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On the realization of VANET using named data networking: On improvement of VANET using NDN-based routing, caching, and security

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Summary

Named data networking (NDN) presents a huge opportunity to tackle some of the unsolved issues of IP-based vehicular ad hoc networks (VANET). The core characteristics of NDN such as the name-based routing, in-network caching, and built-in data security provide better management of VANET proprieties (e.g., the high mobility, link intermittency, and dynamic topology). This study aims at providing a clear view of the state-of-the-art on the developments in place, in order to leverage the characteristics of NDN in VANET. We resort to a systematic literature review (SLR) to perform a reproducible study, gathering the proposed solutions and summarizing the main open challenges on implementing NDN-based VANET. There exist several related studies, but they are more focused on other topics such as forwarding. This work specifically restricts the focus on VANET improvements by NDN-based routing (not forwarding), caching, and security. The surveyed solution herein presented is performed between 2010 and 2021. The results show that proposals on the selected topics for NDN-based VANET are recent (mainly from 2016 to 2021). Among them, caching is the most investigated topic. Finally, the main findings and the possible roadmaps for further development are highlighted.

KEYWORDS

caching, named data networking, routing, security, vehicular ad hoc networks

1 | INTRODUCTION

Vehicular ad hoc networks (VANET)[1] are a key enabler of intelligent transportation system (ITS).[2] Communication in VANET is done among vehicles and other capable wireless devices (road side units [RSU], pedestrian smartphones, and other vehicles). Each of these nodes can have a role either as a wireless router or as an end-host, supporting various types of communications. Due to the potential of VANET in improving traffic efficiency, road safety, and comfort to drivers and passengers, it has become an active topic for research and standardization.

Many of the current VANET routing protocols are TCP/IP based. The TCP/IP protocol stack is host-centric; that is, the main communication element is the host. However, current communications are content-centric based; that is, the main element for communication is the content, not the host. This shift in communications poses new challenges to IP-based networks. This fact demanded the development of new architectural paradigms capable of supporting natively this new reality. Among the several proposed content-centric architectures, named data networking (NDN), a particular implementation of content-centric network (CCN), has been considered as the most promising solution.[3,4]

The core characteristic of NDN is the identification of contents by name. This characteristic provides the separation of the content identity from its physical location. Moreover, this characteristic provides the possibility for caching and ubiquitously sharing contents in the network. Caching and routing contents by name opens a myriad of opportunities for node mobility and network scalability, key properties for VANET. In fact, considering both characteristics of NDN and VANET, there is an enormous potential of advantages on realization of NDN-based VANET. The combination of both technologies is an exciting topic and one on which recent developing efforts are being put forward.

A quick web search has shown that although several solutions were proposed for improving VANET by NDN, still a scarce number proposed solutions focus on routing. Caching is one of the main properties of content-centric networks. The characteristics and the applications of VANET, security, and privacy are key concerns. Thus, these topics also demand a special attention. The need to access the main gaps on improving VANET by NDN motivated the development of the this work.

We develop this work with the aforementioned aspects in mind, and with the focus on attaining the objectives presented next. To provide an easy reading, we present in Table 1, the list of used acronyms in this paper.

TABLE 1 List of used acronyms

Meaning	Acronym
Access point	AP
Base station	BS
Bloom filter	BF
Cache hit ratio	CHR
Cache pollution/poisoning attack	CPA
Content-centric network	CCN
Content name	CN
Content store	CS
Cluster head	CH
Delay tolerant networks	DTN
Distributed denial of service	DDoS
False information injection attack	FIIA
Forwarding information base	FIB
Global position system	GPS
Hierarchical BF routing	HBFR
Hidden Markov model	HMM
Information-centric network	ICN
Integer linear programming	ILP
Intelligent transportation system	ITS
International Telecommunication Union	ITU
Internet of vehicles	IoV
Interest flooding attack	IFA
Interest satisfaction ratio	ISR
Inter vehicular communication	IVC
Longest prefix match	LPM
Mobile edge server	MES

TABLE 1 (Continued)

Meaning	Acronym
Mobile ad hoc networks	MANET
Named data networking	NDN
Negative acknowledgment	NACK
NDN forwarder daemon	NFD
Pending interest table	PIT
Privacy violation attack	PVA
Quality of experience	QoE
Quality of service	QoS
Research question	RQ
Residual lifetime	RL
Round trip time	RTT
Software defined networking	SDN
Vehicle to everything	V2X
Vehicle to infrastructure	V2I
Vehicle to vehicle	V2V
Vehicular ad hoc network	VANET
Vehicular content-centric networks	VCCN
Vehicular named data networking	VNDN
Vehicular social network	VSN
Virtual nodes	VN
Wireless sensor networks	WSN

1.1 | Objectives

The purpose of this study is to survey the existing contributions on the feasibility of improving the performance of VANET using NDN. Several similar studies exist but as we explain later, they focus in forwarding, or when including other topics such as routing, they treat forwarding and routing interchangeably. Differently, We limit our focus on the solutions for improving VANET by NDN-based routing (not forwarding), caching, and security. From the findings, we also propose the possible lines for further development in the aforementioned topics. This purpose is attained by performing a research based on a systematic literature review (SLR), which covered a period from 2010 to 2021.

1.2 | Main contribution

Although several surveys have been performed on the improvement of VANET using NDN, the topics likely to be covered were not completely or even individually fully surveyed. Thus, we proposed to close the existing gaps. Given that routing and forwarding in NDN are two planes completely separated and likely to be developed separately,[5] and considering that the majority of the related surveys treat these two topics indiscriminately, a survey focusing on bringing the real state-of-the-art of routing in order to provide a clear figure of what has been done is still missing. More precisely, we intent to survey solutions applying routing protocols for NDN-based VANET, not those using pure forwarding, that is, broadcast mechanisms.

In summary, our main contributions include the following: (1) We highlight the need to differentiate the control and data planes in NDN, specifically in case of VANET; (2) given that several surveys focusing on topics including forwarding has been performed, we survey the specific solutions for NDN-based routing. Note that although we scrutinized each of the related work, extracted and discriminated forwarding from routing solutions, none of the related surveys present any routing proposal developed after the year 2019; (3) related work surveyed the topic on caching; however, we felt the surveys were not sufficiently comprehensive (several solutions in the surveyed period were left apart); thus, we closed this gap complementing this topic; (4) surveyed solutions for security are scarce; thus, we also close this gap; and (5) we try to present more precisely the open challenges and future roadmap.

Table 2 (Section 4) shows the summary of the related surveys and their limitations/gaps, which we try to close.

1.3 | Outline

The remaining of this paper is organized as follows: Section 2 the overview of VANET, and Section 3 presents an overview of NDN. Section 4 presents the related work. Section 5 presents the systematic literature review methodology, which will guide this survey, and the data extraction and synthesis of the selected papers. Section 6 presents the main improvements applied to VANET by using NDN. Section 7 presents the conclusions.

2 | OVERVIEW OF VEHICULAR AD HOC NETWORK

VANET is a specific area of networking that has been under intensive research from both academia and industry, due to its foreseen importance to the development of ITS. In fact, the main purpose of VANET is to provide ubiquitous connectivity to mobile users and efficient vehicle-to-vehicle (V2V) communications in order to enable ITS.[6] VANET is a particular case of mobile ad hoc network (MANET) and presents specific characteristics that make it differently challenging compared to the latter, as presented in the next section.

2.1 | Architecture

Communications in VANET are based on the following three network scenarios: (1) V2V or pure ad hoc—which refers to the communication only between mobile nodes, in an opportunistic or ad hoc manner. This scenario is essentially important in environments where fixed infrastructures are inexistent or where the communication cannot allow the delays produced by routing through the infrastructure; (b) vehicle-to-Infrastructure (V2I) or cellular/WLAN—which is created between mobile vehicles and the static infrastructure (e.g., RSU or base stations [BS]) in the network. The static infrastructure is mainly used for routing or as cellular gateways and WLAN access points (AP) to provide Internet; and (c) vehicle-to-everything (V2X)—the hybrid model where the communication can occur from the mobile vehicles to every capable node in the network, and vice-versa.[6,7]

2.2 | VANET proprieties

The main properties of VANET are[2] (1) ad hoc network—an ephemeral network with no previously defined structure; (2) predictable mobility—the RSU/BS are static. The vehicle trajectory is constrained by the topology and the layout of the roads; (3) highly dynamic network topology—although the mobility is predictable, the varying directions taken by the vehicles result in a short life duration of links among nodes (i.e., the nodes present intermittent connectivity). This characteristic is predominant on highways where vehicle speed can go up to 200 km/h[8]; (4) large-scale network—VANET could cover a very large area, from a neighborhood to an entire city; (5) ability to provide continuous power and high computational capability—the power and computational ability of the nodes (vehicles and RSU) in VANET is not a constraint. The nodes are equipped with a variety of computational resources such as sensors, storage, GPS, and processors[9]; (6) partitioned network—the network traffic varies depending on the considered area: rural, suburban or urban. As one move from the rural to the urban area, the network traffic tends to be higher, but the traffic speed of the vehicles will be moderate compared with the rural area.

2.3 | VANET applications

VANET applications are quite vast that various authors end up classifying them differently. For instance, the *European Telecommunications Standards Institute* (ETSI)[10] has identified a Basic Set of Applications (BSA), classified and grouped them into the following classes: (1) *cooperative road safety*—to improve the road safety, decreasing the number of road accidents; (2) *cooperative traffic efficiency*—to improve the traffic fluidity, that is, these applications produce or collect urban monitoring information and share data of common interest in order to improve vehicle mobility within the public roads; (3) *cooperative local services*; and (4) *global internet services*. Both classes in (3) and (4) aim at advertising and providing on-demand information to passing vehicles on either a commercial or non-commercial basis, including infotainment and comfort. To simplify the classification, these classes can be broadly grouped into the safety (i.e., the cooperative road safety) and the non-safety (i.e., the cooperative traffic efficiency, cooperative local services, and global internet services) applications.

Besides, other interesting advantages of VANET include[11] scalability, low infrastructure requirement, low maintenance, and Internet connectivity.

For further references, additional characterization and use cases for VANET can be found in studies such as in literature.[1,7,12] In Saini et al,[11] a comprehensive survey on TCP/IP-based VANET is performed.

2.4 | Routing and forwarding

The high intermittency of links in VANET causes frequent route disruptions. With constant route disruption, the task of maintaining routes in routing tables and use these routes to forward packets in a timely manner is challenging. Nevertheless, several routing proposals for VANET had been proposed.

Depending on the chosen grouping criteria, routing protocols in VANET can be categorized in topology-based and position-based (geographic) or by the addressing mode in unicast, multicast (includes geocast and cluster-based), and broadcast.[13–15]

Topology-based protocols require the knowledge of the network topology before they can make decisions on routing. This category can be further divided into reactive, proactive, and hybrid protocol subcategories. Proactive protocols build and maintain an up to date routing table with existing routes to the content sources. A timely beacon broadcast is an usual adopted mechanism to maintain updated the routes, and discover new paths to the content sources. In a highly mobile environment, routes demand frequent updating. This process can result in an increased network traffic overhead. Reactive protocols in the other hand, need only to maintain a limited number of routes in the routing tables, because the routing and discovery process only takes place when the node requires a path to the content source. That is, the route is established when its is needed. The hybrid subcategory takes synergies from the two aforementioned approaches. Due to the highly changing topology in VANET, topology-based protocols are not well suited for this network.[6,16]

In contrast, position-based (or geographic-based) routing protocols do not need to know the network topology or perform a prior route discovery. Instead, they use the position/location to forward packets hop-by-hop toward the destination. The position/location of the nodes is gathered by means of navigational systems on-board, such as the geographic positioning system (GPS).[17] Given that position-based routing protocols do not need to know the network topology, that is, do not need to store entire routes to the content providers (may only require keeping a list of 1-hop neighbor nodes), they are more scalable and more suited for highly mobile environments. Position-based routing protocols are reactive, in the sense that the next-hop node is selected on demand, taking in account aspects such as the geographical distance to the content provider. This category may be grouped into the delay tolerant networks (TDN), non-DTN, and hybrid.

2.5 | Security, privacy, and trust

Different safety and emergency related information is constantly shared by nodes in VANET. Drivers make critical decisions based on this information, and then its correctness must be assured. Key aspects in VANET communication are security, authenticity, and integrity.[18] Common VANET privacy and security vulnerabilities include[11,19,20] (a) jamming—a node can deliberately send interfering messages that can prevent communication among vehicles in their communication range; (b) forgery—where a node can forge and disseminate false emergency information; (c) traffic tampering—the attacker node can modify traffic information eluding the drivers about the real state of the traffic; (d) impersonation—a node can masquerade and act as an emergency service and disseminate false emergency information; (e) location tracking and privacy violation—achieved from the collection of various information about the mobility and preferences of a given driver; (f) sensor data faking—achieved by bypassing the sensor data and fake information such as the speed or position; (g) Sybil attack—where a node use multiple identities to send multiple messages as if it was multiple sources sending the messages; and (h) black hole attacks—the dishonest node pretends to have the shortest path to content sources, eluding the other nodes to choose this path but the packets never reach the destination.

Several security mechanisms have been proposed in order to protect privacy, integrity, achieve anonymity, and authenticity, which are also key aspects of VANET communication.[18] Some of these schemes include[21–23] (a) trust-based mechanisms (which can be grouped into authentication-based and reputation-based[11]); (b) group communication; (c) data fusion schemes; (d) identity-based signature schemes; (e) pseudonym approaches; (f) public key infrastructure (PKI); (g) k-anonymity schemes; (i) aggregate signature schemes; and (j) certificate revocation.

2.6 | Main challenges and research issues

The main technical challenges that compose the main areas for the research in VANET[12,24–26] are (a) signal fading; (b) bandwidth limitations; (c) short period of connectivity; (d) small effective diameter; (e) security and privacy; (f) routing protocols; (g) data administration and storage; and (h) time constraints.

Signal fading (related to the propagation model): In a road vehicular communication where buildings and other vehicles are in between two communications nodes, the transmitted signal tend to deteriorate. With more obstacles as the case of urban areas, the signal fading may lead to infeasibility of the communication. Although rural areas with less buildings may benefit the signal propagation, the high speed of the vehicles will affect the signal, making it difficult to model the channel.

Bandwidth limitations: VANET applications use a limited range of bandwidth frequency, as such in a highly dense environment, inefficient use of the bandwidth may result in a channel congestion.

Short period of connectivity (link intermittency): due to high mobility of nodes that result in a highly dynamic topology, the connectivity between nodes in VANET is inevitably short, causing the instability of the routing paths. Exchanging information in a such small period of time demands the development of more advanced and rich network topology model, different from traditional models that have larger period of interaction between sender and receiver.

Small effective diameter: This leads to the challenges in maintaining the global network topology and resulting in problems when applying existent network routing protocols to VANET.

Security and privacy: Being an open network where any node is allowed to join, these challenges demand a good balance. For trustworthiness a receiver would require to know the source of the received information. However, this aspect could violate the privacy of the sender. Having in mind that one of the applicability of VANET is the safety of vehicles and pedestrians (it directly involves human lives), the security and trustworthiness of the information must be guaranteed.

Routing protocols: Routing protocols are one of the fundamental elements in networks and in special for VANET. Routing protocols are responsible for initiating and managing routes to facilitate multi-hop communications. Routing is a critical challenge and the difficult in resolving this challenge comes from two of the main characteristics of VANET: the high mobility of nodes and the highly dynamic topology.

Data administration and storage: For large scale networks, the number of nodes can increase and generate a large amount of data to manage.

Time constraints: Applications in VANET can be divided into two groups concerning their sensibility with time: (a) delay-tolerant, mostly the entertainment applications, and (b) delay-sensitive, which is related to the safety applications and where reliability, responsiveness, and data quality are critical. Time constraints must be assured in order to enable the driver take right and timely decisions, when required.

3 | OVERVIEW OF NAMED DATA NETWORKING

The TCP/IP based network is host-centric; that is, the main element for communication is the host. However, current communications are content-centric based (i.e., the main element for communication is the content itself) instead of the host. This shift in communications poses new challenges to the current IP-based Internet. This fact demanded the development of new architectural paradigms capable of supporting natively the new reality. Former and current content-centric networking projects including their standardization are comprehensively detailed by previous studies.[27,28] Among these proposals, NDN, a particular implementation of CCN, has been considered as the most promising solution.[4]

3.1 | Architecture

The following architectural principles guided the design of NDN[5]: (1) the use of hourglass architecture, focusing minimum functionality in the network layer, similar to the TCP/IP protocol stack. The network layer in NDN should support scalability, security, resilience, and efficiency (to support multipath routing and management of packets in content stores). Two additional layers (security and strategy) are appended to NDN protocol stack (Figure 1). The new layers provide (a) security layer, security for packets in the network, and (b) strategy layer, strategically supports the forwarding plane in managing the statuses of each connection, for a better forwarding decision; (2) security built into the structure—security in the NDN is naturally guaranteed by forcing the producer to sign all data packets; (3) NDN traffic is self-regulating—the forwarding plane has the responsibility of recording the state of each node. This information can later be used to make decisions about traffic behavior; (4) separated routing (control) and forwarding (data) planes—this way, each plane can be developed and improved with less interference from each other.[29]

NDN architecture implements forwarding strategy per node. The responsibility of the data plane is to make decisions including (a) which packets to forward, and which interfaces to use; (b) which level of unsatisfied packets should be allowed; and (c) what are the relative priority of different packets. Each node also makes local decisions to balance traffic by forwarding through multiple and alternative paths.[29]

NDN adopts pull-based communication model. For communication, two types of packets are adopted: the *Interest* and the *Data* packet. See Figure 2. A consumer initiates the communication process by sending a request by means of an Interest, for the desired content.

