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RESEARCH ARTICLE

VAL–Vehicular Adaptation Layer, for NDN

JOÃO F. PEREIRA, M. JOÃO NICOLAU, AND ANTÓNIO D. COSTA, (Member, IEEE)
ALGORITMI Research Center/LASI, University of Minho, 4710-057 Braga, Portugal

Corresponding author: João F. Pereira (b12267@algoritmi.uminho.pt)

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ABSTRACT High mobility and intermittent connectivity of nodes are the main characteristics of Vehicular Ad-Hoc Networks (VANETs). These two aspects cause problems in traditional IP networking. Named Data Networking (NDN) is presented as one of the most promising paradigms for the future Internet. NDN is a data-centric architecture. It relies on data names instead of the host's location to make forwarding decisions. In NDN, any node can be a candidate for supplying the desired content. This feature makes the NDN architecture appealing for VANET scenarios (V-NDN). This paper presents a strategy for applying NDN to VANETs with support for geographical-based forwarding. For this purpose, an additional layer called Vehicular Adaptation Layer (VAL), is proposed to illustrate how this can be performed without altering the NDN primitives and core structure. VAL provides: 1) a mechanism to bind NDN data names to the producers' and consumers' geographic areas; 2) a discovery mechanism to find producers' areas and 3) the capability of implementing, in a plug-and-play manner, geo-forwarding algorithms capable of guiding Interests towards data producers and Data packets towards data consumers.

INDEX TERMS Geographical-forwarding, NDN, VANETs, V2V.

I. INTRODUCTION

Vehicle Ad-Hoc Networks (VANETs) are a subtype of Mobile Ad-Hoc Networks (MANETs) characterized by the node's high mobility, interrupted connections, lack of guaranteed end-to-end connectivity, variable nodes density and dynamic network topology. Similar to MANETs, this network paradigm does not rely on infrastructure to support communication between nodes. The VANET scenario has been intensively studied in recent decades, where the challenges have been met with solutions based on the TCP/IP network stack. However, the high mobility of nodes, resulting in short-lived intermittent connections and unpredictable network topology, makes applying IP-based networking to VANETs problematic. Furthermore, in an IP-based network (TCP/IP), nodes require addresses to communicate with each other. Therefore, creating and maintaining IP-based routes to support forwarding decisions has proven to be an arduous task in VANETs.

Network architectures centered on information, Information-Centric Networking (ICN), aim to respond to these problems by passing communication to a request-response model. The focus of this model is the content. Thus, the paradigm changes from obtaining the content of a specific source/location as a network based on TCP/IP to obtaining the content from the network itself.

Named Data Networking (NDN) is an ICN architecture. It is presented as one of the most promising architectures for the future Internet. NDN focuses on named data and follows the request-response model. A consumer node that intends to access certain content makes its intention known to the network by issuing a message of Interest with the name of the desired content. Then, the network is responsible for choosing the best node to obtain the content in question and, through a Data message, returns it to the consumer node via the reverse path. As NDN supports in-network caching, any node in the network has the potential to be the best source for a given content [1].

These characteristics of the NDN architecture, content referenced by names and in-network caching, make it quite appealing when it comes to VANETs because:

- by focusing on the content name, there is no need to define addresses, mitigating the necessity of topology knowledge which is a significant advantage in high mobility scenarios.

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- it supports in-network caching by default, which facilitates the implementation of the store-carry-and-forward paradigm.
- it supports consumer mobility. For example, after changing zones or networks, a consumer only needs to generate an Interest message to resume communication.
- is designed as a solution for a content distribution network, which aligns with VANET's characteristics.

The application of NDN to VANETs (V-NDN) is not a plug-and-play solution. Although some problems are mitigated, others remain, and new ones arise.

In native NDN, routing protocols propagate data name prefixes throughout the network to advertise where the content resides. However, in V-NDN, due to producers' high mobility, this approach becomes very challenging and ineffective [2]. Therefore, V-NDN tends to rely on the forwarding plane to forward Interest and Data packets toward the best next-hop nodes to achieve efficient content availability. Even so, making an Interest packet reach a producer when they are highly mobile is a demanding task. Flooding solutions may overcome this issue, but they may lead to broadcast storms, where every node attempts to forward the Interest packet to every vehicle in the communication range. In high-density scenarios, this leads to a broadcast storm.

We argue that geographical information can be used to mitigate broadcast storms, support forwarding decisions, and assist producer mobility within a network. Moreover, many VANET applications, such as safety and traffic applications, generate geographically dependent information.

This paper presents a new Link Adaptation Layer (LAL) denominated Vehicular Adaptation Layer (VAL) that uses geographical information to mitigate broadcast storms and support forwarding without compromising the NDN architecture or its primitives. The solution presented here is based on the works [3] and [4].

The following guidelines supervised VAL design:

- Not change any NDN structures.
- Not alter any NDN primitives.
- Not overlap functionalities with the NDN data structures.
- Be capable of making forwarding decisions based on location information.
- Be modular. It should allow for the inclusion of different geo-forwarding strategies.
- Support both location-dependent and location-independent information.
- Implement V-NDN with support for V2V communications.

