byzantine vehicles or even byzantine infrastructures will have to focus on performance (mainly low latency), robustness (vehicles may be out of range after a short period of time), and caching support (some vehicles may have cached copies of other vehicles' information).

3.4. Naming of Content

As already discussed there exist still not yet fully solved problems regarding naming and prefix attestation prevalent in NDN. In vehicular networks we may use names in a more querying based fashion as shown in [41,42]. In [41] a naming scheme for vehicular networks is introduced. In particular, the proposed scheme looks as follows: */query/node-selector/conditions/selected keys/time condition*, where */query* denotes the prefix and the remainder of the name is the key-value pair. The *node-selector* allows to specify which type nodes shall process the query (e.g., RSU, traffic light, vehicle). It also allows to query for the *condition* of the object (e.g., speed, direction, section) and provides the possibility to use logical statements such as $\text{speed} > 10 \frac{\text{m}}{\text{s}} \wedge \text{section} = \text{intersection10}$. *selected keys* specifies what data should then be in the returning Data packet (e.g., position, velocity, direction). Finally, constraints on the time can be provided by *time condition* such as when has the queried condition be observed. Naming in a more general setting for vehicular networking with NDN is discussed in [42].

3.5. Wireless Communication in NDN

Zhu et al. [43] provide an outlook on the advance of research in wireless communication for V2X via ICN. Chen et al. [7] studied the applicability of NDN for Vehicular Ad-hoc Networks (VANET) and proposed extensions to NDN for vehicular networks. In particular, they showed that the inherent caching capability of NDN provides a benefit when retrieving data from content providers. They observed that, for the investigated scenario, it is possible to offload huge portions of the data on the mobile nodes (cars). Therefore, the load on the bottleneck from content providers to wireless infrastructure is decreased and the Round-Trip-Time for data packets at vehicles is reduced. Grassi et al. discuss a possible implementation of NDN for vehicular network (V-NDN) in [14] and Tarroumi and Jabri [44] its enhancement (EV-NDN).

Amadeo et al. [45,46] introduced content-centric networking (CCN) on top of IEEE 802.11p [47] and evaluated its performance in terms of consumers successfully retrieving content bytes,

downloading time, and content delivery duty in terms of task distribution of transmitting and forwarding among the Relay Station Unit (RSU) and present vehicles. The results show that the inherent in-network caching of CCN provides a tremendous benefit over the legacy solution. In [48] the signalling part of NDN is also moved to cellular networks and its performance is investigated by simulation of a urban scenario with different traffic density.

An interesting report of a life-size Internet of Things (IoT) NDN deployment with devices spread over several rooms and floors is provided in [49]. In addition to the experiment description (and the data gathered) the authors also propose enhancements leading to a decreased energy consumption and routing state of their NDN IoT deployment. An interesting review of open challenges of ICN in IoT is provided by [50]. The potential of ICN in wireless sensor and actor networks (WSANs) is investigated in [51]. More specifically, Dinh et al. [51] investigate how ICN is able to improve the performance of WSANs with respect to efficient coordination, service discovery and traffic engineering (prioritized routing).

The advantages of NDN for applications, such as the delivery of multimedia, in particular of dynamic adaptive streaming of multimedia, are investigated in [52]. An information-centric cost-efficient optimization for the delivery of multimedia content for vehicular networks is presented in [53]. The authors model the content mobility and supply demand balance. These are used to formulate a mixed integer problem that aims on minimizing the economic cost for guaranteeing the quality level of multimedia services. A dissemination protocol that resembles ICN/NDN for safety information in vehicular ad-hoc networks is presented in [54]. The proposed information-centric vehicular networking (ICVN) is compared against the conventional approach using 802.11p [47]. Another architecture for enabling vehicle-to-vehicle communication using NDN is presented in [55].