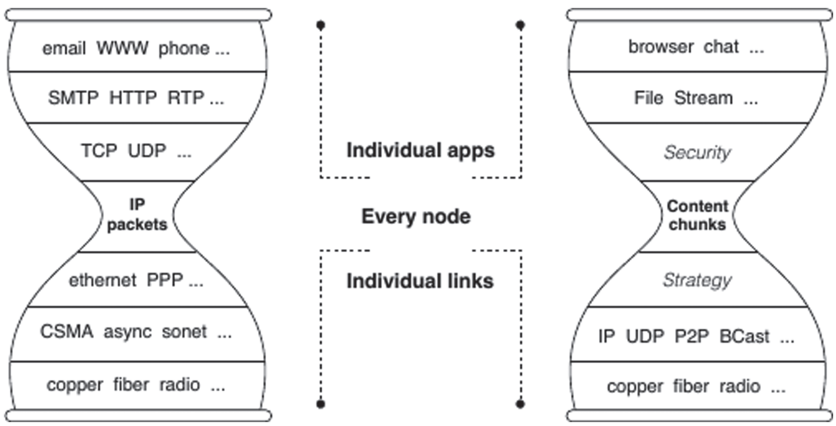


FIGURE 1 Hourglass-shaped Internet (left) and NDN (right) architecture. The main difference and advantage of NDN is reflected in the network layer. The Internet equivalent transport layer is embedded in the NDN network layer[29]

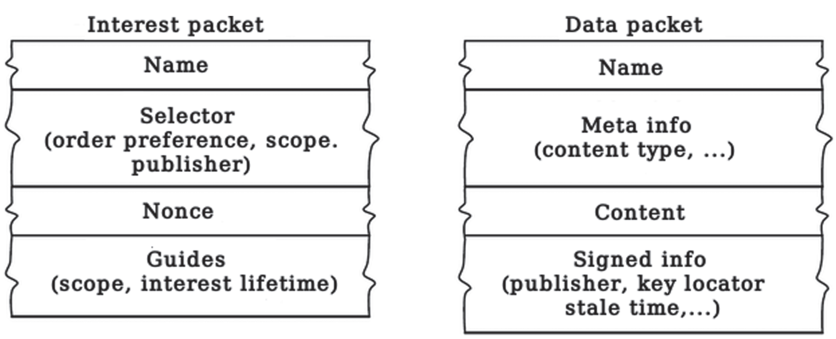


FIGURE 2 NDN packets. Interest (left) and Data (right). Details for packets specification in previous work[30]

When an Interest is sent out, it is forwarded (upstream path) through different nodes toward the content provider. When corresponding content is found, it is sent back (downstream path) to the requester node following the reverse path used by the Interest (i.e., by breadcrumbs). The status information created and saved along the upstream path is used to guide the data back. With this approach, data looping is avoided. Interest looping is avoided by combining the content name (CN) with a *Nonce*—a random number generated to unambiguously identify an Interest. Figure 3 shows the forwarding process within the NDN forwarder daemon (NFD).[31]

Each NDN node contains a structure composed by the content store (CS), the pending interest table (PIT), and the forwarding information base (FIB), for packet (interest and data) management.[4,5]

3.2 | Routing and forwarding

The core characteristic of NDN paradigm shift compared with the host based is the content naming and its subsequent name-based routing and forwarding. In NDN, all contents are unambiguously identified and retrieved by their names—a content name (CN). The CN is opaque to the network, which means that NDN routers know nothing about their meaning; however, they know how to delimit each component of it. This scheme brings the possibility for applications to be able to choose the naming standard and allows naming schemes to grow individually within the network.[32]

The CN is unique. However, the content it identifies may be spread over several locations on the network, from servers that share content to different routers across the network. It must be globally unique if used to access content globally, but does not need to be global for local networks where it can be based on the local context. Differently from other similar projects that adopt the flat scheme, NDN adopts a hierarchical structure for the CN, allowing the routing scalability. The CN lookup in the CS or PIT is performed by searching with one-to-one correspondence. In FIB, the lookup is performed by longest prefix match (LPM).[5]

NDN is designed with routing and forwarding planes separated (Figure 3). This separation allows their development separately. With a complementary role to the forwarding, NDN uses routing to generate and disseminate the initial topology and its policies and to manage the long-term changes.[33] It populates the FIB, and in coordination with the forwarding plane, it makes the assessment and testing of the forwarding interfaces. Whereas the routing plane calculates and decides globally on routes availability, the forwarding plane makes per node decisions about the preference and use of these routes based on their performance and status. That is, routing plane finds and calculates costs of routes toward the requested contents and provides them to the forwarding plane. Figure 4 shows a hypothetical routing procedure in NDN. As referred, routing is name-based. FIB in each node stores the name-prefix and corresponding next-hop (s), in terms of the Face to which the Interest should be sent toward the content provider. There can be multiple stored next-hop for each name-prefix. Moreover, due to node mobility, stored next-hop(s) may be obsolete and thus not leading to any content. Content may be fetched from different sources (which can have the content stored on their CS), or through different paths to the same content provider (multipath routing). For instance, any hypothetical file *report*1, a content under */uminho/algorithm/docs*, required by node A, can be fetched from path $[R1, B]$ or $[R1, R2, B]$, where R1 and R2 are intermediate routers.

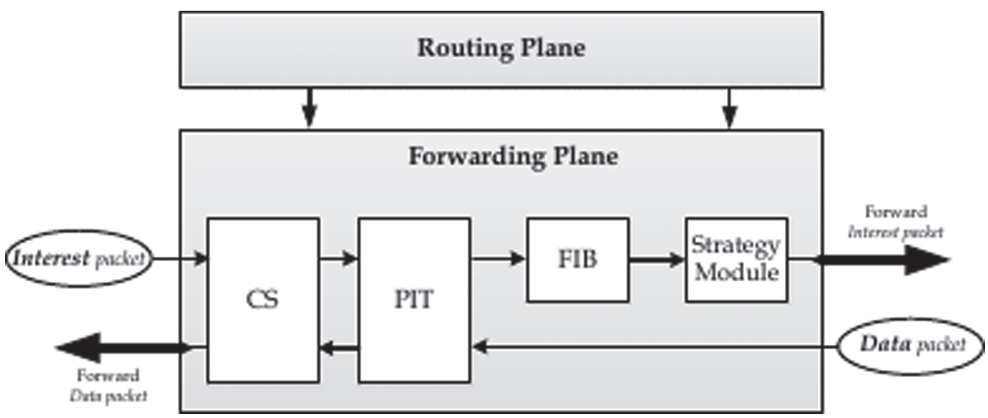


FIGURE 3 Routing and forwarding planes in a NDN router[35]

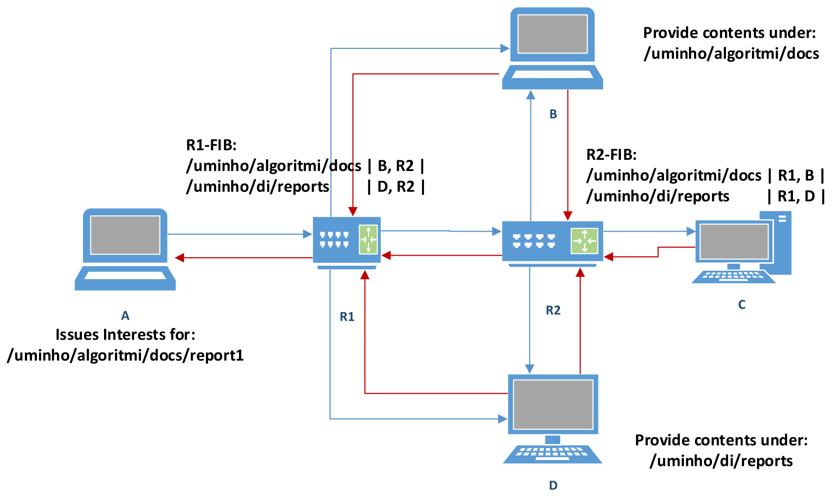


FIGURE 4 Routing procedure

The forwarding plane forwards Interest and contents to the next hop based on these routes or based on broadcasting. Instead of using routing protocols, small NDN-based environments can learn paths and discover the availability of Data by flooding and self-learning.[34]

In contrast with the IP-based network where the forwarding plane is stateless and depends strictly on the routing plane, in NDN, the forwarding plane is similarly intelligent and adaptive, and able to make forwarding decisions based on the interface status in each node.

Although NDN can work without a routing protocol given the intelligence of the forwarding plane, which can detect and recover by itself from any situation of network failure, the need for routing is exhaustively investigated and justified in Yi et al.[33] The aforementioned study raised three questions (i.e., whether the forwarding plan would be capable of retrieving Data on a stable network; if the plane would be capable of efficiently handling link failures; and if it could efficiently handle link recovery) in order to study whether routing would still be as essential as it is in IP-based networks. The aforementioned study concludes that although NDN forwarding plane is smart and capable of handling data dissemination based on flooding and self learning, routing is still necessary. In fact, even for a highly dynamic network, proposals aiming at maintaining and managing some routes in FIB have been proposed.

A good routing protocol should conform with the following functional requirements[13]: (a) present a low latency; (b) present the capability of adapting its addressing mode to unicast, broadcast and multicast; (c) present high delivery rates; (d) at most, cause low additional load; and (e) adapt itself to the specific VANET environments (i.e., highway, suburban, and urban).

Routing in VANET is challenging (if not infeasible at all[36]), due to the characteristic (e.g., high node mobility and intermittent connectivity) of these networks. For this reason, the majority of research for data dissemination in NDN-based VANET resort to broadcast for data dissemination and do not keep and manage routes in FIB (i.e., are based on forwarding strategies and not on routing). Nonetheless, there are several proposed solutions designed to populate and manage routes in FIB and use them to disseminate data. These routes would be more cluster-based than global due to the mobility of the nodes. Several studies deal with these two topics (routing and forwarding) indiscriminately; thus, we discriminate them and focus our survey mainly on routing.

3.3 | In-network caching

One of the most important proprieties of NDN is the capability of caching contents. This is only capable because NDN content is a self-consistent unit.[37] Caching is performed at the node level. Each node is capable of caching content. Resource availability is the only limitation for caching. A cached content can be forwarded to any node requesting it, without the need to retrieve it from the original content source. This propriety provides the possibility of sharing (speeding up content retrieval and delivery), saving bandwidth and decreasing the response time for content request.

TABLE 2 Summary and comparison of a representative related survey papers

Ref.	Year	Period	Cited	Surveyed papers by topic						Total	Limitations of the approach (related to this survey)
				Naming	Forward.	Routing	Caching	Mobility	Security		
Amadeo et al.[56]	2014	[2010–2014]	065	02	05	01	01	00	01	09	Missing relevant literature;
[37]	2015	[2010–2014]	020	00	04	01	00	00	00	05	Limited on routing. Caching and security not included;
Zhang et al.[65]	2015	[2006–2014]	055	00	00	00	16	00	00	16	Only surveys caching and misses relevant literature;
Amadeo et al.[58]	2016	[2010–2014]	015	06	04	01	05	00	02	18	Missing relevant literature;
Yaqub et al.[57]	2016	[2013–2015]	024	00	03	00	00	00	00	03	Only surveys forwarding and misses relevant literature;
Zhu et al.[66]	2016	[2010–2016]	048	03	06	02	04	00	00	19	Missing relevant literature;
Zhang et al.[53]	2016	[2012–2015]	028	00	00	00	00	13	00	13	Only surveys mobility and misses relevant literature;
Liu et al.[59]	2017	[2010–2016]	136	04	18	03	02	00	01	28	Missing relevant literature;
Shemsi and Kadam[67]	2017	[2015–2017]	030	01	11	00	00	00	00	12	Missing relevant literature;
Kerrche et al.[60]	2019	[2010–2019]	055	00	06	00	09	00	03	18	Routing not included; Missing relevant literature on caching;
Khelifi et al.[24]	2020	[2010–2018]	199	11	40	05	07	07	05	75	Relevant literature are missing for routing and caching;
Tariq et al.[61]	2020	[2010–2019]	082	00	23	00	00	00	00	23	Caching, routing and security not included;
Ahed et al.[62]	2020	[2010–2020]	065	00	34	00	00	00	00	34	Caching, routing and security not included;
Chen et al.[63]	2020	[2010–2020]	174	00	00	00	31	00	00	31	Only caching but missing some relevant literature;
Rao and Sharma[64]	2021	[2014–2019]	037	07	00	00	00	00	00	07	Only naming schemes but missing some relevant literature;
Our	2022	[2010-2021]	197	00	00	31	46	00	12	89	Comprehensive but only specific for the selected topics.

NDN is capable of communicating asynchronously; that is, no simultaneous presence of consumer and provider is required. This capability is further empowered by the in-network caching, which also provides the store-and-forward capability required under intermittent connectivity conditions.[38]

3.4 | Built-in security

IP-based VANET inherits the security issues and challenges from that underlying technology, in which the security is based on creating a secure host-to-host channel, to secure the content transmission between them, for each session. In this mechanism, the secure information cannot be re-used when a session expires.[24] To worsen this aspect, the main VANET proprieties (i.e., the varying density, high node mobility, and the time-critical nature of the most VANET applications) enforce that the security mechanisms be time- and bandwidth-efficient.[11]

Security, authenticity, and integrity are key aspects in VANET, and NDN inherently provides them.[18,37] Instead of securing the communication channel, NDN security mechanisms are provided to the content itself.[24] Each NDN Data packet contains a signature piggyback with content source information. Different Encryption/Decryption techniques are used to provide access control.[37]

3.5 | NDN and VANET synergies

Considering the aforementioned NDN characteristics—the name-based content identification for flexible content retrieval, built-in security, and in-network caching combined with the fact that most applications in VANET a content-centric,[39] NDN have been seen as a highly suitable architectural model for VANET, in order to eliminate the TCP/IP related issues. As such, the integration of both VANET and NDN has been proposed by many researchers. Current integration proposals are based on optimized forwarding strategies with customized naming and caching schemes, clean application design, and seamless mobility support, by introducing modifications into the core of NDN, or by proposing new architectural guidelines for adapting NDN for VANET.[24] However, even this integration introduces several issues and challenges which are still lacking effective solutions.

4 | RELATED SURVEYS

Several studies (e.g., literature[36,40–47]) aiming at holistically leverage the characteristics of content-centric networks (CCN)/NDN for VANET have been performed. For specific improvements (i.e., specific for routing, forwarding, caching, privacy, security, and so forth), related references can be found in the many existing reviews and surveys, as presented in Table 2. These studies can be complemented by several surveys and reviews performed on general CCN/NDN (not specific for VANET) issues, such as the naming and routing,[48,49] caching and forwarding,[50,51] transport,[52] mobility,[24,53] and security.[54,55]

The following studies are related surveys. The coverage of these papers ranges from 2014 to 2021, and survey solutions proposed from 2010 to 2020.

Authors in Amadeo et al[56] presented guidelines and highlighted the points of strength and weaknesses on the applicability of CCN principles to wireless networks. The aforementioned study reviewed the state-of-the-art on naming, routing and forwarding, transport, caching, and security applied to mobile ad hoc networks (MANET), VANET, and wireless sensor networks (WSN). This survey is more than 5 years old.

In Bouk et al,[37] concepts such as naming, routing, security, and caching including the research challenges applied to vehicular content-centric networks (VCCN) are presented. This survey is also more than 5 years old, and it is limited in number of surveyed studies.

The surveyed papers by Yaqub et al[57] are also scarce, focusing only on forwarding and missing out several relevant studies within the considered period. This survey is also more than 5 years old.

In Amadeo et al,[58] information-centric networks (ICN) for connected vehicles are surveyed. This study also presents the future perspectives on topics including naming, routing, forwarding, security, and caching. Although covering a large specter of topics, this study does not go deeper on surveying any of these topics, thus leaving out several relevant solutions within the surveyed period. This survey is more than 5 years old.

Aiming at providing references and guidelines for readers with interest on the ICN-based MANET, authors in Liu et al[59] presented a comprehensive overview on this topic and surveyed the proposed solutions including for VANET and delay tolerant networks (DTNs). This study also misses out several studies on the surveyed topics, mainly on routing and caching.