The remainder of this paper is organized as follows. Section II presents an overview of related work on V-NDN and geographical-based forwarding. Section III provides an overview of our solution, and Section IV presents its details. The results are discussed in Section V, and we conclude the paper in Section VI.

II. RELATED WORK

This section presents the literature used as the foundation for this work. The literature presented here can be divided into two groups. The works presented in the first group focus on presenting mechanisms to control packet propagation and, therefore, mitigate broadcast storms. The authors' contributions in the second group center on achieving fast and reliable content access. Therefore, this group describes forwarding strategies that incorporate geographical information in order to select the best next-hop. In addition, there are works such as [4] that contribute to both topics.

A. BROADCAST STORMS MITIGATION

The authors in [5] show that the Data packet does not always take the path done by the Interest. Therefore, they present a mechanism that uses hop counts, incremented in Interest and decremented in the Data packet, to ensure that the path is mirrored, creating a mechanism that mitigates Data packet propagation. Similar work is done in [6]

The authors in [7] evaluate Interest and Data packets propagation in V2V scenarios. The authors show that the average Interest satisfaction delay is unpredictable owing to the multipath propagation of Interest-Data messages. Consequently, there are many unnecessary copies of Interest and Data packets. In [8], the same authors present an adaptive PIT entry lifetime mechanism that mitigates the number of unnecessary copies in the network.

In [3], the authors present a prototype architecture for applying NDN to VANETs. This architecture implements a Link Adaptation Layer (LAL), which is a conceptual 2.5 layer. LAL is designed to take advantage of specific layer 2 technologies by sending all packets as L2 broadcasts. It uses a Wi-Fi frame to carry NDN packets directly. In addition, LAL implements mechanisms to mitigate Interest broadcast storms and endows the network with an acknowledgment process. Each Interest packet carries the sender's location. When a packet is received by multiple vehicles, the furthest from the last-hop should forward the packet. The other receivers do nothing. Upon detecting the retransmission of the packet, every node cancels its broadcast, using that retransmission as an implicit acknowledgment. The authors of this work also argue that every Data packet should be cached, not only the ones that match a PIT entry. Allowing, therefore, for a more significant number of mules to carry the data, increasing the chances of a rendezvous opportunity between consumers looking for specific data and mules carrying a copy of it.

B. GEOGRAPHIC FORWARDING STRATEGIES

Implementing a routing protocol is a challenging task because of the high mobility that characterizes VANETs. Therefore, most literature, [2], tends to look toward forwarding strategies to achieve fast and reliable content access. Geographical forwarding strategies are among the most promising types of forwarding strategies. Some of these strategies are presented in the following paragraphs.

The authors in [9] propose choosing the next-hop by using the geographic location of the Position of Interest (POI) and sharing vehicle trajectories. The authors also introduced forwarding strategies for Interest and Data packets. This work ties the geo-location information within the name structure of the packet.

In [10], the authors propose two new data structures: 1) Neighbors Satisfied List (NSL), and 2) Recent Satisfied List (RSL). Neighbors exchange RSL and populate the NSL. This last structure is used to select only one vehicle among the neighbors to forward the Interest packet.

In [11], the authors propose a geo-based forwarding strategy for urban scenarios. Every node maintains a neighbor table containing the IDs of its neighbors, their positions, and the data source's position for any specific incoming Interest. Allowing, therefore, the selection of the best next-hop forwarder for efficient Interest delivery. This table is periodically updated using beacon messages. Moreover, the authors address the caching redundancy problem based on a density-aware strategy.

Continuing the work done in [3], the authors propose a forwarding strategy named Navigo [4], which couples the content's name with the producers' geographic area. To do so, the authors use the Military Grid Reference System to map geo-locations. Furthermore, they present interfaces that have those geo-locations associated, named GeoFaces, which endows the FIB with an indirect relation between the name prefix and the geo-location. This work focuses on guiding Interest to producers and avoiding Interest broadcast storms. The proposed forwarding strategy is map-topology-aware and is divided into two distinct phases. First, the authors developed a discovery phase to find where the data resides. In this first phase, the strategy uses intersections as a preferred point to broadcast Interest packets. After the producer's location has been discovered, the second phase, a producer-aware geo-location-based forwarding strategy, forwards the Interest packet to the producer's location. This work does not address how the Data packets are treated. Upon receiving a Data packet that matches a PIT entry, that packet is simply broadcasted. This mechanism may lead to Data packet broadcast storms, which presents a scalability problem. The authors argue that this mechanism allows for better dissemination throughout the cache system of the vehicular network. However, it also increases the number of unnecessary packets processed by the network. Furthermore, this work does not provide any means to create a forwarding strategy for Data packets, which is an approach presented by some authors [2].

The authors in [12] argue that selecting the next-hop on the edge of the broadcast range of the emitter leads to significant errors and Interest retransmissions owing to poor signal strength. The authors select a node between the middle and extreme regions of the signal range. This work propagates the Interest packets in all directions.