4. Simulation of NDN Transport in V2X Scenarios

A very important tool for research and development of new mechanisms for NDN in V2X scenarios is *simulation*. Simulation tools allow for testing developed algorithms and mechanisms with a relatively small amount of effort in comparison to physical prototypes, or measurement campaigns using real vehicles. In this section, we present an example toolchain for simulation V2X scenarios. In order to provide a more realistic simulation of V2X scenarios, it is evident that accurate models for channel propagation are essential. Without an appropriate model of the underlying channel, transmission of Interests and/or Data packets can not be simulated accurately and the simulation will (to a certain extent) differ from real scenarios. Thus, before paying attention to the scenario description, we emphasize on the importance of channel propagation models and discuss the impact of a misuse of channel models providing an example simulation.

4.1. A Toolchain for NDN Transport Simulation

In case of NDN, the most elaborated simulation framework is ndnSIM [56] which is based on ns-3 [57]. It utilizes the Network Forwarding Daemon (NFD) and the ndn-cxx library which allow for realistic experimentation (from a software point of view). Ns-3 supports different ways to introduce mobility into the simulation. However, the available mobility models target VANET research and are mostly restricted to a playground (bounding box). For example, ns-3 includes the Gauss-Markov mobility model, random direction, random walk, random way point and many more. However, in V2X use cases (near) realistic mobility of vehicles is required. One of the most elaborated tools allowing the simulation of traffic flows is Simulation of Urban Mobility (SUMO) [58]. It supports map data import from OpenStreetMap and is widely used in VANET and V2X research as well. It furthermore allows to generate mobility traces for ns-3. Besides this *offline* feature it also can be directly paired with the network level simulation via a TCP/IP interface called Traffic Control Interface (TraCi). Please note, that we do not discuss mobility models such as random walk or random direction because these models do limit the expressiveness and goal of a V2X simulation.

4.2. Considerations for a V2X Simulation

Recent advances in forwarding strategies for connected vehicular environments do only consider very limited/simple models in the simulation of the underlying physical transmission channel(s) (i.e., work presentend in [44] uses Nakagami fading, research in [41] also uses Nakagami fading even in highly dense (with respect to the number of vehicles) highway scenarios). The impact of different propagation models and their effects on the performance of Vehicular Ad-hoc Network (VANET) routing protocols has been shown by [59,60]. The consensus is that propagation models tremendously impact the performance of those protocols. However, ndnSIM relies on the channel propagation model implementations shipped with ns-3 when it comes down to wired and wireless channels. This restricts the choice of channel models for obtaining path loss to:

1. Friis' path loss model (free-space, no multi-path propagation, only far field) [61],
2. 2-Ray ground reflection path loss model [62],
3. Log distance path loss model (inside building, densely populated areas) [63],
4. Three log distance path loss model (an enhanced log distance model, for different distances),
5. Nakagami fading [64] (which is not suitable for taking line-of-sight components into account [65]),
6. Fixed receiver signal strength models (matrix propagation model, range propagation model, random propagation model),
7. COST231 propagation model (applicable to urban areas, extends the Hata model which is based on the Okumura model) [66],
8. ITU-R 1411 Line of Sight and Non Line of Sight over roof top propagation models [67],
9. Jakes' propagation model (multi-path fading) [62],
10. Kun's propagation model [68], and
11. Okumura's propagation model [69].

For the frequency ranges of the listed models we redirect the interested reader to the provided references. Furthermore, most of these models assume that there is at least one stationary entity involved in the communication process and are only valid for scenarios from which they are derived (the prevalent geometry is responsible for the obtained channel characteristics which in many cases has been obtained by a measurement campaign and the model represents a good fit). However, the models listed are only used for obtaining path loss. Currently, there are only two models which allow to obtain the propagation latency/delay implemented in ns-3, the constant speed delay model which uses the distance between transmitter and receiver and the speed of propagation (usually speed of light in vacuum $c = 299,792,458 \frac{m}{s}$, slightly reduced in air) and the random delay model.