Authors in Khelifi et al[24] presented a comprehensive survey on vehicular named data networking (VNDN) characteristics, where topics such as mobility, routing, caching, forwarding, and security are presented. Although referred, the topic on routing in contrast with forwarding is not sufficiently surveyed.

Authors in Kerrche et al[60] presented the current status and future challenges related to the internet of vehicles. The study is based on a survey including the following topics: forwarding, mobility, security, and caching. This study misses out the topic on routing and several relevant studies on the selected topics.

Authors in Tariq et al[61] surveyed the forwarding strategies, and like Amadeo et al,[56] the review is based on MANET, VANET, and WSN. Additionally, the study presents the future challenges regarding the forwarding in wireless environment. Similar effort was done by Ahed et al,[62] which also focused the survey on forwarding strategies but only for vehicular networks. Both studies cover relatively the same period and as referred only surveyed the forwarding strategies.

Authors in Chen et al[63] performed a comprehensive survey focusing only on caching. This study was published relatively in the same period when the initial data extraction was being performed for the present study. Anyway, the results presented in that paper are complemented by the results produced here. In Rao and Sharma,[64] a brief survey in content naming schemes is performed.

Table 2 presents the summary of the related works.

As shown in the table, forwarding is the most covered topic by the existing surveys. Although some studies referred routing, in fact they only cover forwarding or when including routing they do it indiscriminately from forwarding. Thus, the need to separately survey routing. Apart from the study in Chen et al,[63] which was published relatively in the same period when the extraction of data for the present work was being performed, all other related papers present a relatively light surveying on caching.

In TCP/IP architecture, data plane performs forwarding based on the decisions given by the control plane. In CCN-based architectures, such as NDN, the forwarding plane is stateful and adaptive and capable of performing in local networks without the routing plane.[4,56] Although both planes are explicitly separated and likely to be developed independently, the aforementioned fact apparently makes that the relative difference in terms of importance of both planes seems irrelevant, making the majority of literature treat these two topics indiscriminately. Differently from the related surveys, we discriminate the forwarding from routing as, in fact, these are two different topics. Given that most of the related work have already dealt with forwarding, we focus our effort on routing.

More precisely, besides the other topics (i.e., caching and security, which are scarcely surveyed by most of the related surveys), this work intent to survey solutions applying routing protocols for NDN-based VANET, apart the studies that only propose forwarding strategies, that is, are broadcast-based. Given that literature[36,68] consider infeasible to run a routing protocol in VANET, it is interesting to survey what proposals and what results are given by those studies proposing routing, compared with the broadcast-based solutions.

5 | METHODOLOGY

This section presents the SLR methodology used to conduct the present study. Authors in Biolchini et al[69] and Tranfield et al[70] define SLR as a research methodology used to collect, map, and evaluate the existing scientific knowledge on a specific topic. Based on SLR findings, the researcher can specify a research question to further develop the body of knowledge. This type of review follows a well defined and strict sequence of steps, according to a protocol developed *a priori*.

The present SLR is based on the guidelines proposed by Tranfield et al[70] and Biolchini et al,[69] and refined by Kitchenham and Charters.[71] The steps to follow for performing the SLR are summarized in Figure 5 and explained as follows: (1) planning phase: planning phase can be thought as the protocol definition phase where the methods used to undertake the review are specified. This activity is fundamental to reduce the possibility of researcher bias. The following activities are developed: (a) research question formulation: the research questions are raised and the objectives of the review are defined and (b) selection of sources: selection of the sources where primary studies will be searched; (2) execution phase: this phase can be divided into the following activities: (a) selection of primary studies from the

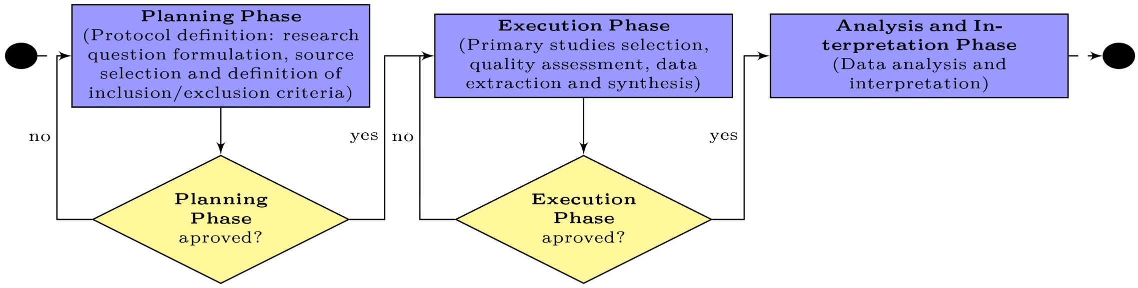


FIGURE 5 Systematic literature review process (adapted from Biolchini et al.[69])

TABLE 3 Keywords and synonyms

Keywords	Synonyms
Named data networking	Named data network; NDN; information-centric network; ICN; content-centric network; CCN
Vehicular ad hoc network	VANET, vehicle to everything, vehicular social, internet of vehicle, IoV, V2X, V2V, V2I
caching	cache; content store

sources; (b) data extraction; and (c) data synthesis; and (3) data analysis and interpretation phase: data are analyzed and interpreted in this phase.

5.1 | Research objectives

The present review aims at studying and assessing the state-of-the-art on improving VANET using NDN. As explained in Section 1, the study focuses in the following topics: routing, caching, and security in NDN-based VANET. An important note is that considering the very specific differences of VANET (i.e., the higher speed, with predictable movements; the highly dynamic network topology with frequent partitions; and the less restrictions related to energy consumption, processing power, and memory availability) from MANET, our study will only focus on VANET.

5.2 | Research questions and search strings

To attain the aforementioned objectives, the following research questions (RQ1, RQ2, and RQ3) are formulated, based on general open challenges for ICN[72–75]:

RQ1. How can named data networking routing be applied to improve VANET?
RQ2. How can named data network caching be applied to improve VANET?
RQ3. How can named data network-based VANET security, privacy, and trust issues be tackled?

From the research questions, *keywords* and *synonyms* were extracted (see Table 3). These keywords are concatenated with boolean operators—*AND* and/or *OR*—to form the *search strings* (see Tables 4 and 5). The search strings are used to gather the primary studies from web search engines. Initially, the search and selection are based on all document metadata and then are refined by reading the title, keywords, abstract, and taking an overview of the full paper.

5.3 | Selected sources and studies

To conduct this study, the following online bibliographical databases were selected: Scopus,[76] Web of Science (WoS),[77] ACM Digital Library (ACM DL),[78] IEEE Xplore,[79] and Google Scholar (GS)[80]—an online search engine (see Table 6).

TABLE 4 Composed synonyms strings per keyword

Composed string (CStr) per keyword	
CStr1	((“Named Data” *AND* network*) *OR* “Information-Centric” *OR* “Content-Centric” *OR* NDN *OR* ICN *OR* CCN)
CStr2	(Cache *OR* caching *OR* “Content Store”)
CStr3	(“Vehicular Ad hoc” *OR* “Vehicle to Everything” *OR* “Vehicular Social” *OR* “Internet of Vehicle” *OR* IoV *OR* V2X *OR* VANET*)

TABLE 5 Strings used to search for primary studies

Search strings	
RQ1	CStr1 *AND* Routing *AND* CStr3
RQ2	CStr1 *AND* CStr2 *AND* CStr3
RQ3	CStr1 *AND* (Security *OR* Privacy *OR* Trust) *AND* CStr3

TABLE 6 Literature sources

Online databases	Scopus, Web of Science, ACM DL, IEEE Xplore
Online Search engine	Google Scholar

The query interface of these databases and search engine is slightly different from each other; thus, a slight adaptation of the search strings was performed for each database or search engine. For instance, a search string composed by three keywords without any explicit boolean operator is interpreted—by Google Scholar, Scopus, and IEEE Xplore—as being AND'd. The same sequence is interpreted by ACM DL as being OR'd. The search strings presented in Table 5 are already adapted to be used on any of the selected source of information without further modification.

Google Scholar, Scopus, and Web of Science are the primary sources used to perform the search. We expect to find, using these search engine and databases, all the studies related to the topics. Nonetheless, the other sources, ACM DL and IEEE Xplore, were also searched, and their results were compared with those obtained with the former search engine and databases.

5.4 | Inclusion and exclusion criteria

To select the correct set of studies related to the researched problem, the inclusion and exclusion criteria must have previously been defined and might be refined along the execution phase. Table 7 presents the inclusion and exclusion criteria defined for this work.

5.5 | Inclusion of primary studies

The search was last updated in June 2022 considered all the metadata for the searched papers. The results are shown in Table 8. A total of 9077, 5300, and 4680 results were found for RQ1, RQ2, and RQ3, respectively.

After this first selection, herein considered as the first stage selection which gave a total of 19,057 articles, a further selection was performed in two more stages.

In the second stage selection, the papers are evaluated by their title and keywords. After the selection, duplicated papers within each query were eliminated. This stage produced 987 papers still to be scanned.

In the third stage selection, the papers were scrutinized by their abstract and by an overview reading. Some selected papers from a given query were found to belong to other queries. The studies were, then, reorganized within the correct query, and the duplicated studies among the queries were eliminated. This stage resulted in a more refined selection of 94 studies.

TABLE 7 Inclusion and exclusion criteria

Type	Criteria
Inclusion	Research papers published either in Conferences or Journals.
	- If a study has conference and journal article versions, the latter is selected;
	- If a study has many published versions, only the newest and the most complete version is selected;
Inclusion	Research papers published between 2010 and 2021.
Exclusion	Studies not specifically addressing elected topics in NDN-based VANET.
Exclusion	Studies only performing surveys and reviews.
Exclusion	Studies not written in English.
Exclusion	Studies addressing the selected topics but with focus on MANET instead of VANET.

TABLE 8 Number of selected studies

						Selection Stages			
	WoS	Scopus	GS	ACM	IEEE	1st	2nd	3rd	%
RQ1	083	2211	6570	107	106	9077	431	34	36.17
RQ2	103	0645	3860	610	082	5300	350	48	51.06
RQ3	058	2437	2030	088	067	4680	206	12	12.77
				Grand total		19057	987	**94**	100.0

Table 8 shows the number of selected studies for each selection stage. The last column shows the percentage of the selected studies per topic, from the total of 94 studies. The papers selected after this process were full read and included in the data extraction process, which is the next step within this execution phase.

Tables 9 , 10 and 11 present the distribution of the primary studies, per sources. As these tables show, only six of the selected studies were found on the ACM DL, and all studies were found using the GS online search engine. Figures 6A, 6B, and 7, respectively, present the same findings by means of bar graphs.

Figure 8 shows the distribution period of the selected studies. The selection of studies was performed between 2010 and 2021, which was chosen considering that the development of NDN architecture started around 2009 and the research aiming at integrating NDN with VANET was started even later. As the figure shows, the development of work aiming at integrating NDN with VANET begun around 2011 with its intensity between 2016 and 2021. It is also shown that among the three selected topics, the majority of studies is being developed for caching in NDN-based VANET (51.06% of all the 94 selected studies).

5.6 | Data extraction and synthesis

After the selection of the primary studies the data extraction process was performed. To facilitate this process, a database sheet was produced. The collected parameters are explained in the following sections, in the following order: routing in Section 5.6.1, caching in Section 5.6.2, and security and privacy issues in Section 5.6.3. We only present extraction and synthesis in this section. Analysis and results interpretation are presented in Section 5.7.

5.6.1 | Research question (RQ1)—routing

This section explains the process of data extraction related to RQ1.

For routing scheme classification, we use the combination of taxonomy and classification proposed in literature.[82,171,172] Table 12 presents the extracted data, based on the aforementioned parameters for RQ1. The first three columns are auto explanatory. The mode of operation indicates the type of proposed protocol, as topology-based, geographic/position-based, based on opportunistic encounters, or cluster-based, as explained in Section 2.4. The type of

TABLE 9 Distribution of the selected primary studies - RQ1

		Source of primary studies				
Study	**Year**	**WoS**	**Scopus**	**GS**	**ACM**	**IEEE**
Arnould et al.[45]	2011	✓	✓	✓	✓	–
Yu et al.[81]	2013	✓	✓	✓	–	✓
Yu et al.[82]	2013	✓	✓	✓	–	✓
Yan et al.[40]	2014	–	✓	✓	–	–
Khan and Ghamri-Doudane[83]	2016	✓	–	✓	–	✓
Wang et al.[84]	2016	✓	✓	✓	–	✓
Anastasiades et al.[85]	2016	–	✓	✓	–	–
Kalogeiton et al.[86]	2017	✓	✓	✓	–	✓
Kalogeiton et al.[87]	2017	✓	✓	✓	–	✓
Kalogeiton et al.[88]	2017	✓	✓	✓	–	✓
Guo et al.[89]	2017	–	✓	✓	–	✓
Maryam et al.[90]	2017	–	–	✓	–	✓
Kalogeiton and Braun[91]	2018	✓	✓	✓	–	✓
Coutinho et al.[92]	2018	–	–	✓	–	✓
Nakazawa et al.[93]	2018	–	–	✓	–	✓
Duan et al.[94]	2018	✓	✓	✓	–	✓
Dong and Li[95]	2018	–	✓	✓	–	✓
Deng et al.[96]	2018	✓	✓	✓	–	✓
Cao et al.[97]	2018	–	✓	✓	–	✓
Rui et al.[98]	2018	✓	✓	✓	–	–
Duarte et al.[99]	2018	✓	✓	✓	–	–
Kalogeiton et al.[100]	2019	✓	✓	✓	–	✓
Xu et al.[101]	2019	–	–	✓	–	✓
Wang et al.[102]	2019	–	–	✓	–	✓
Miyazaki et al.[103]	2019	✓	–	✓	–	✓
Kalogeiton et al.[104]	2020	✓	–	✓	–	–
Xu et al.[105]	2020	✓	✓	✓	–	✓
Yang et al.[106]	2020	–	–	✓	–	✓
Zhang et al.[107]	2020	–	✓	✓	–	–
Ardakani et al.[108]	2021	✓	–	✓	–	✓
Yi et al.[109]	2021	–	✓	✓	–	–
Silva et al.[110]	2021	–	–	✓	–	–
Aldahlan and Fei[111]	2021	–	–	✓	–	–
Siddiqa et al.[112]	2021	–	–	✓	–	✓

application column indicates whether the VANET application is location dependent (e.g., applications related to emergency and traffic information) or location independent (e.g., entertainment applications). When not explicit in the study we considered that the solution is designed for both the location-dependent and location-independent content.

The following are the synthesis of the proposed solutions for NDN-based routing.

In Yan et al,[40] a new vehicular information network architecture is proposed. The proposal includes a naming scheme designed to allow data aggregation and interest segregation, and a proactive position-based routing where the location information is the name of its geographical position. The location information and its correspondent next locations is used in each node to decide which path to forward the content.