In LoICen [13], the authors use the location of the vehicles that have cached content to direct Interest packets to that area whenever possible. Vehicles opportunistically obtain the location information of potential providers that may have the desired content in their cache. This work presents no way to predict the movement of potential providers.

In [14], the authors argue that a valid underlying interface is crucial for an efficient named data transmission in VANETs. The authors present a dynamic directional interface model built in the NDN layer that associates the virtual named data space with the actual network space. It divides the vehicle's wireless coverage area into multiple directional interfaces. Moreover, a method for remapping interfaces during the driving process is also presented. This remapping algorithm updates the FIB and PIT entries of each node. This work leads to a larger number of hops to the provider.

In [15], the authors present a Broadcast Storm Mitigation Strategy (BSMS). This work relies on the distance and relative speed of the vehicles to reach a forwarding decision. This information is aggregated into the Interest packet and stored in the PIT. Therefore, this work presents substantial changes to NDN architecture.

The authors of [16] present a work that mainly focuses on V2R communications. The results presented in this work show higher Data delivery ratios, lower delays, and faster handovers between roadside units. Furthermore, the authors propose a novel vehicle-tracking-based Data packet forwarding scheme (VTDF), in which Data packets are forwarded according to vehicle movement information. In order to track vehicle movement, the authors propose the Tabu search (TS) method. This work also presents a quick handover method (QHM) to improve handover between roadside units. To achieve this, this work changes the NDN packet structure.

Similar to the work done in [4], the authors of [17] present an Interest forwarding scheme based on road topology. The authors also introduce the Interest Suppression Area (ISA) concept, which aims to mitigate broadcast storms. ISA demarcates a geoarea based on the geo-positions and road directions of the nodes. It then assists the forwarding decision, therefore, Interests are forwarded in multiple directions. In this work, changes made to the PIT allow it to accommodate geographical information.

III. VAL—OVERVIEW

The architecture presented in this work has its central point in a conceptual 2.5 layer named Vehicular Adaptation Layer (VAL). We argue that, by applying this new layer, it is possible to accommodate the adaptations required to adjust NDN to VANETs (V-NDN). Therefore, keeping the NDN architecture as intact as possible. This work follows that principle but focuses on adapting geolocation-based forwarding to V-NDN.

Figure 1 shows an overview of the system architecture. As shown, we use the concept of geoFaces introduced in [4]. Here, the incoming geoFace is always associated with the source area of the NDN packet, and the outgoing geoFace with the destination area. This approach allows us to keep PIT mapping the downstream path and FIB the upstream path.

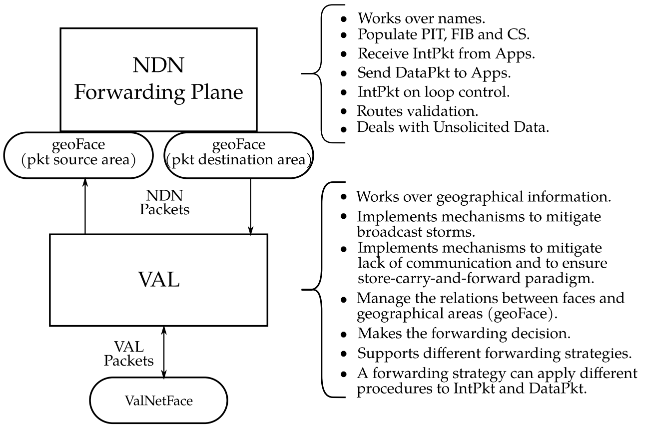

FIGURE 1. System architecture.

GeoFaces are standard interfaces that have a geographical area (geoarea) associated. Using a notion similar to that presented in [4], we define geoareas by dividing the simulation area into smaller areas of 200 × 200 meters. Each of those geoareas has a unique identifier. A geoFace is an interface that represents one of those areas. This mechanism allows FIB and PIT to have, indirectly, geographic locations associated with their entries.

VAL creates and uses geoFaces to exchange NDN packets with the NDN forwarding plane. To interact with the network, VAL uses a V2V interface denominated as ValNetFace, which encapsulates layer 2 logical and physical interfaces.

The packets that VAL sends to the network are denoted as VAL packets. These packets encapsulate the NDN packets and include relevant geographical information. Figure 2 shows their structure.

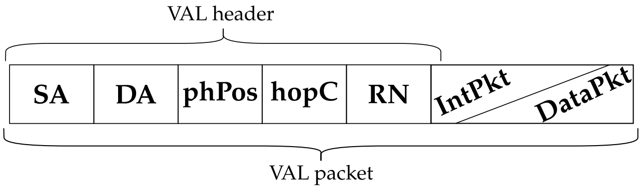

FIGURE 2. VAL packet.

A VAL packet contains the Destination Area (DA), Source Area (SA), Previous-hop Position (phPos), Hop counter (hopC) and a field with the Root Name (RN). The RN is helpful in order to aggregate FIB routes, [4]. There are different name structures in NDN, and even in a hierarchical composition, it is challenging for a router to know where to locate the common prefix for aggregation. That information must travel along with the packet. The assumption is that the consumer and producer applications know the root name.