With the upraise of General Purpose GPU (GPGPU) computing and with even more powerful CPUs/GPUs the use of models which are derived from measurement campaigns is questionable (due to their limited applicability). Other very promising channel modeling approaches are ray tracing (where one differentiates between ray launching, deterministic methods, e.g., image method/theory and distributed wave front, or combinations thereof) and geometry-based stochastic channel modeling (GSCM), a stochastic simplified ray tracing approach. The idea of obtaining characteristics of a wireless propagation channel via ray tracing does already exist since the early 90s (i.e., one of the first proposal to use ray tracing is given in [70]). However, it has gained popularity with more powerful GPUs, lately. It has been shown that ray tracing can provide reasonable results in stationary scenarios [71]. GSCM is a mixture between stochastic modeling and ray tracing. Diffuse (mainly small objects, i.e., traffic signs, traffic lights) and discrete (cars, houses; and other significant scattering points) scatterers are placed in the given geometry and line of sight is assumed between these scatterers and the receiving/transmitting entities (scatterers may also be placed according to a given distribution) [65]. These models provide a non-stationary path loss or received signal strength and also delay/latency. However, there are currently no freely (open source) available implementations which are directly integrated into ns-3.

Besides the physical models, one needs also a medium access and a transport protocol for simulating V2X communication. Ns-3 does support the IEEE 802.11p medium access [47] which was

designed for vehicle-to-vehicle communication. Furthermore, ns-3 also supports wireless access in vehicular environments (WAVE) [72] as transport mechanism. WAVE builds upon IEEE 802.11p and provides services like the communication of vehicle safety information. However, the 5-th generation (5G) of mobile networks does aim on providing new medium access control mechanism for V2X communication in order to enhance its performance in different ways (e.g., enhanced mobile broadband, massive machine type communication, and ultra reliable and low latency communication).

In order to show how one can obtain completely different results when evaluating forwarding strategies for V2X scenarios using/misusing different propagation models, we provide a small preliminary simulation campaign. We use the ns-3 and ndnSIM to build our simulation. Regarding the scenario, we use an intersection with 19 cars approaching from all sides and turning left or right as depicted in Figure 5. The cars do vary their speed by accelerating by $2.6/1.6/3.5/4.6/5.0 \frac{m}{s^2}$ up to a maximum of $14/16/17/20 \frac{m}{s}$ and decelerating by $1.0/2.0/2.5/3.0/4.5 \frac{m}{s^2}$. For the medium access control we use the IEEE 802.11p with a OFDM rate of 6 Mbps and a transmit power of 14 dBm [73]. Each car is also an NDN node and the receiver issues Interests for requesting data with 2 Mbps. For this mobile scenario, we select Stochastic Adaptive Forwarding (SAF) as forwarding strategy, because it is able to discover new paths and does not rely on a priori routing information. Furthermore, the reference implementation is freely available [12]. For the delay model we select the constant speed model available in ns-3. We use SUMO to generate the mobility traces for the 19 different cars, thus providing a scenario where we can reproduce results.