TABLE 10 Distribution of the selected primary studies - RQ2

		Source of primary studies				
Study	Year	WoS	Scopus	GS	ACM	IEEE
Grassi et al.[36]	2014	✓	✓	✓	✓	–
Quan et al.[113]	2014	✓	✓	✓	–	✓
Bian et al.[114]	2015	✓	✓	✓	–	–
Liu et al.[115]	2015	✓	✓	✓	–	✓
Deng et al.[116]	2016	✓	✓	✓	–	✓
Grewe et al.[117]	2016	✓	–	✓	–	✓
Mauri et al.[118]	2016	–	✓	✓	–	–
Quan et al.[119]	2016	✓	✓	✓	–	–
Wei et al.[120]	2016	–	✓	✓	–	–
da Silva et al.[121]	2016	–	✓	✓	–	–
Xu et al.[122]	2016	✓	✓	✓	–	–
Abani et al.[123]	2017	–	✓	✓	✓	–
Modesto and Boukerche[124]	2017	✓	✓	✓	–	✓
Zhao et al.[125]	2017	✓	✓	✓	–	✓
He et al.[126]	2017	–	–	✓	–	✓
Duarte et al.[127]	2018	✓	✓	✓	–	–
Fang and Mao[128]	2018	–	–	✓	–	–
Khelifi et al.[129]	2018	–	✓	✓	–	✓
Ma et al.[130]	2018	✓	✓	✓	✓	–
Modesto and Boukerche[131]	2018	✓	✓	✓	–	✓
Ostrovskaya et al.[132]	2018	✓	✓	✓	–	✓
Yao et al.[133]	2018	–	✓	✓	–	–
Van et al.[134]	2018	✓	–	✓	–	✓
Hou et al.[135]	2018	–	–	✓	–	✓
Grewe et al.[136]	2018	✓	✓	✓	–	–
Huang et al.[137]	2018	✓	–	✓	–	✓
Hasan and Jeong[138]	2018	✓	–	✓	–	✓
Yao et al.[139]	2019	–	✓	✓	–	–
Dua et al.[140]	2019	–	✓	✓	–	–
HUang et al.[141]	2019	✓	✓	✓	–	✓
Yao et al.[142]	2019	✓	✓	✓	–	✓
Khelifi et al.[143]	2019	–	–	✓	–	✓
Park et al.[144]	2019	–	–	✓	–	✓
Wei et al.[145]	2019	✓	✓	✓	–	–
Grewe et al.[146]	2019	–	✓	✓	–	✓
Wang et al.[147]	2020	–	–	✓	–	✓
Hasan and Jeong[148]	2020	–	–	✓	–	✓
Zhang et al.[149]	2020	–	–	✓	–	✓
Ud Din et al.[150]	2020	✓	–	✓	–	✓
Yao et al.[151]	2020	–	–	✓	–	✓
Amadeo et al.[152]	2020	✓	–	✓	–	–
Nam et al.[153]	2021	–	✓	✓	–	–

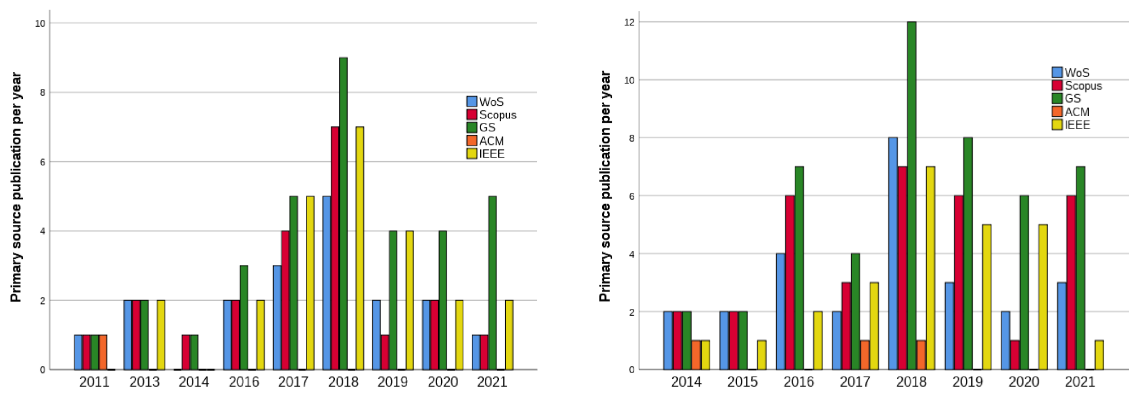
(Continues)

TABLE 10 (Continued)

Study	Year	Source of primary studies				
		WoS	Scopus	GS	ACM	IEEE
Gupta et al.[154]	2021	–	✓	✓	–	–
Yi et al.[109]	2021	–	✓	✓	–	–
Amadeo et al.[155]	2021	–	✓	✓	–	–
Gu et al.[156]	2021	✓	✓	✓	–	–
Kaci and Rachedi[157]	2021	✓	✓	✓	–	–
Chen et al.[158]	2021	✓	–	✓	–	✓

TABLE 11 Distribution of the selected primary studies - RQ3

Study	Year	Source of primary studies				
		WoS	Scopus	GS	ACM	IEEE
Chowdhury et al.[159]	2017	✓	–	✓	✓	✓
Chowdhury et al.[160]	2017	✓	–	✓	✓	–
Zhang et al.[161]	2017	–	✓	✓	–	✓
Khelifi et al.[162]	2018	–	✓	✓	–	✓
Liu et al.[163]	2019	–	–	✓	–	✓
Sattar and Rehman[164]	2019	–	✓	✓	–	✓
Lei et al.[165]	2020	✓	✓	✓	–	–
Manimaran P[166]	2020	–	–	✓	–	✓
Zhou et al.[167]	2020	–	–	✓	–	✓
Rabari and Kumar[168]	2021	✓	–	✓	–	✓
Abdullah et al.[169]	2021	–	✓	✓	–	–
Yao et al.[170]	2021	–	–	✓	–	✓



(A) Primary source publication, per year, for RQ1

(B) Primary source publication, per year, for RQ2

FIGURE 6 Primary source publication, per year, for (A) RQ1 and (B) RQ2

Authors in Kalogeiton et al[87] proposed a routing algorithm based on initial broadcast of Interest for content discovery. Subsequent requests are retrieved by unicast paths created by the Data packet on the downstream. The MAC address is chosen as the unambiguous node identifier and is added as a new field in the NDN packets. The proposal

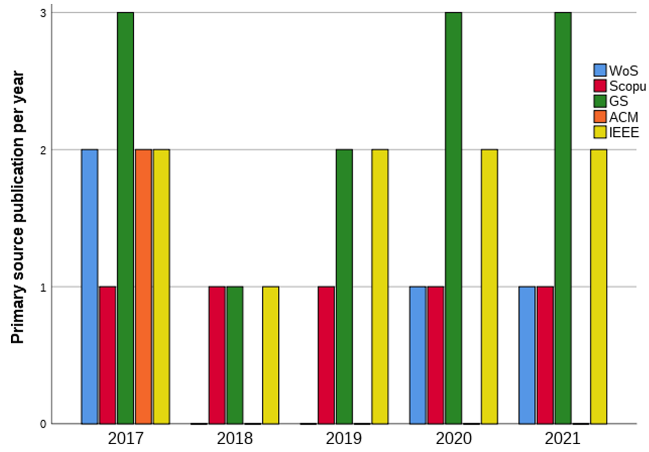


FIGURE 7 Primary source publication, per year, for RQ3

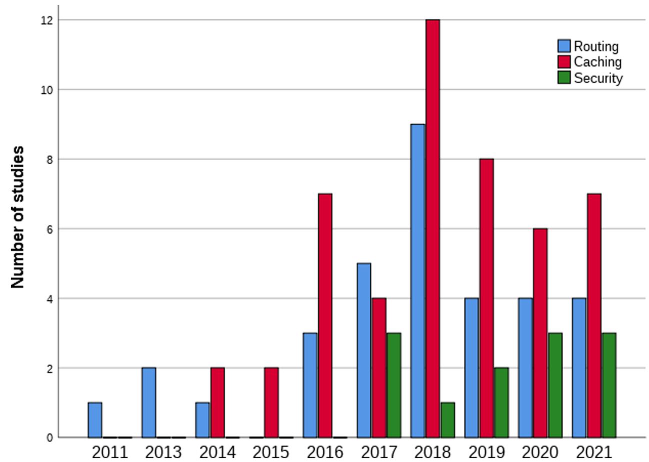


FIGURE 8 Year of publication of the selected studies, per area

uses periodic broadcasts to discover new paths and new content sources. In Kalogeiton et al,[88] the same authors modify the previous proposal now extracting the MAC addresses from the NDN strategy layer. In order to improve the retrievability of information from vehicles and save network resources, the same authors propose in Kalogeiton and Braun,[91] a V2I communication architecture based on NDN, which is then extended to support V2V. For content discovery, the RSU broadcast beacon messages endlessly. The content sources respond the beacon messages by announcing their content prefixes. Also based on MAC addresses to identify the nodes, a geographical aware routing protocol, eGaRP, is proposed in Kalogeiton et al[100] by the same authors. The solution assumes each vehicle has a set of directional antennas used to set unicast transmission to forward the messages in a specific direction after a route has been established. Current geographical coordinates (from a GPS device) of a given vehicle are stored in PIT and FIB and are used by each node to calculate the angle between its own position to the node that should receive the packet to transmit. In Kalogeiton et al,[104] the details of eGaRP, including its performance evaluation, are presented.

Similarly, Anastasiades et al[85] broadcasts the first Interest and when a Data packet returns downstream, by breadcrumbs, the model creates dynamic unicast paths, by setting corresponding FIB entries, that will be further used to retrieve subsequent requests. The model is designed for MANET. Authors in Rui et al[98] adopt the same idea but for VANET and, instead of using CCN Interest and Data for the discovery process, the consumer broadcasts a special packet (REQ), simpler than the Interest, in order to locate the content and then create unicast paths for subsequent packets. The response to the REQ is another special packet, REPLAY, more lighter than CCN Data, which is used to create the unicast paths. Based on nodes' dynamic parameters (e.g., distance, direction, traffic density) the proposal uses the included weight table and the neighbor table to calculate their dynamic score. The node with higher score is chosen as the next-hop.

TABLE 12 Extracted data from primary studies for Research Question (RQ1)—routing

	Model		Mode of operation					Type of appl. (Location-)	
			Topology						
Study	V2V	V2I	Proactive	Reactive	Geographic	Opportunistic	Clustering	Dependent	Independent
Arnould et al.[45]	✓	–	–	✓	–	–	–	✓	–
Yu et al.[81]	✓	–	–	✓	✓	✓	–	–	✓
Yu et al.[82]	✓	–	✓	–	✓	✓	–	✓	✓
Yan et al.[40]	✓	✓	✓	–	✓	–	–	✓	–
Khan and Ghamri-Doudane[83]	✓	✓	✓	–	–	–	–	✓	✓
Wang et al.[84]	✓	–	–	✓	–	–	–	✓	✓
Anastasiades et al.[85]	✓	–	–	✓	–	–	–	✓	✓
Kalogeiton et al.[86]	✓	✓	–	✓	–	–	–	✓	✓
Kalogeiton et al.[87]	✓	–	✓	–	–	–	–	✓	✓
Kalogeiton et al.[88]	✓	✓	✓	–	–	–	–	✓	✓
Guo et al.[89]	✓	–	–	✓	–	–	–	✓	✓
Maryam et al.[90]	✓	–	✓	–	–	–	–	✓	✓
Kalogeiton and Braun[91]	✓	✓	✓	–	–	–	–	✓	✓
Coutinho et al.[92]	✓	–	–	✓	✓	–	–	✓	✓
Duarte et al.[99]	✓	–	–	–	✓	–	–	–	✓
Rui et al.[98]	✓	–	–	✓	–	–	–	–	✓
Nakazawa et al.[93]	✓	–	–	✓	–	–	–	✓	–
Duan et al.[94]	✓	–	–	✓	–	–	–	✓	✓
Dong and Li[95]	✓	–	–	–	–	–	✓	✓	✓
Deng et al.[96]	✓	–	✓	–	–	–	–	–	✓
Cao et al.[97]	✓	–	–	–	✓	–	–	–	✓

TABLE 12 (Continued)

Study	Model		Mode of operation					Type of appl. (Location-)	
			Topology						
	V2V	V2I	Proactive	Reactive	Geographic	Opportunistic	Clustering	Dependent	Independent
Kalogeiton et al.[100]	✓	–	–	✓	✓	–	–	✓	✓
Xu et al.[101]	✓	✓	–	✓	–	–	–	✓	✓
Wang et al.[102]	✓	✓	–	✓	–	–	–	✓	✓
Miyazaki et al.[103]	✓	–	✓	–	–	–	–	✓	–
Yang et al.[106]	✓	✓	–	–	✓	–	–	✓	✓
Kalogeiton et al.[104]	✓	–	–	✓	✓	–	–	✓	✓
Xu et al.[105]	✓	–	✓	–	✓	–	–	✓	✓
Zhang et al.[107]	✓	–	–	–	–	–	✓	✓	–
Ardakani et al.[108]	✓	✓	–	–	–	–	✓	✓	✓
Yi et al.[109]	✓	✓	–	✓	–	✓	–	✓	✓
Silva et al.[110]	✓	✓	✓	–	✓	–	–	✓	✓
Aldahlan and Fei[111]	✓	–	–	✓	–	✓	–	✓	✓
Siddiqa et al.[112]	✓	✓	–	✓	–	✓	–	–	✓

Authors in Cao et al[97] proposed an unicast-based routing protocol for efficient video sharing in vehicular networks. Having demonstrated in Xu et al[173] that users with similar interests present higher probability to request similar videos, the proposal classifies the mobile users into multiple families (relying on the estimation of mobility similarity and user preference similarity pattern) based on which the videos are shared.

Authors in Yu et al[82] propose a hierarchical NDN-based routing scheme that uses bloom filters (BF)[174] for content advertisement—hierarchical bloom filter routing (HBFR). The authors assume that data in ICN can be categorized into (1) popular public data services—where the services retrieve publicly shareable data; (2) popular private data services—related to popular data services that produce private data; and (3) unpopular data services, such as private messaging. Moreover, they consider that for each of these categories, it may be necessary to choose an appropriate routing design category. Thus, they chose and designed their proposal for the popular data services (1 and 2). In HBFR, nodes in their corresponding clusters periodically summarize the content to create their content digests (a BF), which are then used to advertise (by flooding) the local content of the partition where they belong to. For rebroadcast avoidance, the study uses a purposely designed forwarding mechanism based on defer timers.

A reactive socially aware routing protocol is proposed in Khan and Ghamri-Doudane.[83] The proposal is based on vehicle centrality metrics (leveraging the vehicles computing, caching and communicating capabilities) and confine the packet broadcast by routing it selectively toward information facilitator vehicles with the best vehicle centrality score.[175,176]

Authors in Wang et al[84] propose a routing protocol that optimizes the routing path by a distance metric, in place of the hop-count, to estimate the link quality of communication nodes. Additionally, the proposal uses what the authors dubbed as the incremental broadcast and adaptive broadcast strategy, which are based on the vehicle density (i.e., sparse, normal and dense) in the network.

Authors in Guo et al[89] proposed a content routing based on link expiration time (LET), which is used to calculate the expiration time of each interface listed on FIB and select from it the best routing path. This proposal does not describe much of the mechanism that take place to populate or maintain the FIB.

The study in Nakazawa et al[93] proposes a CCN-based framework for IVC that first tackles the content naming (a scheme based on geographical and traffic information) in IVC, then routing (for relay vehicle selection) and caching search, to minimize the cache miss. In the proposed mechanism, data packets are also forwarded by selecting relay nodes instead of using breadcrumbs.

The study by Duan et al[94] explores caching for routing decision by allowing each vehicle in the network to perform flooding, requesting each other node to share the list of their cached content. In addition, the study refers to a supposed distance prediction algorithm, which calculate a next hop close to the one forwarding the Data. The aforementioned method is not described in the study and it is unavailable. Authors in Silva et al[110] present an idea for a context-aware routing and forwarding model, enhanced by mobility prediction and caching for routing decision. The proposal is based on the hypothesis that for better efficiency, routing should adapt to the specific environment or for each specific application type, because they present different characteristics among them.

A topic (i.e., road and safety, entertainment, public services) based clustering and routing mechanism is proposed in Dong and Li.[95] A periodic beacon (which includes the cluster's information topic and the expiration time) broadcast is the mechanism adopted by each cluster head (CH) to announce the existence of its cluster. One of the main aim of this proposal is to maintain and control the growth of the FIB. Also based on clustering, Ardakani et al[108] proposed a routing model where the single-hop clusters are formed according to the mobility of nodes (e.g., vehicles moving in the same region, on the same road and lane) using Hamming distance technique. A CH in each partition is responsible of performing data aggregation, intra-cluster communications, and dissemination of content among clusters. Authors in Zhang et al[107] combined the advantage of encounter-aware and clustering to propose a cluster and CCN-based routing protocol. The proposal introduces a new table, in place of FIB, that aggregates the encounter information. Based on this new table, CH is responsible on forwarding requests toward vehicles in the cluster or to other CH belonging to other clusters. The CH periodically updates and exchanges cluster tables in order to share the encounter information among them. Vehicles are clustered according to their trajectory. Also based on tracking the content locations and using last encounter information, a routing protocol is proposed in Yu et al.[81] Vehicles keep exchanging their content list and locations whenever they encounter each others. Vehicles periodically advertise to one-hop neighbors a list containing a summary of contents in the node. When later a node receives an Interest with a name matching an entry on the list of content locations, geo-routing is used to forward the Interest. Other way, the Interest is flooded. For rebroadcast avoidance, the proposed scheme adopts a timer-based rebroadcast mechanism used to allow the broadcast when the timer elapses before the vehicle overhear a broadcast of the same packet. Also using a defer timer for retransmission control is the proposal by Coutinho et al,[92] in which the TTL is used to control the number of transmissions in each node.

Authors in Siddiqa et al[112] propose a cluster-based social vehicular routing protocol focused on avoiding broadcast storm when vehicular communication links breaks. Vehicles are clustered in communities. RSU concentrates information about all clusters and is responsible of electing new CH whenever the previous leaves the cluster. The work in Aldahlan and Fei[111] proposes a new routing algorithm based on the road traffic distribution. Vehicles opportunistically exchanges beacon messages in order to identify each other on the same road. For packet forwarding, the proposal uses, the exchanged information to build a map graph and compute a shortest path toward the content source. The well-traveled roads are chosen over the less-traveled ones. In Yi et al,[109] the authors propose a routing scheme in which the degree of centrality and content interest are used as base for content routing. This proposal constructs community areas around the RSU coverage area. A mobile edge server (MES), which deals with real-time content requests, is deployed in each community and is responsible of managing communications among vehicles and the RSU. A fog server, which deals with non-real-time content requests, is deployed to manage the content distribution between two or more communities.