VAL uses five data structures to implement its control mechanisms and support its forwarding strategy module, as described later in this document. The following list presents these structures and provides a brief overview of their purposes.

- Face to Area (F2A), stores the relation between geoFace and geoarea.
- Interest from Network Table (IFNT), stores the information of Interests that arrived via the network.
- Data from Network Table (DFNT), stores the information of Data packets that arrived via the network.
- Pending Implicit ACKs Register (PIAR), stores the information of packets just sent to the network that are waiting for retransmission.
- Forwarding Timer Register (FTR), stores the information of packets scheduled to be sent to the network.

A. CONTROL MECHANISMS

Two mechanisms must be implemented to mitigate broadcast storms: forwarding cancellation and implicit acknowledgment.

The forwarding cancellation mechanism is the capability of a node to identify whether it has received a packet that is scheduled to broadcast. In this case, the node should cancel the broadcast.

By listening to the medium, node ‘A’ can identify when node ‘B’ broadcasts a packet previously transmitted by node ‘A’. This mechanism induces an implicit acknowledgment mechanism, and node ‘A’ cancels the packet retransmission.

B. LOCATION-INDEPENDENT INFORMATION SUPPORT

To support both location-dependent and independent information, a special geoFace without any associated geographical area, the *floodFace*, is needed. An Interest emitted without a destination area is associated with this special geoFace. When this occurs, the Interest is in the discovery phase. Once the Interest reaches a node that knows the location of the requested data, the packet changes from the discovery phase to the known-destination phase. Once the Data packet reaches the consumer, it learns where the data resides, and the following Interests are sent with that destination area.

An Interest in the discovery phase can be treated differently, allowing for a more aggressive dissemination mechanism, such as flooding the network.

IV. VAL—SPECIFICATION

In this section, the specification of VAL is accomplished using block diagrams that illustrate VAL structures and their interactions. Figures 4 – 7 show how VAL treats Interest and Data packets. Figure 3 presents legends for these diagrams.

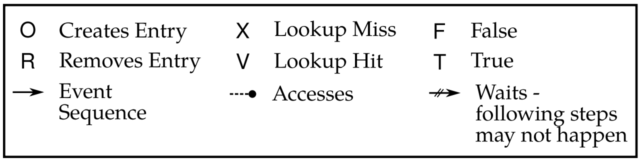

FIGURE 3. Legend for the VAL information flow figures.

Figure 4 describes how VAL treats an Interest that arrives from the network. When VAL Forwarder receives a VAL

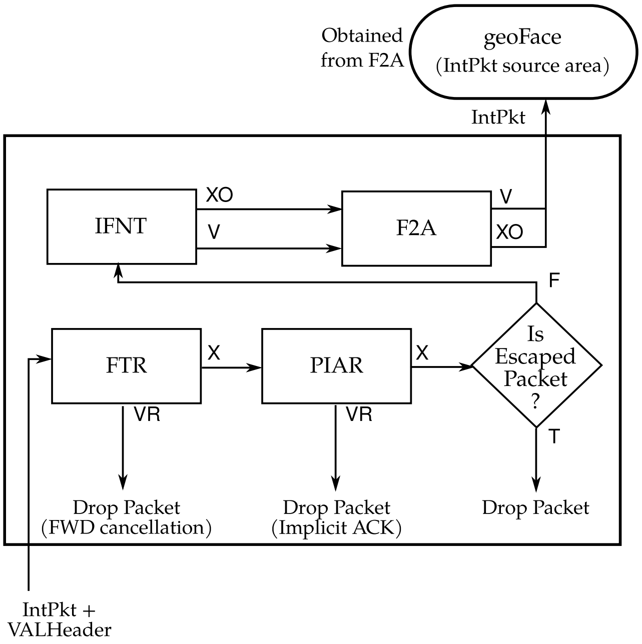

FIGURE 4. VAL information flow - incoming interest.

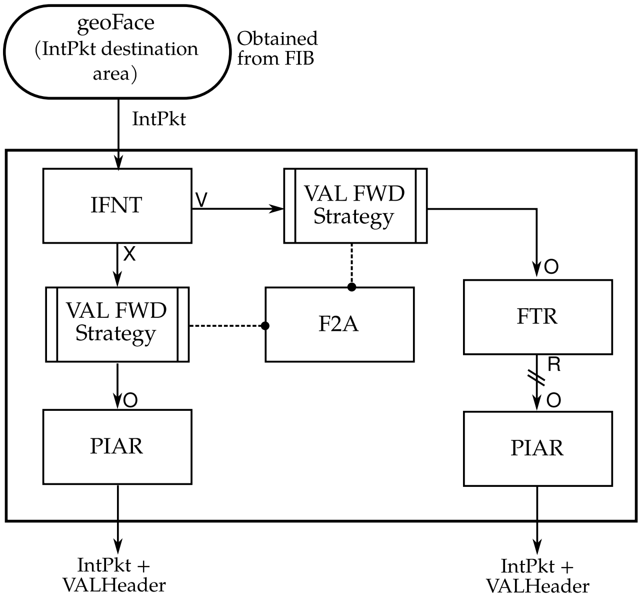

FIGURE 5. VAL information flow - outgoing interest.