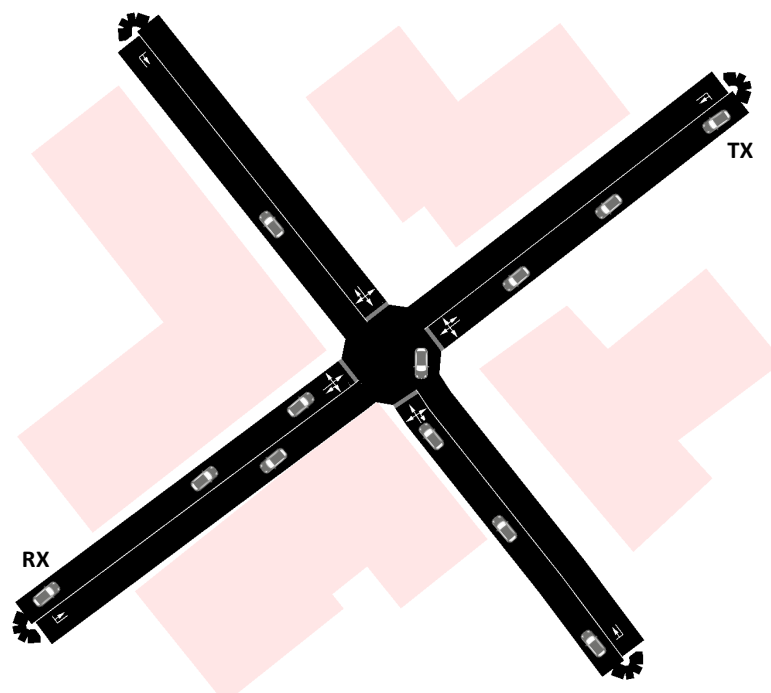


Figure 5. Scenario for the simulation campaign. Receiver (RX) and transmitter (TX) are approaching the middle of an intersection with other vehicles.

For each propagation model we repeat the simulation twenty times and measured the interest satisfaction ratio and the delay of satisfied Interests.

The results of this preliminary simulation campaign are summarized in Figures 6 and 7. The satisfaction ratio (cf. Figure 6) already indicates that different models provide different results when applied to the same scenario. Even more insights are gained by investigation of the CDF of the delay of satisfied Interests (cf. Figure 7). The CDF of the delay indicates that the various propagation models lead to different results. The results especially differ when receiver and transmitter are far

away of each other, such that the other vehicles are used as *relaying* units by the forwarding strategy (reflected by the satisfied Interests with higher delay). For instance with Nakagami fading we obtained the lowest satisfaction ratio but the best performance with respect to delay. Conversely, the satisfaction ratio with the LogDistance model was one of the highest but scores as one of the lowest when it comes to delay (such as the TwoRayGround model). Thus, a meaningful conclusion cannot be drawn from the simulation with respect to the performance of SAF in the used scenario. Thus, optimizing parameters of SAF (such as interval length/numbers of Interests defining an calculation interval or other parameters) does not pay off as each of the used models will lead to different parameters.

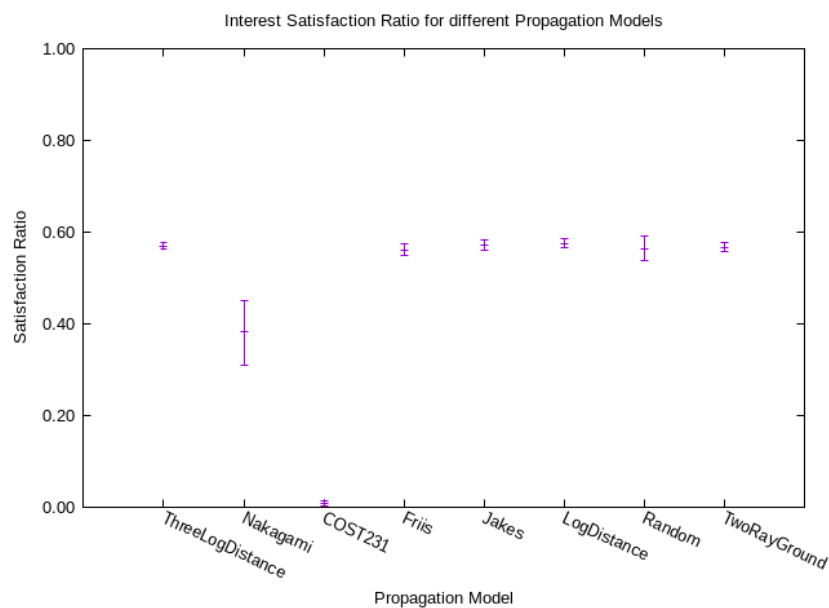


Figure 6. Satisfaction ratio for different propagation models using SAF.