Authors in Deng et al[96] proposed a routing protocol in which FIB entries are incrementally updated, instead of deleting and reconstructing them when the vehicle routes change due to its mobility. A new packet, dubbed resource packet, is added to the architecture and periodically broadcasted to announce new prefixes.

CCN architecture is extended in Arnould et al[45] to include a so-called event packet, which can be seen as a modified unsolicited Data packet. The task of this packet is to disseminate push-based messages about emergency events or road traffic. In addition, FIB is modified in order to adapt it to be able to prefer and choose some faces, depending on their characteristics (e.g., cost, latency requirement or bandwidth). The study in Duarte et al[99] extends the functionality of NDN for VANET by introducing a new packet, advertisement packet, that is send by the content source to announce its new content. In addition, FIB is modified to include the geographical location of the content source, from where the advertisement packet originated, instead of storing the next-hop information. Two content dissemination approaches are considered: (1) the advertised content, which refers to sending the advertisement packet, and (2) the on-demand content, where vehicles requests content not yet advertised.

Authors in Xu et al[101] proposed a transmission protocol based on dynamic directional interface mapping, which in turn, is based on the node movement patterns. Vehicles are equipped with virtual interfaces which a remapped whenever driving directions of vehicles change. The remapping method is responsible for updating and maintaining the validity of FIB and PIT entries. One directional interface is selected for forwarding according to the position of the next hop. All interfaces are used to broadcast when no corresponding FIB entry is matched.

A NDN-based framework for vehicle communications is proposed in Wang et al.[102] In the proposal, vehicles and infrastructure cooperate to facilitate the communication process, and the RSU are responsible for caching popular content.

The study by Miyazaki et al[103] proposed a vehicular traffic information collection and routing protocol using virtual nodes (VN). A virtual node is a logical node maintained at a specific road intersection, and it is responsible for collecting traffic information from all road segments adjacent to the intersection and share it with all vehicles passing by that intersection. When a virtual node moves from the intersection, another vehicle is selected, and FIB, PIT, and CS are transferred from the former virtual node to it, which then is assumed as a new virtual node. Routing relays packets preferentially via VN.

Authors in Xu et al[105] proposed a hybrid routing protocol based on Name and ID. The protocol combines the routing based on names, from CCN architectures, and the ID-based routing, from IP based architectures to address the mobility issue and the broadcast storm problem. In the proposed protocol, the nodes request data by CN. Then, having the content location, the ID-based routing is triggered. Using the corresponding position, the protocol computes the route toward the destination host. When the content provider is unknown, a flooding process takes place. In order to reduce the impact of broadcast storm, the flooding is controlled by counting the number of forwarded packets in each node. When this number reaches a specified threshold the node stops sending packets.

The study in Kalogeiton and Braun[90] proposed a proactive routing, which uses a neighborhood table (NT) as a complement to the FIB in order to maintain route entries toward the content sources. A periodic beacon is broadcasted to keep updated the NT and FIB.

Authors in Yang et al[106] configured static FIB routes on NDN routers deployed in a hierarchical hyperbolic NDN-based backbone architecture, to achieve an efficient and scalable content retrieval from data centers. The model defines hyperbolic planes in the hierarchical architecture to offload the traffic to high-level routers, making static FIB entries able to forward packets.

5.6.2 | Research question (RQ2)—caching

This section explains the process of data extraction related to RQ2.

For classification of caching scheme we use the combination of taxonomy and classification proposed in literature.[24,117,177] Table 13 presents the extracted data, based on the aforementioned parameters, for RQ2. The parameters used in the mentioned table are explained as follows: The type of scheme can be either (a) the content caching strategy, which is used to decide *where* to store *which* Data and (b) the content replacement policy, which is used to decide *which* content to evict when the CS is full and new content need to be stored. The caching schemes can be grouped into (a) popularity—when caching is performed based on the content requesting frequency; (b) cooperative—when the caching nodes cooperate to make a decision on where to store *which* content; (c) probabilistic—when the probability of content requesting is the main metric used to decide on caching; and (d) location based or mobility aware—when content is cached in pre-selected nodes, to attain higher cache hits (e.g., core/edge routers, BS, AP, or RSU). The caching mode can be either (a) reactive—when caching is triggered on consumer request and (b) proactive—when the content is pre-fetched, before it is requested.

Proactive schemes

The proposal in Modesto and Boukerche[131] proactively distributes and caches popular content in the selected and reserved CS, within the network. The caching mechanism is based on collaborative observation of locality in request frequency, which is assessed by means of a log record of overheard requests stored in each node, whenever it receives a location-dependent content request. Another proactive caching mechanism is proposed in Grewe et al.[117] The proposal proactively caches content at a predicted AP where a vehicle will connect to. To activate the mechanism, vehicles must request an initial INTEREST (which includes the current position/location, speed, INTEREST frequency, Data Object, RSU position, and the transmission range of the RSU) for a data object from the network. The provided information is used by the strategy to calculate the optimal chunk distribution onto the available RSU. Authors in Mauri et al[118] propose a proactive solution that formulates the optimization problem as an integer linear programming (ILP) problem of optimally placing the content chunks. The impact of the following parameters on the retrieval probability, number of users in the system, the AP available bandwidth, the propagation latency, and the size of the available caches, is also evaluated.

Authors in Quan et al[119] propose a proactive and popularity-aware caching strategy where the content popularity is calculated both at the whole content and at the chunk level. Another cooperative- and popularity-based caching scheme is proposed in Yao et al.[133] The proposed solution caches popular contents at a set of mobile nodes presenting the longest sojourn time in a given hot spot region. The proposal is based on mobility prediction. The vehicle's mobility history is used to train the prediction algorithm (based on partial matching) in predicting vehicle's probability of reaching a given hot region. The same authors[139] proposed another cooperative caching scheme with mobility prediction, but this time based on social attributes. The scheme design is based on the observation that moving vehicles are liable to contact each other according to common interests, or social similarities of their drivers/users. Yet another collaborative caching strategy based on socialized relations is proposed by Liu et al.[115] The solution is designed only for video streaming, and its caching decision is based on the minimum vertex cover set theory in static networks. Authors in Wei et al[120] encode video streams into different layers depending on the video quality. When requesting video, the consumers indicate the desirable quality, then the intermediate nodes cooperatively cache the video chunks according to the requested layers. Another proposal for video streaming is proposed by Gupta et al.[154] This proposal is based on a two layer hierarchical architecture (core layer and the edge layer), with the nodes in edge layer grouped into clusters. Only edge routers perform caching. In addition to the content popularity, the proposal includes the predicted rating score for content placement decision.

Authors in Hou et al[135] considered the problem of caching services in VANET, looking at both the mobility and storage. The problem was modeled using Markov decision processes. A heuristic Q-learning solution together with a mobility prediction scheme is proposed. Based on the speed of a requester vehicle, authors in Chen et al[153] calculate the downloadable amount of an intended content to be pre-cached at the next RSU, where the vehicle is heading to. The proposal by Park et al[144] proactively distributes content at the RSU according to the movement of the vehicles. The strategy calculates the content size needed by a vehicle and caches some chunks onto present RSU, and based on transition probabilities derived by Markov model, it distributes the remaining content chunks on other RSU. Also, mobility-aware is the proactive caching strategy proposed by Khelifi et al.[129] On content request, the proposed solution calculates and selects the next number of chunks that will be fetched by this vehicle and caches them on the next RSU, as

TABLE 13 Extracted data from primary studies for Research Question (RQ2)—caching

Study	Pred.	Type of Solution		Caching scheme				Caching mode		Commun. mode	
		Strategy	Policy	Popularity	Cooperative	Probabilistic	Location	Reactive	Proactive	V2V	V2I
Grassi et al.[36]	–	✓	–	–	–	–	–	✓	–	✓	✓
Quan et al.[113]	–	✓	–	–	✓	–	–	✓	–	✓	✓
Bian et al.[114]	–	✓	–	–	–	✓	✓	✓	–	✓	–
Liu et al.[115]	–	✓	–	✓	✓	–	–	–	✓	✓	✓
Deng et al.[116]	–	✓	–	–	–	✓	–	✓	–	✓	–
Grewe et al.[117]	✓	✓	✓	–	✓	–	✓	–	✓	–	✓
Mauri et al.[118]	–	✓	✓	–	–	✓	✓	–	✓	–	✓
Quan et al.[119]	–	✓	–	✓	–	–	–	–	✓	✓	✓
Wei et al.[120]	–	✓	✓	–	✓	–	–	–	✓	✓	✓
da Silva et al.[121]	–	✓	–	–	–	–	–	–	✓	✓	✓
Xu et al.[122]	–	✓	–	–	✓	✓	–	✓	–	✓	✓
Abani and Braun[123]	✓	✓	–	–	–	✓	✓	–	✓	–	✓
Modesto and Boukerche[124]	–	✓	✓	✓	–	✓	✓	✓	–	✓	–
Zhao et al.[125]	–	–	✓	✓	✓	✓	–	✓	–	✓	–
He et al.[126]	–	✓	–	✓	–	✓	–	✓	–	✓	✓
Duarte et al.[127]	–	✓	–	✓	–	✓	–	✓	–	–	✓
Fang and Mao[128]	–	✓	–	✓	✓	–	–	✓	–	✓	–
Khelifi et al.[129]	✓	✓	–	–	–	–	✓	–	✓	–	✓
Ma et al.[130]	–	✓	–	✓	✓	✓	✓	✓	–	–	✓
Modesto and Boukerche[131]	–	✓	–	✓	✓	–	✓	–	✓	✓	–
Ostrovskaya et al.[132]	–	–	✓	✓	–	–	–	✓	–	–	✓
Yao et al.[133]	✓	✓	✓	✓	✓	✓	✓	–	✓	–	✓
Van et al.[134]	–	✓	✓	✓	–	✓	–	✓	–	✓	–
Hou et al.[135]	✓	✓	–	✓	–	–	–	–	✓	–	✓
Grewe et al.[136]	–	✓	–	✓	–	–	–	–	✓	✓	✓
Huang et al.[137]	–	✓	✓	✓	✓	–	–	✓	–	✓	✓
Hasan and Jeong[138]	–	✓	–	✓	–	–	–	–	✓	✓	✓
Yao et al.[139]	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓
Dua et al.[140]	–	✓	–	–	–	✓	–	✓	–	✓	–
Huang et al.[141]	✓	✓	✓	✓	✓	–	✓	–	✓	✓	✓

(Continues)

TABLE 13 (Continued)

Study	Pred.	Type of Solution		Caching scheme				Caching mode		Commun. mode	
		Strategy	Policy	Popularity	Cooperative	Probabilistic	Location	Reactive	Proactive	V2V	V2I
Yao et al.[142]	–	–	✓	✓	–	–	–	–	✓	–	✓
Khelifi et al.[143]	–	–	✓	✓	–	–	–	✓	–	✓	–
Park et al.[144]	✓	✓	–	–	–	✓	✓	–	✓	–	✓
Wei et al.[145]	–	✓	✓	–	–	–	–	–	✓	✓	✓
Grewe et al.[146]	–	✓	–	–	✓	–	–	–	✓	✓	✓
Wang et al.[147]	–	✓	–	✓	–	✓	–	✓	–	–	✓
Hasan and Jeong[148]	–	✓	✓	✓	–	–	–	–	✓	✓	✓
Zhang et al.[149]	✓	✓	–	✓	–	–	–	–	✓	✓	✓
Ud Din et al.[150]	–	✓	–	✓	–	–	–	–	✓	–	✓
Yao et al.[151]	✓	✓	–	✓	–	–	–	–	✓	✓	✓
Amadeo et al.[152]	–	✓	✓	✓	–	–	–	✓	–	✓	–
Nam et al.[153]	✓	✓	–	–	–	–	–	–	✓	✓	✓
Gupta et al.[154]	–	✓	✓	✓	✓	–	–	–	✓	✓	✓
Yi et al.[109]	–	✓	✓	✓	–	–	–	✓	–	✓	✓
Amadeo et al.[155]	–	✓	✓	✓	–	–	–	✓	–	✓	✓
Gu et al.[156]	–	✓	✓	✓	✓	–	–	✓	–	✓	✓
Kaci and Rachedi[157]	–	✓	–	✓	–	–	–	✓	–	–	✓
Chen et al.[158]	–	✓	✓	✓	–	✓	–	✓	–	✓	✓

predicted by the mobility prediction algorithm, proposed in Zhao et al.[178] Another proactive and mobility prediction-based scheme is proposed in Abani et al.[123] This scheme calculates and locates the pre-fetching node that minimizes uncertainty. The uncertainty is quantified by entropy. The mobility prediction algorithm is based on Markov models and a set of prior mobility traces. Authors in da Silva et al[121] consider the existing access points (AP) alongside the road for caching. Additional control packets are used to disseminate individual interests containing information regarding users' trajectories. Also with mobility prediction, authors in Huang et al[141] propose a cooperative and cluster-based caching scheme that aims at mitigating the impact of node mobility on the network performance. Prior to caching, the proposed solution performs the clustering of vehicles presenting similar mobility patterns. Then, it creates communication among clusters by enabling the RSU to cache popular Data to the CH. The authors prior study, in Huang et al,[137] does not include mobility prediction. It includes a replacement strategy based on content popularity.

With focus on autonomous vehicles, the proposal in Zhang et al[149] predicts a user mobility (based on the velocity and position) and the user's preferences (based on user's demand and previous video popularity) and then proactively caches the videos that are likely to get requested at the next fixed infrastructure (i.e., RSU or BS). The proposal in Yao et al[151] takes advantage of the past mobility history of vehicles to estimate the time gap from the current location to the new (predicted by HMM) location. It uses the time gap to estimate the sequences of video chunks needed around that predicted location and proactively caches them on the existing RSU, to provide them to the vehicle as soon as they arrive at the predicted location. Without predicting the vehicle mobility, the proposal by Grewe et al[136] learn the data popularity and prefetches popular content at the network edge AP. The same authors[146] propose a cloud-like caching-as-a-service infrastructure, where opportunistically vehicles exchange their cache contents whenever they encounter each other. This scenario is referred to as a potential virtual cache area where vehicles proactively store and retrieve contents.

In Hasan and Jeong,[138] the content store is divided into two categories (i.e., proactive caching storage and reactive caching storage). The Zipf distribution is used to calculate the content popularity, from which the most popular content is proactively cached into the first caching category. In Hasan and Jeong,[148] the same authors proactively cache popular content at the RSU for better content distribution, when vehicles in the vicinity of the RSU require it. The cache prediction mechanism (which uses the principle of the content locality) is rewarded whenever a proactively cached content is accessed.

Authors in Ud Din et al[150] add a new table (named Address Table [AT], for storing the addresses of left, right, and front RSUs) to ICN. All content requests are forwarded to the RSU, which are responsible for caching contents. When a requested content is not available, the RSU forwards the request further to the BS, which is designed to have a broader information about all the RSU in a given area. Each RSU forwards back the requested content and caches the content to their next left, right, and front RSUs.

A caching strategy that uses machine learning to predict the requests for Interest and build a decision tree is proposed in Wei et al.[145] The strategy works following the three steps: (a) sample extraction; (b) feature calculation; and (c) construction of decision tree and the pruning optimization. This strategy and an alternate replacement policy (based on popularity and request cost) are only deployed on the RSU.

Reactive schemes

In Quan et al,[113] a cooperative caching strategy based on social cooperation schemes is proposed. The cooperative scheme is grouped into (1) partner-assisted, composed of vehicles within one-hop range and moving in the same lane with the consumer or producer vehicle, and (2) courier-assisted, composed by vehicles within the communication range of the consumer or producer, but circulating in adjacent lanes.

In Modesto and Boukerche,[124] the caching decision is recommended by the content provider. The recommendation is based on the actual cache distance and frequency of the content requests. In Fang and Mao,[128] the decision on which content chunks to cache is based on content: (a) popularity; (b) vehicle connectivity; and (c) the vehicle caching status, which is obtained by other vehicles with the assistance of a BS. In the aforementioned proposal, vehicles select and only cache some chunks of the overheard content. When a vehicle overhear a transmitted content, the algorithm proposed in Zhao et al[125] decides whether to cache the content or not. This decision is determined by assessing the content similarity which indicates whether the vehicle drivers have similar hobbies. The authors also proposed a popularity-based prediction replacement mechanism, designed to reduce the overhead of cache replacement by predicting and evicting the content with the lower popularity whenever necessary. Another popularity based scheme is proposed by Yi et al.[109] This proposal divides the CS into two, that is, 80% of CS for popular contents and the remaining 20% for the non-popular contents. A table, content popularity monitor table (CPMT), is included for monitoring the content popularity.

CPMT is updated by abstracting the content name and type of Interest instead of Data. Also based on content popularity, Van et al[134] propose a caching strategy whose caching decision is based on the requirements of different types of applications and metrics, such as the vehicle link stability, content popularity, and CS occupancy. The first step performed by the strategy is to identify the application type based on the application name in the Data packet. Then, the decision is triggered and computed considering the identified application type.