packet containing an Interest, it first compares it against the entries of the FTR. If it finds a match, the same Nonce, and the same number of hops, it drops the packet and considers that a node in a better position has broadcasted the Interest. This match cancels the forwarding timer for that packet and removes the FTR entry. If no match is found, the received packet is compared with the entries in PIAR. In the case of matching an entry, the same Nonce, and one less hop than the PIAR entry, it considers this an implicit acknowledgment. Therefore, leading to the cancellation of the packet retransmission timer, the PIAR entry is removed afterward. Therefore, FTR and PIAR maintain records of VAL Packets scheduled to be sent and those already sent, respectively. These tables represent the backbone of the strategies used to mitigate broadcast storms.

If a packet does not hit PIAR, it reaches the decision point. This validates whether the Interest is leaving the Destination Area (DA). Therefore, no Interest in the discovery phase, without DA, is included in this decision. This mechanism ensures that the Interest does not propagate beyond the destination area. Subsequently, VAL attempts to create an IFNT entry. These entries are composed of information from the VAL header and the Nonce. Upon creating the IFNT entry, the packet is considered to be in a loop and is dropped if the entry is duplicated. Therefore, we rely on the Interest Nonce to assert its uniqueness.

Following the IFNT entry creation, VAL uses the SA and DA, if any, to check with F2A if those geoFaces exist. It creates them otherwise. It then uses the geoFace associated with the SA to send the Interest to the NDN Forwarder. It also passes the geoFace associated with DA, if any, to NDN Forwarder as a forwarding hint.

The description of how the VAL handles an Interest that came from NDN Forwarder is shown in Figure 5. The Interest is passed via geoFace. This geoFace is associated with the Destination Area. First, VAL compares the Nonce of the received Interest with the Nonces in the IFNT entries. If a match is found VAL Forwarder knows that the packet initially originated from the network. Otherwise assumes that this packet was generated locally. In both cases, the Interest and the IFNT entry, if any, are passed to VAL Strategy.

The purpose of the VAL Strategy is to:

- Build the VAL packet (VAL header + NDN packet).
- Make a forwarding decision, forward the packet or drop it.
- Calculate the forwarding timer.

This mechanism is not embedded in the VAL to be easily altered without meddling with VAL logic. This feature allows VAL to support different forwarding strategies and perhaps multiple forwarding strategies in the future. A description of the VAL Strategy is provided later in this document.

If the Interest was locally generated (IFNT miss), the VAL Strategy always returns a VAL Packet, and the duration of the forwarding timer is zero. Therefore, only a PIAR entry is created, and the packet is sent.

After an IFNT hit, VAL Strategy may or may not return a VAL packet. If the current node is in a better position than the previous-hop, VAL creates an FTR entry. Then, it sets the duration of the forwarding timer according to VAL Strategy indications. After that time runs out, a PIAR entry is created, and the packet is sent. Meanwhile, if a VAL packet with the same Interest and number of hops arrives from the network, the node cancels the forwarding timer and never creates a PIAR entry.

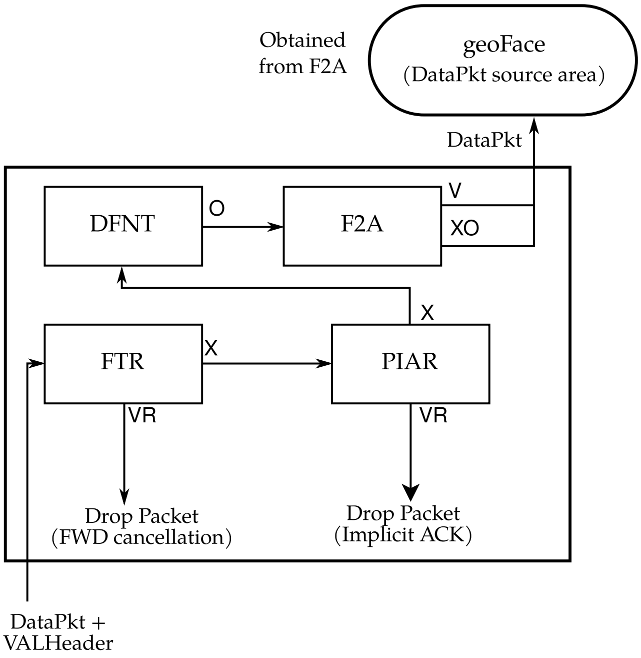

FIGURE 6. **VAL information flow - incoming data.**

Figure 6 describes the behavior of the VAL when receiving a VAL packet, composed of a Data packet and a VAL header, from the network. This process is similar to that illustrated in Figure 4.