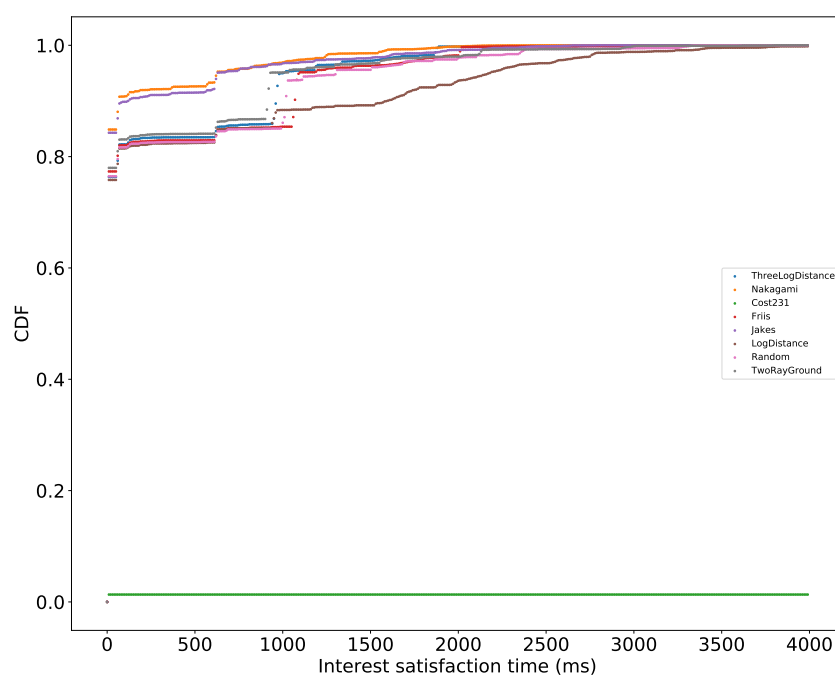


Figure 7. Cumulative Distribution Function (CDF) for satisfied Interests over time and a specific run (same run for all models).

4.3. Simulation Scenarios for V2X Communication

In this section we summarize the most used scenarios for simulating V2X communication in literature and discuss their properties. A V2X communication scenario is defined by street alignment, environment geometry and environmental conditions, road users and infrastructure, incidents, and its use case. While street alignment, as well as environment geometry and environmental conditions impact simulation of V2X communication on a physical-level, road users and infrastructure, incidents, and use case influence network communication on a high-level basis.

Street alignment. Additionally to highways and intersections, which are predominantly used street alignments in recent literature, we propose to simulate roundabouts, as traffic flow in roundabouts is fundamentally different to the intersection case. We found that SUMO currently does not correctly translate roundabouts, as they are interpreted as intersections. For an illustration of these basic street alignments, please refer to Figure 8. Please note that the number of lanes per direction is an additional variable of the simulation scenario. In addition to the literal street alignment, this dimension also defines the presence and position of classical traffic infrastructure, such as traffic lights or pedestrian crossings. At intersections, red traffic lights, and at pedestrian crossings, cars should share information for following cars, in order to optimize traffic flow and subsequently minimize travel time.