Besides the popularity, Amadeo et al[152] include the content residual lifetime (RL) for caching decision. RL is included in order to limit the number of packet replacement due to lifetime expiration. In Amadeo et al,[155] the same authors extend the previous work, adding the availability of the content in the neighborhood, to improve content diversity. Instead of using availability for content diversity, Gu et al[156] distribute content evenly, resorting to the differences between the popularity of different types of content. This study introduces the node value (determined according to the connectivity, betweenness centrality, and eigenvector centrality) for selecting cache content and cache location.

A content location-aware and probability-based caching scheme is proposed in Ma et al.[130] When a content is overheard, the proposed scheme calculates the content relative popularity and the cache interval, both metrics used to estimate the caching probability. For content popularity, different weights are used and larger wights are assigned to requests coming from nodes closer to the current RSU.

Authors in Bian et al[114] propose three heuristic strategies (i.e., random caching, density aware, and forwarder-centered strategy) to reduce the cached copies produced by the NDN default strategy. For caching, the scheme chooses a sample of vehicles among all capable of caching, instead of allowing all vehicles to cache. The solution focuses on globally reducing the number of individual content copies instead of the cached content of a particular vehicle. The authors in Chen et al[158] divided the IoV applications in categories (i.e., emergency safety, traffic efficiency, and infotainment message) and then designed a caching decision strategy tailored to the specific characteristics of each of these categories. For the specific case of the emergency safety messages, given that NDN uses pull-based mechanism for data dissemination, vehicle in the proposed solution periodically sends a series of interest packets requesting the traffic safety events.

The proposal by Deng et al[116] focuses on probabilistically deciding whether to cache content or not, on intermediate nodes. This decision is evaluated in order to solve the problem of cache redundancy. Three factors are considered for this evaluation: (1) preference of vehicles; (2) importance of the vehicle, assessed by measuring the centrality of the vehicle in the ego network (local network formed by a node and its one-hop neighbors); and (3) relative movement of the vehicles.

In Grassi et al,[36] the authors present a description and a performance assessment of their previous study,[68] where they proposed a NDN-based VANET architecture. Considering characteristic of VANET, such as the ability to provide continuous power supply and high computational capability (storage), and leveraging the wireless broadcast nature, the proposed architecture[68] presents a caching scheme where instead of only caching content corresponding to the issued Interest, the design allows every node in the broadcast range to accept and store all overheard content, regardless of whether it has a matching PIT entry or whether it needs the received content.

Authors in Duarte et al[127] propose an SDN-based caching scheme where RSU controller (instructed by the SDN controller) set chosen vehicles in the network, as influential nodes.[179] When the number of requests for a particular content reaches a previously defined popularity threshold (fixed by the SDN controller), the RSU and the content provider sends to these vehicles the popular contents to be stored. Designed for video streaming, Xu et al[122] proposed a cooperative caching mechanism that is based on Information centric cloud. The information-centric cloud calculates the available load space for the nearby nodes of the requesting vehicle, to determine the proper cooperative caching nodes. The selected caching nodes are assigned the probability of caching, which increases with the available load space. The study in Kaci and Rachedi[157] proposes NDN-based networking architecture for IoV. The architecture, which is based on Real-time Onsite Operations Facilitation (ROOF),[180] is composed of three levels (i.e., a Cloud level, a Fog level, and a ROOF level). To facilitate content caching, the authors propose a machine-learning–based data caching mechanism, used to predict the content popularity and store popular content in the Roof level (i.e., in the RSU) and the less popular content in the Fog level.

Replacement schemes

The proposal in Yao et al[142] incorporates the future content popularity for caching replacement decision. Metrics such as the characteristic of the received interests, the verified request ratio and frequency, and the content priority are used to access the content popularity. The content popularity is predicted by a Hidden Markov Model (HMM) based algorithm. The received content is stored in CS by a descending order of the predicted popularity, and similar to Zhao et al,[125] whenever necessary the content with lower popularity is (automatically) evicted.

A caching replacement policy based on multiple metrics is proposed in Ostrovskaya et al.[132] The scheme considers three factors for replacement decision: (1) the content popularity; (2) the freshness; and (3) the distance between the location of two specific nodes. When a replacement is required, the proposal uses the aforementioned factors to calculate the candidacy score for each content in CS. The three factors are all mandatory to calculate the candidacy. The average weight of each of these parameters is computed and the content with the lower weight is the candidate for replacement. Another caching policy, aiming at selecting and caching the highest popularity and evicts the lowest popular content is proposed by Khelifi et al.[143] The proposal is based on (1) content classification and cache splitting into subcache stores, according to traffic classification and (2) caching and replacement whenever necessary, based on content popularity where each sub-cache store is allowed to only cache Data related to its class.

5.6.3 | Research question (RQ3)—security, privacy, and trust

This section explains the process of data extraction related to RQ3—security, privacy, and trust.

Security and privacy issues posed by the underlying IP protocol stack in VANET[181–183] are naturally resolved by the core characteristics of NDN. However, new security and privacy challenges, specific for the underlying NDN architecture[54] still need to be tackled. Several vulnerabilities that can be exploited by attackers in NDN-based VANET include (a) Interest Flooding Attack (IFA); (b) Cache Poisoning Attack (CPA); (c) False Information Injection Attack (FIIA); and (d) Privacy Violation Attack (PVA) (e.g., vehicle tracking) by means of the content names.[55,184–186]

Although some security and privacy issues related to IP-based VANET are common to the NDN-based VANET, we only focus our attention on the security and privacy issues related to NDN-based VANET. Besides, we only survey solutions for NDN-based VANET not for the general NDN architecture (which can be found in studies such as[187–191]). The reasoning behind this exclusion is that we found several studies/surveys already treating the issues for the IP-based VANET that are common in NDN-based VANET.

Table 14 presents the extracted data for the proposed solutions for security and privacy in NDN-based VANET, and the synthesis of the studies is presented next. The *Collaboration scope* field in the table indicates whether the solution requires collaboration among vehicles or if the nodes independently perform the countermeasure.

Aiming at tackling false information injection and vehicle tracking threats,[159] proposed a four-level hierarchical trust model (which includes autonomous-vehicle organizations, manufacturers, vehicles, and data) and a naming scheme for vehicular authentication. To avoid vehicle tracking, the authors propose a pseudonym scheme whose responsibility is to anonymize vehicle names to protect vehicle identity. In Chowdhury et al,[160] the same authors extend

TABLE 14 Extracted data from primary studies for Research Question (RQ3)—security

					Mitigation			Collaboration scope	
Study	FIIA	IFA	CPA	PVA	Prevention	Detection	Recovery	Individual	Collaborative
Chowdhury et al.[159]	✓	–	–	–	✓	–	–	✓	–
Chowdhury et al.[160]	✓	–	–	–	✓	–	–	✓	–
Zhang et al.[161]	–	✓	–	–	–	✓	–	–	✓
Khelifi et al.[185]	–	–	✓	–	✓	–	–	–	✓
Liu et al.[163]	–	–	–	✓	✓	–	–	–	✓
Sattar and Rehman[164]	–	✓	–	–	✓	✓	–	–	✓
Lei et al.[165]	–	–	✓	–	–	✓	✓	–	✓
Zhou et al.[167]	–	–	✓	–	✓	✓	✓	✓	–
Manimaran P[166]	✓	–	–	–	–	✓	–	–	✓
Yao et al.[170]	–	–	✓	–	✓	✓	–	–	✓
Rabari and Kumar[168]	–	✓	–	–	✓	✓	–	–	✓
Abdullah et al.[169]	–	✓	–	–	✓	✓	✓	–	✓

the previous work,[159] to include an anonymous pseudonym-renewal scheme that combines self-insurance and third-party issuance, and pseudonymous authentication scheme which uses public-key cryptography. The work in Manimaran P[166] also aims at detecting the dissemination of false information, precisely the safety information. The authors propose the use of a set of rules, verified from the information provided by the vehicle sensors. The defined rules are the following: (a) the vehicle should be on the move before the reported event; (b) after the event, the vehicle should have reduced its speed; (c) after the reported event, the vehicle should have its speed reduced by a certain value; d) the heart rate of the driver should have increased after the event; and (e) the vehicle airbags should have been activated after the event.

To mitigate the CPA in the CS, the authors in Khelifi et al[185] propose a reputation-based blockchain mechanism, in which newly connected nodes are assigned a reputation-value to indicate the degree of their reputation as cache stores. The reputation is increased whenever a consumer receives a valid content from the node CS. The trust is then based on the actual reputation value, the highest the value, the more trustable a specific node is. Another blockchain-based proposal, but for cache poisoning, is presented in Lei et al.[165] The proposed mechanism is based on a three-stage scheme to detect all categories (i.e., corrupted content, unauthentic content, and fake content) of the content poisoning attacks: (a) retrieval stage—for untrue poisoned contents identification, and elimination; (b) recovery stage—for corrupted contents, that cannot be identified by intermediate nodes due to the lacking of a signature verification; and (c) feedback stage—for fake contents and potentially malicious content publishers identification. The work by Zhou et al[167] also aims at resolving the cache pollution problem. This work proposes a cache partition mechanism in which the CS is divided into two parts, and the content is stored in each part, depending on its popularity. A popularity monitoring algorithm is used to monitor the changes of the content popularity. The content with abnormal popularity is analyzed and accordingly marked whether it is an attack or not. A game theory-based mechanism to mitigate cache pollution is proposed in Yao et al.[170] In this proposal, the RSU is responsible for gathering individual lists of suspicious vehicles from the mobile nodes and generate the global black lists recording the attackers.

To mitigate the IFA, Sattar and Rehman[164] add a new field (consumer_id) in the Interest packet, and a new table (restricted id table), which is used to list the banned vehicles in the network. A threshold is fixed, and a number of requests for a specific prefix is counted and compared with the threshold. When the counted requests reach the threshold, the requester vehicle is marked as suspicious and its id is broadcasted and included in the restricted id table. Considering that an attacker can bypass the proposed solution by requesting contents using a prefix distribution that for a specific name prefix does not exceed the fixed threshold, and therefore be undetectable, Rabari and Kumar[168] propose the use of per-vehicle coarse granularity instead of per-prefix granularity, to overcome the mentioned shortcoming. Additionally, the proposal uses RSA-based cryptographic certificates in order to ensure non-repudiation, which is necessary for vehicle granularity. A prevention and mitigation scheme for IFA is proposed in Abdullah et al.[169] The mechanism monitors the incoming Interest per-flow instead of monitoring per-interface. The proposed per-flow monitor is composed of four components: (a) a prefix analyzer—to validate the naming scheme for the incoming Interest; (b) the priority checker—which assign priority to the incoming Interest flow; (c) suspicious list—the incoming flow that has low priority after some iteration is considered suspicious and moved to this list; and (d) a scheduler—responsible for sorting the flow of the incoming Interest prefixes according to its assigned priority. A node reputation value-based scheme for detecting a malicious node (responsible for IFA) is proposed by Zhang et al.[161] Nodes calculate their neighbors' reputation value by direct and indirect evaluation. Then, by means of Markov chain and reputation history, they predict the current node state (in terms of reputation). These metrics are then used to determine whether to accept or discard the incoming Interest packet.

The name-based content identification (i.e., the hierarchical namespace with readable names), routing, and the security mechanism in which content providers cryptographically sign each Data packet can be exploited to identify the intervening nodes. This can be done by correlating the Data requests and the Data names in the Interest packets. This situation can facilitate the PVA. To resolve this kind of issue, Liu et al[163] present an identity privacy protection strategy, which is based on ring signature[192] scheme. The ring signatures are used to hide the correlation between the signature and the data provider. In addition, the scheme uses the anonymous proxy to protect the real identity of the data requester.

5.7 | Data analysis and results interpretation

This section presents the analysis of the extracted data and their interpretation.

5.7.1 | Research question (RQ1)—routing

Although studies such as Grassi et al[36] consider that the main characteristics of VANET—high node mobility, dynamic topology, and intermittent connectivity—make it difficult or even infeasible to run a routing protocol to populate and maintain FIB, several efforts are being made to overcome such difficulties and develop routing solutions for NDN-based VANET. The main objectives of these solutions are (a) the elimination of the broadcast storm problem posed by the flooding approaches; (b) the optimization of the resource usage; and (c) the improvement of data retrievability.

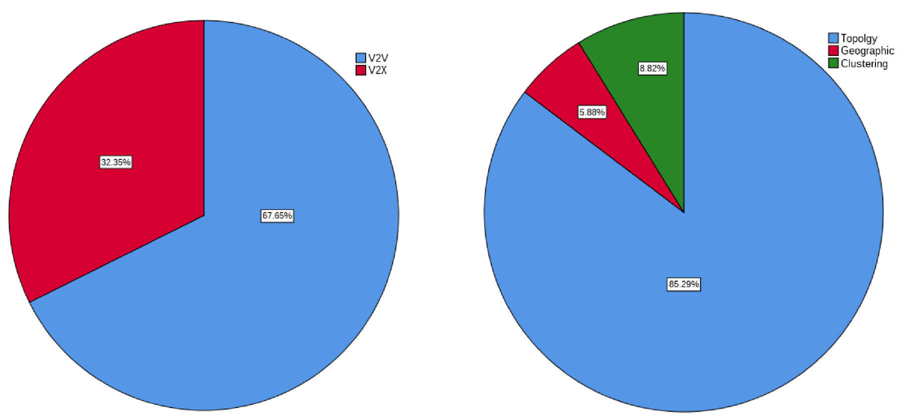
In this work, for 9077 studies found, only 34 were selected for data extraction based on the inclusion/exclusion criteria. As presented in Table 12, the majority of the selected studies are designed for V2X communication model (see Figure 9A).

The rationale behind this choice is that, although desirable to provide autonomy to VANET, giving it the capacity to perform all the needed actions to communicate without infrastructure assistance, the development of routing protocols for V2I communication is much necessary if one considers, for example, the need to leverage the SDN and Fog computing or the benefits of the RSU for caching in urban environments. Furthermore, the difference between the rural and the urban environments in terms of density, average speed of vehicles, and the existence of infrastructure to assist VANETS may require the development of adaptable routing protocols, performing both communication models—V2V or V2I.

The selected studies show that although some proposals are categorized as hybrid (i.e., classified into more than one operation mode, leveraging the synergies from these models), the majority of the proposed solutions are topology-based, as shown in Figure 9B.

Considering the VANET fast-changing topology and the fact that typical vehicular applications are geography- and time-dependent, and normally targeting vehicles within one specific region,[73] it may be beneficial to combine the synergies of a hybrid mode of operation and a deep route/mobility prediction, mainly for the content provider. Although Yan et al[40] propose a scheme designed to route data packets considering the next location of a moving node, the process of acquiring the next locations is not explained. The aforementioned study only refers that the next location is sent within the Interest packet. If the next location is provided by the moving node, a way of updating this information is important. Furthermore, the presented solution only deals with the consumer mobility. A solution with mobility prediction, in which a node not only indicates the next location but, could also predict and indicate the mobility route and inform the network in case of deviation from the planned route could be considered. The proposal presented in Silva et al[110] aims at tackling the aforementioned issue.

For the topology-based proposals, 11 out of 28 studies propose a proactive topology-based solution. The choice for proactive routing is justified by the better performance of this approach, in terms of latency, as indicated by these studies. The overhead posed by this approach, however, is not negligible. Thus, additional work need to be developed to



(A) Communication model for the proposed routing schemes

(B) Operation mode of the proposed routing schemes. The topology-based mode is predominant.

FIGURE 9 Routing communication model and operation mode ratios of the selected studies. (A) Communication model for the proposed routing schemes. (B) Operation mode of the proposed routing schemes. The topology-based mode is predominant solve the excessive communication overhead. The majority of the studies propose reactive routing to avoid the aforementioned issue.

Six routing proposals are designed for location-independent applications, and only five are designed for the location-dependent application. The distinction between the two groups is important in the sense that, the location-dependent application are usually related to the emergency and safety applications, which only makes sense on a reduced area of interest, and share short-lived contents. The dissemination of this kind of content requires short delays, thus, broadcasting instead of routing them is the better solution. The work by Arnould et al[45] propose a mechanism to disseminate push-based messages and modifies FIB in order to adapt it to be able to prefer and choose some faces, depending on their characteristics (e.g., cost, latency requirement, or bandwidth).

None of the selected studies consider the incorporation of caching mechanisms in the routing design. To further mitigate the latency and the provision of content with the content provider mobility, the in-network caching may present a better solution. Considering parameters such as the type of information and mobility (of content provider or consumer) and the type of the network (rural or urban, and density of the RSUs), a context-aware routing scheme able to dynamically adjust to network context could also be beneficial for VANET.

Table 15 presents the summary of the results to complement the data presented in Table 12.