After handling forwarding cancellation and implicit acknowledgment, VAL Forwarder creates an entry in the DFNT. This entry comprises the VAL header information and the signature of the Data packet. Indeed, the signature of a Data packet does not work as a unique identifier as the Nonce does. Instead, the signature serves, among other aspects, to associate the data with a producer. In summary, a single data chunk from the same producer always has the same signature. Nevertheless, because the entries in this data structure (DFNT) are short-lived, the risks of collisions are mitigated.

After creating the DFNT entry, VAL obtains or creates the geoFaces associated with the SA and DA of the packet from the F2A table. It then sends the Data packet to the NDN Forwarder via the geoFace associated with the Source Area of the information. Even if the Data packet results in *Unsolicited Data* the NDN Forwarder caches the packet. In this way, we attempted to create more data mules, allowing for better dissemination of content.

The last case, VAL receiving a Data packet from the NDN Forwarder, is also the most complex. Figure 7 illustrates how a Data packet is processed in this case.

The NDN Forwarder passes the Data packet and a Nonce list - the Nonces of the Interests satisfied by the Data packet. VAL first finds and extracts the matches in IFNT using the received Nonce list. It then uses the Data packet signature to find and extract the entry from DFNT. If it finds no entry, DFNT miss, it assumes that the Data packet was generated locally.

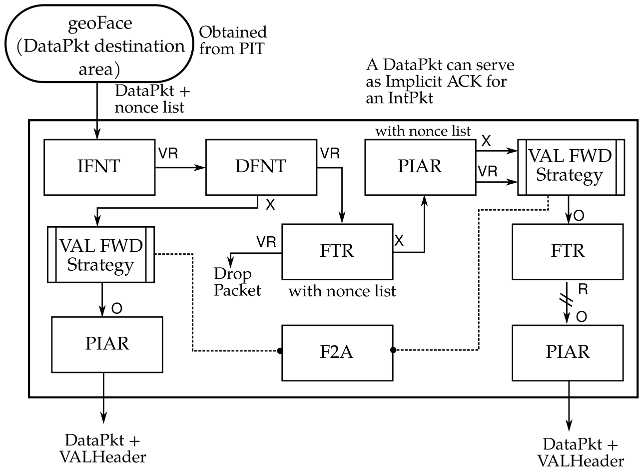

FIGURE 7. **VAL information flow - outgoing data.**

For a locally generated Data packet, VAL delivers the Data packet and the entries extracted from IFNT to VAL Strategy. VAL Strategy builds the VAL packet and calculates the duration of the forwarding timer, which is zero in this case. It then passes the VAL packet back to the VAL, creating a PIAR entry and sending it.

In case of DFNT hit, VAL uses the Nonce list to find matches in FTR and PIAR. This process is necessary because Data packets can serve as forwarding cancellations or implicit acknowledgments for Interest packets. Subsequently, VAL delivers the Data packet and the entries extracted from IFNT and DFNT to VAL Strategy. It may or may not return a VAL packet. For example, if the current node is in a better position than the previous-hop, the VAL receives a VAL packet and the duration of the forwarding timer. It then creates an FTR entry and a forwarding timer. After that time runs out, a PIAR entry is created, and the packet is sent. Meanwhile, if a VAL packet with the same data signature and number of hops arrives from the network, the node cancels the forwarding timer and never creates a PIAR entry.

An extra note. A geoFace is associated with a geographical area, but Interests requesting different data may originate from the same geographical area. Here resides the reason why the NDN Forwarder needs to send all the Nonces of the Interests satisfied by the Data packet to VAL. If only the geoarea associated with the incoming geoFace were used to find matches in IFNT, IFNT entries in which the Nonces were not satisfied by this Data packet could be removed. Receiving the Nonce List allows VAL to support different data requests from the same geoarea.

A. FORWARDING STRATEGY

This subsection presents an overview of the forwarding strategies implemented in the VAL FWD Strategy module. The VAL FWD Strategy treats five cases: (1) Interest generated locally, (2) Interest from the network in the discovery phase, (3) Interest from the network in the known-destination phase,