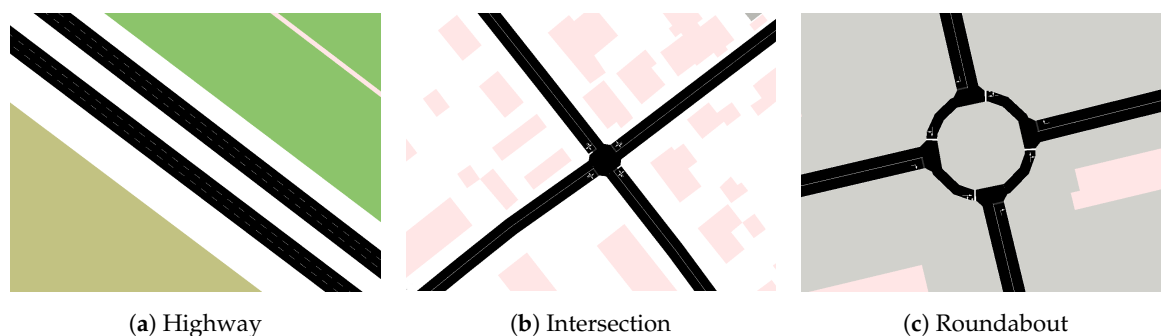


Figure 8. Basic street alignment types. Examples have been taken from SUMO TAPASCologne scenario.

Environment geometry, environmental conditions. Another factor with a big impact on the physical aspect of a simulation scenario is the geometry of the environment. This category defines attributes of possible obstacles for V2X communication, such as buildings or trees. While the position of an obstacle is self-explanatory, we identified surface character and physical shape as remaining important attributes of the environment geometry. Depending on these geometry attributes, channel model selection heavily impacts the simulation outcome for the scenario. Environmental conditions, such as weather street conditions affect physical data transmission (e.g., reflection properties) as well as physical simulation properties (e.g., stopping distance or sight distance).

Infrastructure and road users. As already discussed in previous sections, several related work assume base stations or a fixed RSU in place (i.e., as in [14,41,43]). While the assumption of having base stations available in communication range is illusory for the fact of high hardware cost, we propose to use base stations for selected applications, such as signaling the availability of parking space. Infrastructure nodes thus act as a communication party providing potentially beneficial information for traffic safety and traffic flow. A major point of interest concerning fixed base stations is the kind and availability of provided data. In contrast to fixed infrastructure, road users are moving entities. We classify road users as vehicles, priority vehicles, public transport, cyclists, and pedestrians. Vehicles are traffic actors, with the goal to minimize travel time from source to destination location. They exchange relevant information in order to achieve the goal of safe and fast travel within the framework of road traffic regulations. Priority vehicles are vehicles which are exceptions to road traffic regulations, such as fire engines, the ambulance, or police cars. In order to allow these cars to quickly reach their destination, the communication with such vehicles has to be prioritized. Public transport, cyclists, and pedestrians are further special cases of road users as special road

regulations apply. Especially in the case of cyclists and pedestrians, we can not assume active communication, so autonomously driving cars have to rely on (not necessarily their own) sensor data only. As already apparent from the fact that we include pedestrians, we foresee partially autonomous traffic. In addition to pedestrians, we assume that selected vehicles may be operated by humans. Furthermore, we want to emphasize the fact that some road users may not be able to communicate at all. We assume that the number and behavior (routes, behavior at traffic accidents, ...) of the human-operated vehicles and vehicles that do not communicate must be well defined for simulation. In order to allow for safe traffic, special simulation use cases for these road users must be prepared. The last point of interest regarding infrastructure and road users are the destinations of all autonomously driving vehicles, as well as further simulation-relevant vehicle parameters (e.g., acceleration rate, deceleration rate, or turning circle).

Incidents. Another characterization category of V2X scenarios are incidents, such as traffic jams, traffic accidents, and blocked routes. These incidents are highly unpleasant for road users, as they reduce traffic flow. However, especially in urban environment, information about such incidents may lead to efficient change of driving routes. Furthermore, information on incidents increases road safety.

Use cases. To fully characterize a V2X scenario, we need use cases, e.g., parking, changing lanes, behavior at intersections, behavior with approaching priority vehicles. At performance evaluation, we distinguish between traffic flow and communication evaluation. Examples for traffic flow evaluation are throughput in number of cars on a specific road point, average time to pass a road segment, or jam lengths in before bottlenecks, such as traffic lights, unmanaged intersections, or roundabouts. Examples for communication evaluation are interest satisfaction ratio, or delay.