TABLE 15 Summary of results for Research Question (RQ1)—routing

Study	Main features	Main limitations
Arnould et al.[45]	FIB modified to be able to favor some faces depending on their characteristics (bandwidth, cost, etc.). Introduces a push-based mechanism for emergency- or safety-related content.	Routes in FIB may become obsolete as they are not frequently updated. Only for urban environments.
Yu et al.[81]	Uses exchanged last encounter information to keep updated the geolocation of content sources. Reduces flooding overhead.	Only deals with location-independent content. Last encounter information may become obsolete, with less node encounters. Does not take in consideration the content source mobility. Only for urban environments.
Yu et al.[82]	Resorts to BF as a content digest to announce only the data service prefixes from the selected categories. Uses a timer-based mechanism to reduce the impact of the advertisement flooding. For mobility-awareness, the BF are periodically refreshed to reflect the topology change.	Classifies Data in three categories and only adapts for two categories. Assumes the availability of a network edge service used to classify the content. Only for urban environments.
Yan et al.[40]	Proposes a push-based mechanism. Piggyback some sensing information (small sized) in the Interest packet. For mobility-awareness, the vehicle movement information is contained in the CN.	Only deals with location location-dependent content. Routes in FIB may become obsolete as they are not frequently updated.
Khan and Ghamri-Doudane[83]	Proposes a publish-subscribe ICN model. Avoids flooding by forwarding Interest to vehicles with high centrality. For mobility-awareness, path breaks are supported by beacon broadcasting.	Routes in FIB may become obsolete as they are not frequently updated. Only for urban environments.
Wang et al.[84]	Avoids beaconing by using estimated link cost as a distance metric instead of hop counts.	The mobility of the provider (*Responder*) is not taken in consideration. Only for urban environments.
Kalogeiton et al.[87]	Reduces message broadcasting by creating unicast paths from a requester to a content source. For mobility-awareness, path break supported by constant broadcast using the native NDN messages, instead of Beacon messages.	Uses broadcast MAC addresses to flood messages in the network. FIB entries may become obsolete. Only for urban environments.
Kalogeiton et al.[88]	Reduces message broadcasting by creating unicast paths from a requester to a content source.	Initial flooding necessary to populate FIB. FIB entries may get obsolete. Only for urban environments.
Guo et al.[89]	-	Use Face system without node identification. However, the wireless channel is broadcast by nature. If no corresponding FIB entry is found, the incoming Interest packet is dropped. Only for highways.

TABLE 15 (Continued)

Study	Main features	Main limitations
Maryam et al.[90]	The neighborhood table, which acts as a FIB is periodically updated.	Periodic beacon broadcast to update the neighborhood table may increase network traffic. Only for highways.
Kalogeiton and Braun[91]	Uses either vehicles (V2V) or RSU (V2I) for content retrieval. FIB is deleted each 10 seconds to keep it manageable and in comfortable size.	Continuous Beacon broadcasting to discover content sources, may increase network traffic. When no FIB entry is found the model delays the process until an entry is created. Only for urban environments.
Coutinho et al.[92]	Vehicles opportunistically obtain content source location from the received Data packets. Uses the link stability-based Interest Forwarding for Content Request (LISIC)[193] to control Interest flooding, when no corresponding FIB entry is found.	Does not consider mobility of the content provider. Recently obtained location information of a content provider may become obsolete before the content is requested.
Duarte et al.[99]	For mobility-awareness, uses the store-and-forward (for consumer mobility) and floating content (for content source mobility) mechanisms, and periodic message retransmission.	-
Rui et al.[98]	Uses a neighborhood table and motion parameters (e.g., speed, direction, traffic density) to estimate the future location of a forwarding node.	Inclusion of nodes ID may re-introduce security and privacy concerns from the IP-based protocol. The process of discovering content sources (with new REQ REPLAY packets) then crating path may increase delay on retrieving contents.
Nakazawa et al.[93]	Combines relay vehicle selection, packet forwarding and cache search. For mobility, performs periodic exchange of node position.	Only for urban environments.
Duan et al.[94]	Predicts the node trajectory. Vehicles maintain a table of neighbors' cache information.	Periodic Beacon broadcast with node position and cache information, among nodes, may increase network traffic. The inclusion of nodes ID may re-introduce security and privacy concerns known from the IP-based protocol.
Dong and Li[95]	Expiration time and the previous hop is used to avoid beacon rebroadcast. Prevents FIB from expanding too large.	Periodic beacon broadcast from CH to announce the cluster, and update FIB, may increase network traffic.
Deng et al.[96]	Incrementally updates the FIB to copy with the topology changes, instead of reconstructing it. Differently manages consumer and producer mobility.	Only designed for infotainment dissemination. Flooding a *hello* packet, alongside the *Resource* packet, increases network traffic. Only for urban environments.
Cao et al.[97]	Reduces bandwidth consumption and searching delay by using the unicast addressing mode.	Gathering users' behaviors may introduce privacy concerns. Only for urban environments and video fetching.
Kalogeiton et al.[100]	Uses directional antennas to direct traffic, and unicast communications to reduce network resource usage. A content-based forwarding, using timers, is proposed to support vehicle mobility.	FIB entries holding geographical coordinates may become obsolete given that they are not periodically updated.
Xu et al.[101]	An Interface remapping method is used to correct the directionless way of broadcasting, in wireless channel.	Only for urban environments.
Wang et al.[102]	-	Does not consider the mobility of nodes.
Miyazaki et al.[103]	-	Only for urban environments.
Yang et al.[106]	Seamlessly switches hierarchical routing and hyperbolic routing for ensuring routing efficiency. FIB routes are static and use hyperbolic coordinates.	RSU is a key element for translating addresses. Thus, the proposal is not generalizable for environments without wireless static infrastructure. Querying the Location Name Service Server, my increase the delay for content retrieval. Only for urban environments.

(Continues)

TABLE 15 (Continued)

Study	Main features	Main limitations
Kalogeiton et al.[104]	Uses directional antennas to direct traffic, and unicast communications to reduce network resource usage. A Contention and time-based retransmission mechanism based on own proposed CBF.	The inclusion of nodes ID may re-introduce security and privacy concerns known from the IP-based protocol. Only for urban environments.
Xu et al.[105]	Leverages synergies from name-based, and ID-based routing for better mobility and flooding management. Resort to a BF-based CS structure for better content lookup. An algorithm to predict the link breaks and compute a new path in advance is proposed.	The use of IDs to identify vehicles may re-introduce security and privacy concerns known from the IP-based protocol. Only for urban environments.
Zhang et al.[107]	Clustering is done according to the node mobility pattern. For mobility awareness, opportunistic exchange of node historical information, on node encounters is performed.	Nodes only make requests via CH, not among themselves. Traffic overhead at the CH can be high. Periodic beaconing for neighborhood discovering increases network traffic. The inclusion of nodes ID may re-introduce security and privacy concerns from the IP-based protocol.
Ardakani et al.[108]	Combines Dedicated Short Range Communication (DSRC) and Mobile Agent (MA)[194], and clustering for better routing decision. For mobility awareness, periodic information is exchanged among clusters.	Depends on availability of RSU, which are responsible for providing location codes to vehicles. Periodic information exchange among clusters increase network traffic.
Yi et al.[109]	A Fog network is used to facilitate the content sharing among different communities, thus improving content delivery rates.	RSU plays the role of communication medium, i.e., only V2I communications in the community area. Thus, a single point of failure. In each community, MES is a single point of failure. Only CH shares popular content via MES, with other communities.
Silva et al.[110]	Context-aware routing and forwarding. Application-aware caching. Routing and forwarding planes enhanced by mobility prediction.	The inclusion of nodes ID may re-introduce security and privacy concerns known from the IP-based protocol.
Aldahlan and Fei[111]	Beacon broadcast are only exchanged with encountered (opportunistic) vehicles along the road.	Map graph may rapidly become obsolete, increasing the risk of packet looping.
Siddiqa et al.[112]	Performs a network load management.	Only for multimedia content dissemination. Community head and other vehicles cache information at a centralized entity, i.e, the RSU (a single point of failure). Community information table at RSU may rapidly become obsolete.

Possible roadmap for further developments

In summary, a possible roadmap in terms of future work to further answer the RQ1 might be (1) exploit in deep the content provider mobility prediction; (2) incorporate the mobility prediction in a context-aware V2X routing scheme; (3) design a model that can distinguish and prioritize content dissemination based on VANET application type, given that, for example, the safety-related applications are time sensitive, thus demanding highest priority; (4) exploit the incorporation of caching mechanisms to help mitigate the latency on content discover; and (5) further minimize the network overhead caused by the broadcast of infotainment-related applications.

5.7.2 | Research question (RQ2)—caching

The critical challenge on improving CHR and access delay is the selection of an appropriate caching node within the network.[142] Standard NDN caching decision strategies are reactive-based, where the caching process starts with a content request, and then, some copies of the content are cached somewhere along delivery path, according to the proposed caching strategy. For VANET, the conclusion from the selected studies indicates that proactive caching provides more efficient solution than reactive caching. As stated by Abani et al,[123] proactive caching can enable latency reduction on retrieving predictable content requests. Additionally, proactive caching can alleviate backhaul traffic and mitigate the latency caused by handovers.

Study by Pentikousis et al[73] presents key challenges for caching in VANET, such as (1) scenarios with geographically disconnected segments; (2) environments involving both consumer, and provider mobility; and (3) development of caching techniques that consider spatial and temporal relevance, node mobility patterns, social relationships, and content popularity. The majority of the selected studies aim at solving the aforementioned challenges.

Forty eight studies, out of 5300, were selected for data extraction. As summarized in Table 13 and particularly shown in Figure 10A, the majority (52.08%) propose a proactive mechanism for data caching. For both modes (proactive and reactive), the studies leverage the advantages provided by various caching schemes (e.g., popularity, cooperative, probabilistic, and location-based), for better cache management.

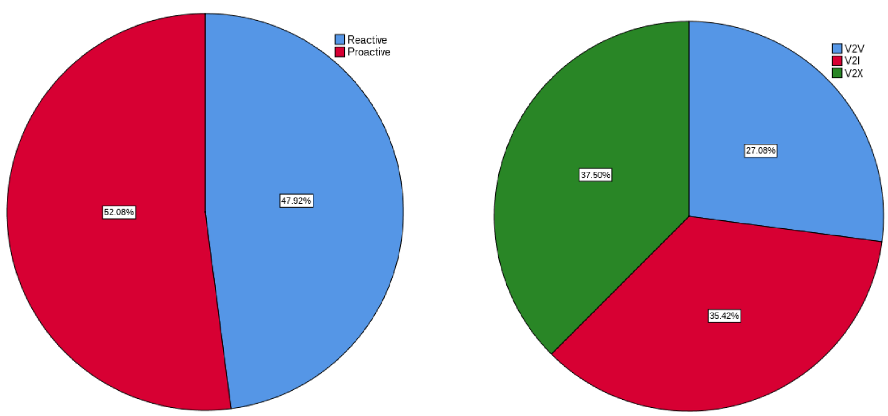
Three of the selected studies[132,142,143] propose only a caching replacement mechanism.

Eleven studies, out of the 25 proactive-based caching solutions rely on mobility prediction for path and node selection. In environments with high mobility, such is the case of VANET, the mobility prediction is challenging, however, fundamental for appropriate selection of next nodes for caching. Besides, considering the difference of characteristics between the location-dependent content (which is ephemeral and generally delay sensitive) and the location-independent content (which is long-lived and delay tolerant), an appropriate mechanism to differentiate and treat accordingly these groups of information is essential. All proposals based on the mobility prediction[121,123,129,133,139,141,144,149,151,153] rely on the existing infrastructure. Only 27.08% are pure V2V, see Figure 10B.

The majority of the selected studies relies on redundant caching at multiple nodes to reduce the effect of uncertainty presented by the proposed mobility prediction models. Studies in Abani et al[123] and Park et al,[144] for instance, minimize this issue by quantifying it by entropy. However, the solution in Abani et al[123] does not determine which content to fetch and how nodes are notified for pre-fetching.

The studies consider unlimited CS size, except literature,[117,118,125,133,139,141] which additionally propose a mechanism to manage the CS when it is full. Considering an unlimited caching size is clearly a limitation of the proposed solution.

Although all solutions are designed to solve the aforementioned challenges, they present some gaps that need to be tackled. For instance, the proposal in Mauri et al[118] is restrictive: Nodes move along fixed routes and have a constant connection with the RSU. Chunks in each CS are considered as unchanging according to a caching policy. Study[117] makes a set of assumptions which are, in fact, limitations on the generalization of this proposal. The study considers only V2I communication with vehicles having constant speeds, and focuses on downloading only large files capable of being separated in smaller chunks for transmission. Furthermore, the study suggest the pre-fetching to all potential AP which may bring inefficiency to the caching system. In Park et al,[144] each RSU is connected to a content server via backhaul link. This is a centralized approach. A single point of failure problem should be considered in this situation. The target in literature[113,115,119,120,122,129,154] is video streaming. Like the other studies, the contents are only pre-cached in infrastructure (i.e., RSU, BS, and AP) not in other vehicles. In Hou et al,[135] the mobility prediction model is



(A) Distribution of the selected studies in terms of the proposed caching mode.

(B) Distribution of the selected studies in terms of the communication model adopted in the solution.

FIGURE 10 Caching communication model and operation mode ratios of the selected studies. Distribution of the selected studies in terms of the (A) proposed caching mode and (B) communication model adopted in the solution developed by a deep learning model, capable of improving the mobility accuracy. But, due to the instability of VANET topology, it should be well measured whether this advantage outweighs the introduction of additional complexity in the system, which may increase the latency. Study[141] uses the request frequency to classify the contents into most popular and least popular. The most popular content is stored in all cluster heads. With this solution, within a given area the location dependent content will be most frequently requested, thus becoming most popular and leading to cache this type of content for long time.

In Yao et al,[142] the social similarity is used to exploit the social relationship among nodes, bridging centrality to select important nodes for information dissemination. The authors justify their choice stating that a vehicle driving toward an area with sparse vehicles is not a good option to be selected for caching, because it may encounter fewer nodes. But, if we consider, for example, the need to connect geographically disconnected areas (using "data mules") or provide safety information to vehicles possibly heading to an affected area, such a vehicle may be of importance. In Yao et al,[133] the prediction and the key factor for choosing a vehicle as caching node is its past trajectories, and the long sojourn in a hot zone. As stated before, a vehicle without these requirements may still be of a importance to disseminate location-dependent contents.

Only Modesto and Boukerche[131] are designed for location-dependent content, where the information about the location is provided in the Interest/Data packet. This solution, however, does not predict the node mobility but it is stated in conclusion that increasing cooperation and cache coordination based on mobility patterns and group-forming can further increase the caching efficiency of this solution.

Cooperative schemes such as those proposed in literature[115,120,122,139,154] require sharing information among existing nodes. This additional signaling increases the network traffic and cannot be negligible when measuring the overall network traffic.

Table 16 presents the summary of results, in terms of main features and limitations for each selected study, to complement the data presented in Table 13.

Possible roadmap for further developments

The possible challenges to solve in order to further answer the RQ2 might be (1) to develop a solutions with an improved prediction accuracy, designed to reduce cache redundancy on selection of caching nodes; (2) as the majority of selected studies do not distinguish between location-dependent and location-independent content, the development of caching solutions that can adapt to both type of information and application type, would be desirable; (3) develop a mobility-based caching scheme that could prefetch contents not only to infrastructures (RSU) but also to mobile nodes; and (4) design cache replacement mechanisms that can also include the type of content for caching replacement decision.

5.7.3 | Research question (RQ3)—security, privacy, and trust

This section presents the data analysis related to RQ3. As presented in Section 5.6.3, the main security and privacy attacks related to NDN-based VANET are (a) false information dissemination and cache pollution/poisoning (these are actually different types of attacks,[167] we just put them together given that we found scarce references for each, and are all related to the cache management).

Figure 11 shows that the majority (33.33%) of the selected studies deals with the FIIA and IFA, separately. Only one study deals with the privacy issue.

In terms of collaboration scope, the majority of the proposed solutions impose that nodes work in collaboration among them. This type of solutions may result in inefficiency if one considers that VANET can be highly dense. Processing security algorithms in a highly dense and volatile environment can be challenging.

The study by Manimaran et al[166] is specific for tackling the FIIA related to accident involving the vehicle that is disseminating the information; otherwise, two of the defined rule (i.e., the vehicle airbags should have been activated after the event, and the rate of the driver should have increased after the event) could not be verified. This is a limitation concerning the generalization of this solution.

The proposal in Yao et al[170] depend on the existence of RSU. Thus, this proposal cannot be generalized to infrastructure-less environments. Another limitation is presented by the proposal in Liu et al,[163] which is concerned with protecting the identify of content requesters. The proposal does not generalize to protect the content source identify.