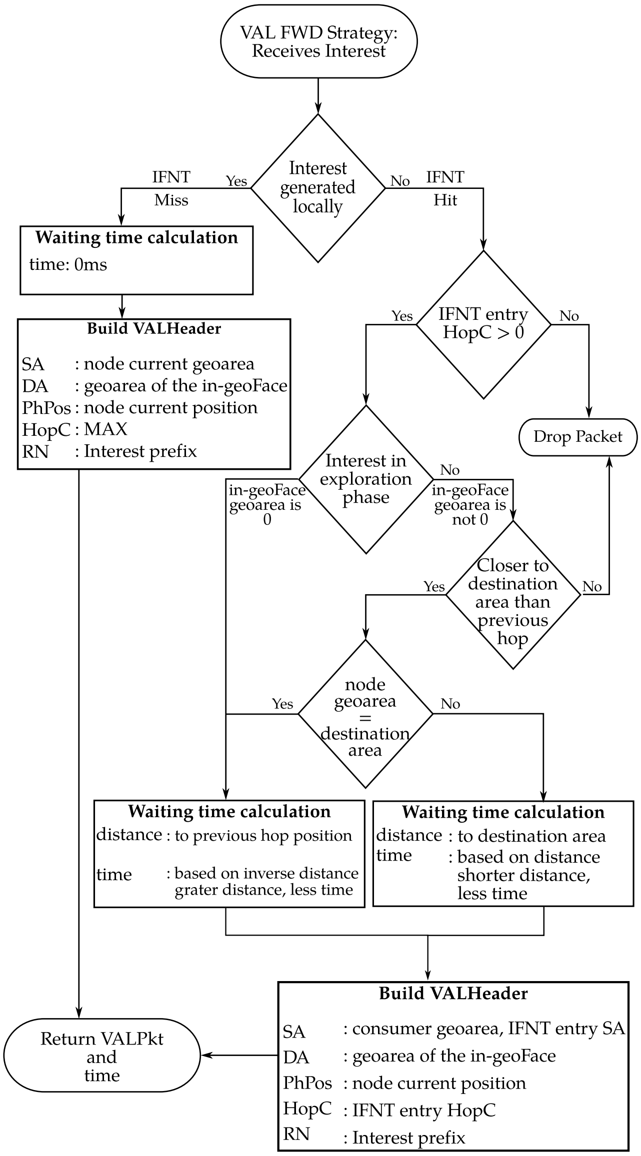

FIGURE 8. VAL FWD strategy - interest.

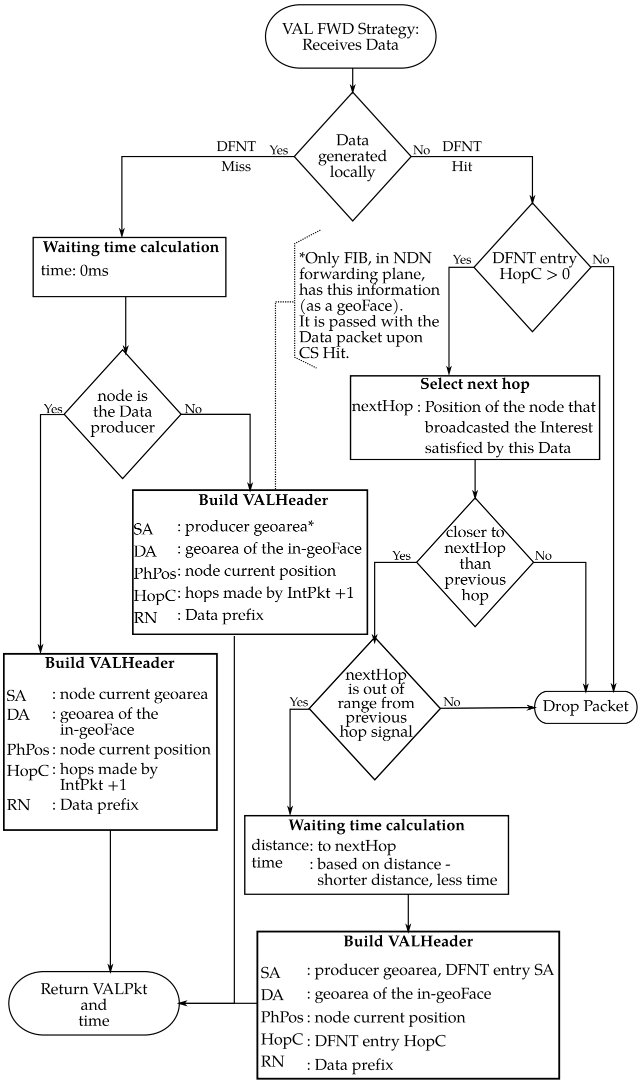

FIGURE 9. VAL FWD strategy - data.

(4) Data generated locally and (5) Data from the network. Figure 8 shows the strategy applied to Cases 1 – 3, and Figure 9 shows how it operates for Cases 4 and 5. The forwarding strategy presented here uses the distances between nodes and distances to destination areas (DA) to calculate waiting forwarding timers.

Figure 8 shows the forwarding strategy applied to the Interest Packets. It receives the IFNT entry, the incoming geoFace and the Interest. The first step is to ascertain whether the Interest was generated locally. If the IFNT entry is empty, we have an IFNT miss, and the packet was locally generated. Figure 8 shows how the VAL Headers are built for Cases 1, 2, and 3.

Figure 9 reflects how the forwarding strategy treats Data packets. It receives the DFNT Entry, the IFNT Entry, the incoming geoFace and the Data packet. If no DFNT entry is passed, a DFNT Miss, the data was generated locally. In this case, the data can come from the CS or the node can be a producer. We differentiate these two scenarios to ensure that the VAL Header is always built with the source area (SA) of the producer.