Example scenarios. Four examples scenarios incorporating challenging communication aspects are:

S1 *Several cars driving alongside each other on a highway with approaching priority vehicles.*

This is a one-way traffic high-speed use case. The challenging networking aspect of this scenario is that on car has to switch lanes such that the priority vehicle is able to overtake. Information from the priority vehicle has to travel and be processed in driving direction faster than the vehicle is driving, and actions have to be taken until the priority vehicle reaches the two cars' geo-location. Additionally, measures have to be taken that assure the authenticity of the priority vehicle's messages.

S2 *Turning left at a traffic light controlled intersection in an urban environment (buildings near the road) at a rainy day.*

This scenario is especially challenging to simulate realistically. Here, the applied channel model is essential for a realistic simulation, as buildings near the road cause reflections of the electromagnetic waves and wet weather conditions alter the electro-magnetic properties of the various surfaces.

S3 *Turning left at an unmanaged intersection. A rear-end-collision is blocking the turn-left lane five car lengths before the intersection.*

This scenario covers an intersection where the lane which should be used in normal circumstances is blocked by a traffic incident. However, there is enough space for avoiding the accident and turning left. As in S1, the networking challenge is message authenticity as well as timeliness.

S4 *Taking a roundabout exit with crossing pedestrians at this exit.*

While recent literature covers intersections, we also propose to simulate other bottlenecks such as roundabouts. From a communication point of view, this scenario is interesting, as following cars can be warned of potentially crossing pedestrians that are in general not part of the communication network.

5. Conclusions

In this paper, we review dynamic forwarding, caching, security, naming, and wireless communication aspects of named data networking for vehicle-to-everything communication. Our contribution to the field is the identification of future challenges and opportunities in these sub-fields. We found that NDN, as a technology, is promising, as it features inherent security concepts, dynamic packet forwarding, and inherent caching. Achieving the aforementioned features with IP requires tremendous effort.

For dynamic forwarding in NDN, we found that there is unexploited potential in the Interest packet format, as the ForwardingHint is not leveraged by current forwarding strategies. Furthermore we identified the problem of forwarding unsolicited data which arises through node mobility. Currently, this case would require retransmissions of Interests and consequently increase the delay. Additionally, we found that many forwarding strategies are impractical for a mobile scenario, as they require a priori routing information or knowledge of the overall network topology. Eventually, the question of how to prevent broadcast storms caused by Interest flooding remains.

The aspect of content caching is well researched in current literature. While most of them approach the problem of vehicle mobility, data category is not taken into account. With driving assistance systems and autonomously driving vehicles, there will be data vital for traffic safety which has to be cached differently than conventional data, e.g., a video stream.

From the point of view of vehicle-to-everything communication, NDN inherently covers security and authenticity. Security currently comes at the cost of bad cache hit ratio. Considering authenticity, there is no feasible solution against content poisoning attacks. Data integrity, as well as byzantine vehicles are not extensively covered in current literature. We argued that simulation of V2X use cases is essential for progress in the field. Therefore, we characterized V2X scenarios and discussed simulation of NDN transport. We found that in ns-3, at a fixed delay model, the choice of channel model has a high impact on the delay. We therefore emphasize that one has to be careful to choose the appropriate channel and delay model for the current simulation.

We end this work with a summary of possible research questions for future work:

- How to deal with unsolicited data in V2X context?
- How to incorporate vehicular mobility (vehicles entering/leaving communication range) in the forwarding process?
- How to make use of the NDN ForwardingHint?
- How to prevent broadcast storms originating in Interest flooding?
- What should a caching strategy for multiple types of data look like?
- How to combine geo-location and popularity information in content caching?
- How to deal with caching, encrypted content, and the lack of computational resources?
- How to deal with content poisoning attacks without verification at intermediate routers?
- How to detect and deal with byzantine vehicles?
- How well do models of the physical channel map the uses cases we want to simulate?

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