TABLE 16 Summary of results for Research Question (RQ2), related to caching

Study	Main features	Main limitations
Grassi et al.[36]	Takes advantage of the low vehicle restrictions in terms of storage, to cache all content and use moving vehicles as *data mules*.	Only Urban environments. Considers unlimited CS size. Caches transient contents.
Quan et al.[113]	Improve QoE of multimedia streaming.	Only highway environments and multimedia streaming.
Bian et al.[114]	Three different heuristics are presented in order to avoid cache redundancy.	Only urban environments. Considers unlimited CS size.
liu et al.[115]	Improve QoE of multimedia streaming.	Only highway environments and video streaming. Cooperation depends on the will of the neighboring nodes.
Deng et al.[116]	Factors such the preference of vehicles, importance of the vehicle and relative movement of the vehicles are taken in consideration for caching decision.	Only urban environments. Caches transient content. Users preferences and demands are extracted from the collected Interest, privacy concerns may arise.
Grewe et al.[117]	Replacement policies: LRU, LFU, FIFO. Mobility prediction using node position and velocity, INTEREST frequency.	Only motorway environments. Only deals with large files, which needs to be separated in chunks. Constant velocity. Signaling information required for calculating the list of chunks, which increases network traffic. RSU is a key resource and a single point of failure.
Mauri et al.[118]	Calculates the optimal CS size of the whole network in order to reach a desired retrieval probability.	Vehicles move along pre-defined paths. Caches only on RSU and AP. Chunks in the CS do not change over the time. Caches transient contents.
Quan et al.[119]	Independently witches the retrieval modes between V2V and V2I according the content popularity. Popularity metric enhanced by the reference frequency of the object (the chunk belongs to) and the reference frequency of the chunk.	Only urban highway environments and content streaming.
Wei et al.[120]	Replacements policy: LRU. Improve QoE by selecting content to cache based on the video specific bit rate.	Only urban environments and video streaming. Only caches on RSU.
da Silva et al.[121]	Take advantage of the user trajectory information to select AP where to proactively cache desired content (i.e., predicts mobility).	All nodes promiscuously cache, but only RSU and AP cache proactively. Caches transient content.
Xu et al.[122]	Use Information centric cloud to calculate and decide in which node to cache.	Only urban environments and video streaming.
Abani et al.[123]	Predicts the node mobility (using 1st-order Markov Model). Use entropy to measure mobility prediction uncertainty and locate the best pre-fetch node.	Caches only on RSU.
Modesto and Boukerche[124]	Replacement policy: LFU. Besides popularity, the network knowledge (cache distance) is taken as advantage to increase cache diversity.	Only urban environments. Cache transient contents.
Zhao et al.[125]	Replacement policy: PPCCR. Encourages the cache contribution of the private vehicles. Avoid redundancy by introducing popularity rating and hop number for selecting caching nodes.	Only urban environments. Caches transient contents.
Duarte et al.[127]	Avoids network overloading with replicas of the same content by selecting influential vehicles as caching nodes.	Only highway environments. SDN controller, a centralized entity, being the owner of the caching logic can be a single point of failure.
Fang and Mao[128]	Besides popularity, the caching status of neighboring vehicles is used for caching decision.	Only urban environments. Cached content do not change. BS being a key element responsible of sharing the caching status of the existing nodes can be a single point of failure.

(Continues)

TABLE 16 (Continued)

Study	Main features	Main limitations
Khelifi et al.[129]	Uses deep learning to predict the mobility of the nodes, to the next RSU.	Only highway environments and video streaming. Only caches on the RSU.
Ma et al.[130]	RSU perceive the surrounding cached-content locations by using the weighted recursive sum of the neighboring cache intervals.	Only urban environments. RSU are central entities responsible for caching and managing caching.
Modesto and Boukerche[131]	–	Only location-dependent contents. Beacon broadcast for social cooperation. Data packet have fixed and same size.
Yao et al.[133]	Own policy for cache replacement. Predicts the vehicle future location, based on trajectory history (using PPM).	Only urban environments. Caches transient contents. RSU are key elements responsible on recording trajectory records. RSU do not cache contents.
Van et al.[134]	Replacement policy: LRU. Besides the popularity, considers other metrics (e.g., type of VANET application, cache occupancy, user's preference, and stability link of the vehicles) for caching decision.	Only urban environments.
Hou et al.[135]	Predicts vehicle mobility using LSTM, Deep learning.	Only urban environments and non-safety related applications. Only caches on RSU.
Grewe et al.[136]	Uses content freshness and the number of hops for caching decision.	Only highway environments. Caches on edge routers (RSU, BS or AP). Designed for transient content (e.g., traffic updates, querying parking services).
Huang et al.[137]	Mobility prediction (mitigate mobility issues in VNDN). Reduce redundancy by caching on selected nodes. Provides own cache replacement policy.	For urban environments. Only CH (which can not be accessible) and RSU (only available in some environments) cache contents. RSU selects CH for caching. Broadcasts beacon messages for sharing mobility information.
Hasan and Jeong [138]	Solution combined with the cellular network (LTE network infrastructures).	For urban environments. Requests are directed to the neighboring RSU which decides what to do further. Caches transient contents.
Huang et al.[141]	Take advantage of mobility prediction (using 2^{nd}-order Markov model) to cluster vehicles with similar mobility patterns. Provides own cache replacement policy.	For urban environments. Includes caching transient content. Signaling information required for node cooperation which increases network traffic. RSU are central entities responsible for selecting the caching CH, can be a single point of failure.
Yao et al.[139]	Predicts the vehicle future location (using HMM), based on vehicle behavior. Besides popularity, the social relationship is explored for better caching decision. Provides own cache replacement policy.	For urban environments. Caches transient contents. RSU are key elements responsible on recording trajectory records. Periodic beacons are broadcasted in order to share social attributes and determine hot zones.
Park et al.[144]	Predicts vehicle mobility (using 1^{st}-order Markov Model, and entropy for prediction accuracy).	For urban environments. Centralized content server. Caches only on RSU.
Wei et al.[145]	Uses decision tree prediction for caching decision. Provides own cache replacement policy on RSU and LRU in vehicles.	For urban environments. Caches transient contents.
Grewe et al.[146]	Virtual cache area for proactive caching in infrastructure-less environments. Infrastructure-assisted cache-as-a-service. Use passing vehicles as data mules for caching.	For highway environments. Multi-hop communications not supported in all simulations. Caches transient contents. RSU beaconing for choosing potential caching node.
Wang et al.[147]	Resorts to Stackelberg game, as the cache allocation initializing procedure.	For urban environments. Vehicle beacon broadcast for sharing mobility information with one-hop neighbors may increase traffic. BS is a key element responsible of rewarding caching vehicles, a possible single point of failure.

TABLE 16 (Continued)

Study	Main features	Main limitations
Hasan and Jeong[148]	Besides popularity, considers content locality. Resort to cloud servers as an additional caching resource. Includes own replacement mechanism (not described).	Caches only on the RSU. Caches transient contents.
Zhang et al.[149]	Includes mobility prediction (mitigate mobility issues and predict user future demands). Uses 5G-ICN-based vehicular network.	For highway environments and video downloading. Caches only on BS and RSU.
Ud Din et al.[150]	Provides a mechanism for the timely dissemination of safety-related messages (push-based).	For urban environments. Only caches on RSU and BS. Caches transient contents.
Yao et al.[151]	Predicts vehicle mobility using HMM, to mitigate mobility issues.	For urban environments and video downloading. Only RSU are responsible for caching and predicting vehicle mobility.
Amadeo et al.[152]	Besides popularity, includes *freshnessPeriod* (RL) for better caching decision. Uses RL-based eviction plus LRU policy.	–
Nam et al.[153]	Predicts vehicle mobility.	For urban environments. Only caches on RSU.
Gupta et al.[154]	Besides the content popularity, the model includes the predicted rating score for content placement decision. Includes own cache replacement policy.	For urban environments and multimedia streaming. Only routers on the edge cache content.
Yi et al.[109]	Considering the friendship and in order to further improve sharing, nodes can suggest to cache non popular content into the reserved 20% of the CS. Includes own cache replacement policy.	For urban environments. The MES is a single source of failure regarding that specific community area (an area covered by a single RSU).
Amadeo et al.[155]	Besides the popularity, the caching decision is also based on the content residual lifetime and the perceived availability of the same content in the neighborhood. Includes own cache replacement policy.	Only the RSU provide content.
Gu et al.[156]	Besides the popularity, the model introduces the node value concept for content and cache location selection. Includes own cache replacement policy.	No mobility awareness.
Kaci and Rachedi[157]	Caching is improved by leveraging Fog computing, to extend the CS capacity of the RSU.	Content is only routed through RSU. Only RSU and Fog are used to cache content.
Chen et al.[158]	Improve caching efficiency by differentiating IoV application content by classes. Includes a replacement mechanism. Besides the popularity, the caching mechanism includes spacial-temporal characteristics.	The sending frequency of emergency safety querying messages may affect the network traffic. RSU (a single point of failure) as a centralized entity used to determine the area of interest, for the traffic efficiency messages.

Possible roadmap for further developments

Name-based routing provides natural countermeasures for DDoS attacks, by not providing the ID of the intervening nodes. The wireless channel is broadcast by nature, limiting the use of NDN Face system to identify the forwarding node. Several NDN-based routing for VANET, as presented in Section 5.6.1, proposes the inclusion of nodes ID either to the Interest or Data packet. The inclusion of this node identifier could bring back the security and privacy vulnerabilities that exist in the IP-based VANET. Moreover, VANET scalability, partitioning and density, are some of the main challenges that can affect the design of a robust security, privacy and trust solutions. Therefore, in summary, a possible roadmap in terms of future work might be (1) designing a generalizable and scalable solution; (2) designing solutions capable of adapting to the density of the network; (3) Given that trust and privacy are generally conflicting issues, the design of a mechanism that can equitably deal with both issues is desirable; and (4) advising new mechanisms to address the new security issues that arise by including the node ID in the NDN packets.

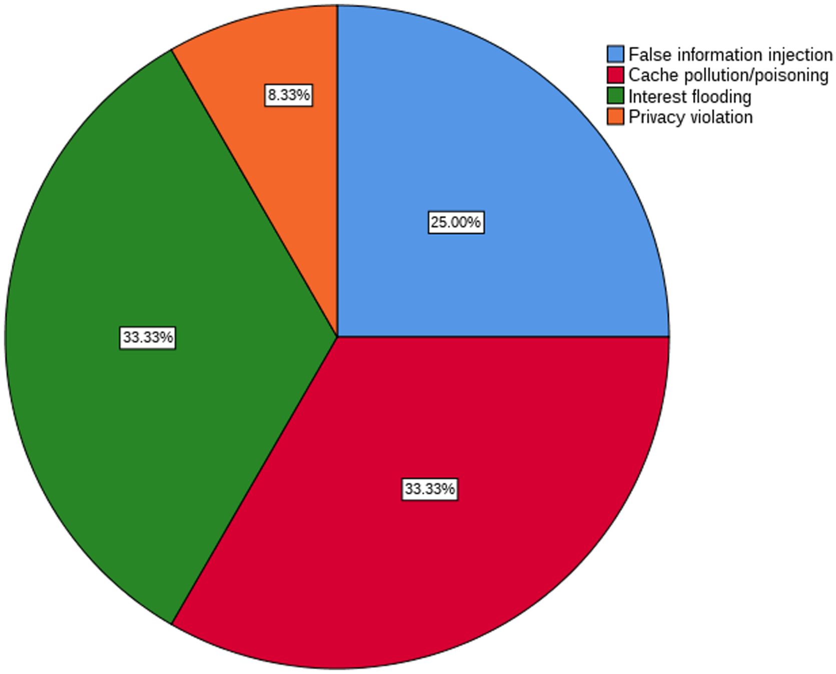


FIGURE 11 The surveyed main security and privacy attacks in NDN-based VANET

6 | IMPROVING VANETS USING NDN

Implementation of VANET by NDN has been seen as a solution to overcome several challenges posed by the IP protocol. In fact, NDN characteristics (e.g., name based node identification and routing, in-network caching and the signing of each Data packet) provide natural solutions for several issues including (a) the node mobility; (b) scalability; (c) security and privacy; and (d) content sharing model.

Although already presented for each RQ, we summarize here the lessons learned on improving VANET using NDN.

6.1 | Research question (RQ1)—routing

In terms of routing, although opening door for increased network overhead due to the frequent beacon broadcast to update the topology information, the proactive topology-based routing solutions is the most adopted. Taking advantage of all overheard packets to extract topology information, instead of broadcasting a specific packet, can be a better solution to avoid the network overhead.

If one considers, as explained in Section 3.2, that a solution is routing-based (belonging to the control plane) when a FIB management takes place, in contrast with flooding-based solution, which do not manage FIB, and simply broadcast the Interest into the network, then the reactive topology-based routing solution can be seen as belonging to the forwarding plane. The main issue presented by the latter solution is the delay on retrieving contents because the request is performed on-demand.

Besides the local-minimum issue, the location-based (or geographic-based) solutions are also prone to the delay issue presented by reactive topology-based solutions. To avoid the local-minimum issue, (only) one study propose geographical routing based on the (hierarchical) hyperbolic space. More research on this topic could be considered.

Although from the selected studies few hybrid solution (i.e., based on more than one mode of operation) were proposed, these have the potential for catching the synergies among the chosen schemes. Therefore, much research on the hybrid solution should be considered.

VANET communication depends on the wireless channel. The inclusion of node ID for node identification and relay selection is mandatory in this channel. However, security and privacy problems may arise by adopting this solution. Therefore, solutions proposing the inclusion of node ID require some mechanisms for tackling the aforementioned possible issues.

6.2 | Research question (RQ2)—caching

In order to catch the synergies among the various caching schemes, the majority of proposed solutions adopt a hybrid scheme for caching decision. VANET application may either have short lifetime (e.g., the safety or emergency related applications) or a relatively long lifetime (e.g., infotainment related applications). Besides, the applications may be location dependent (e.g., the safety or emergency related applications) or location independent (e.g., entertainment related applications). Therefore, additional metrics should be considered for deciding on which content to cache. One of the metric to consider is the lifetime of the received message. Actually, two of the selected studies do consider this metric. Caching content with short lifetime may result in an increased overhead on processing the CS, to frequently remove outdated content. More studies exploring this metric and considering the VANET application types (to consider the location dependency, for example) are desirable.

VANET should be capable of communicating without infrastructure (e.g., RSU, AP, and BS). Although expensive, infrastructures are a normal reality on developed countries and are foreseen as being a key element to support VANET. It is easier to deal with the infrastructures, that are static, than with the mobile nodes. Having this in mind, several proposed solutions are developed to work with infrastructure. All proactive caching proposals explore the infrastructure (i.e., are either based on the V2I or V2X communication model). Proactive caching could also be considered in V2V communications, using the Floating Content (FC) concept,[195–197] which is similar to the concept of VN proposed in Miyazaki et al[103] for content routing or virtual cache area, proposed in Grewe et al.[146] The mobility prediction, which the selected studies combined with the proactive caching, could also be explored with the aforementioned concepts to proactively cache contents in the infrastructure-less environments.

6.3 | Research question (RQ3)—security, privacy, and trust

The characteristics of VANET (e.g., sporadic connectivity, high speed of vehicles) impose specific challenges on developing security mechanisms. Therefore, security mechanisms should be designed with these aspects in mind.

Interaction among vehicles in VANET is a key aspect. Indeed, VANET is based on this interaction. Personal and private information (e.g., geographic coordinates, vehicle speed, or even vehicle identification in case of an accident investigation) is shared among vehicles. Generic security mechanisms capable of balancing privacy and trust are desirable.

Security mechanisms are required to take the delay constraints (crucial for safety-based applications) into consideration. Therefore, they should be designed with low processing requirements and reduced messaging overhead. This is important mainly for the mechanisms that require collaboration among the nodes.

Node density in VANET can be sparse, normal or dense. Therefore, security mechanisms should be designed to scale proportionally to the node density and the network dimension.

7 | CONCLUSIONS

Resorting on a systematic literature review, this work proposed to investigate the existing solutions and the main open challenges on how to improve VANET using NDN. Three research question were defined and a total of 94 studies spanning from 2010 to 2021 were selected for data extraction.

This extracted data shows that studies within the selected topics are recent (from 2016 to 2021) and the majority of them (i.e., 51.06%) deal with the caching system.

Existing gaps extracted from the cumulative findings and the future work presented by the studies themselves were presented for each topic, highlighting the need for studying and better integrating the mobility prediction with routing and caching.

In summary the present SLR recommends: (1) the development of work aiming at improving the mobility prediction accuracy; (2) the development of a context-aware routing and caching scheme, considering the different characteristics of the network environment, such as the network density, the type of application (for location-dependent/independent content), the model of communication (V2V/V2I), and the integration of caching mechanisms in routing decisions with mobility prediction; (3) the development of a more generic security and privacy solution for better prevention, detection and recovery from an attack; (4) the selected studies generally propose solutions in a disjunctive way, that is, when proposing a routing solutions, for instance, they usually do so without regard to security or caching. The integrated solutions are scarce but desirable.

An equally not less important note is that, for each study the authors conclude that their own proposal generally presents better performance than the others for practically the same metrics. The availability of the source codes would be a good opportunity to better assess and globally compare the performance of existing solutions.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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