With the proposed strategy, the Data packets follow the path left by the Interest packets, also known as the following breadcrumbs strategy. In compliance with the breadcrumbs strategy, the DA of a Data packet is not used to make forwarding decisions or calculate the forwarding timer. Instead, the last known position of the node that transmitted the Interest, satisfied by the Data packet, is used. An approach based on the DA of the Data packet is left to future work.

V. EVALUATION AND RESULTS

The scenarios created for simulation intend to test VAL's functionalities. The scenarios presented here aim to test the following:

- The consumer node can learn routes after receiving the first Data packet.
- Packet retransmissions are recognized as an implicit acknowledgment.
- The correct node position is obtained.
- The transmission of a packet by a node in a better position triggers the cancellation of the forwarding process in every other node competing to send that same packet.
- After learning the position of the producer, the nodes can forward the Interest packets toward the producer geoarea.
- VAL's behavior with different vehicle densities.

The simulator used was ndnSIM – version 2.7 [18]. The ndnSIM is a module for NS3 that supports the NDN architecture in the NS3 simulator. To facilitate the duplication of results, we published our code [1] as well as the raw-results-data and data-treatment scripts.[2]

A. SCENARIO

We used SUMO to generate the two-by-two grid design, presented in Figure 10, as well as the mobility of the vehicles according to the manhattan mobility model. Each simulation lasts 200 seconds, and the number of consumers and producers is fixed. Each simulation has ten consumers and two producers. However, the behavior of a node as a consumer, producer, or forwarder is randomly defined. Each consumer generates an Interest per second, at most, 200 Interests per node. In order to bring more realism and complexity to the simulation, the ten consumers request different sequence numbers. Each consumer broadcasts 200 Interests, and the first sequence number to be transmitted is different for all consumers. The sequence numbers for transmission are calculated as follows:

```
$n$ = Consumer number
$x$ = First Sequence number
$y$ = Last Sequence number
for all $n \in [0, 9]$ do
    $x \leftarrow n \times 120$
    $y \leftarrow x + 200$
end for
```

Another variable in our simulations was the number of vehicles per simulation, leading to a set of four scenarios: 30, 50, 70, and 100 vehicles. Thirty simulations were run for each scenario.

The following list shows the parameters used for these tests:

- The standard used is 802.11p.
- The modulation is set to OFDM.
- The bit rate to 24Mbps.
- Two propagation loss models are set. One is to account for variations in the signal strength due to multipath fading. The other factor accounts for path loss owing to the distance traveled by the signal.
- The max signal range is set to 80 meters.

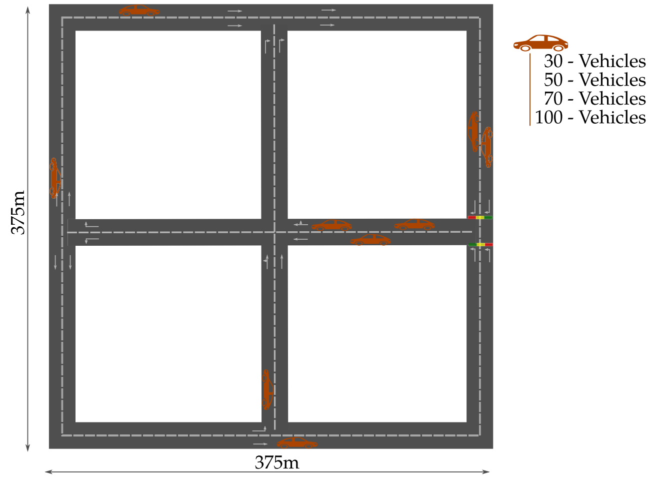

FIGURE 10. **Simulation scenarios.**

The following items show the minimum and maximum waiting times for the respective NDN packets.

- Interest minimum waiting time = 32 ms
- Interest maximum waiting time = 62 ms
- Data minimum waiting time = 0 ms
- Data maximum waiting time = 30 ms
- Interest retransmission waiting time = 40 ms
- Data retransmission waiting time = 40 ms

B. RESULTS

The results presented here are in the form of ratios. As we analyze VAL's functionalities with different vehicle densities, presenting raw packet numbers could lead to a more ambiguous analysis. Figures 11 – 15 show the results for each type of vehicle density. Each result is presented with a 95% confidence interval.

Figure 11 shows two metrics. In red is the Satisfied Interest Ratio (SIR), which is the most common metric used in this type of evaluation. As we can see, the SIR for simulations with 30 vehicles is relatively low, just 0.436. This result is to be expected, with a signal range of 80 meters and the propagation loss models in place. A scenario with only 30 vehicles on the map presented in Figure 10 is an extreme scenario with a low chance of vehicle encounters. In the 100 vehicle scenarios, we have a SIR of 0.876, meaning that within 30 simulations with 100 vehicles, the mean of Satisfied Interests was 87.6%, with a very close confidence interval. Conveying that 87.6% of all data requests were satisfied.

The second metric in Figure 11 is System Out Interest Ratio (SOIR). This metric requires explanation. What we understand by "System" is the association of two components, VAL + Named Data Networking Forwarding Daemon (NFD). This metric conveys the impact of the System in mitigating the propagation of unnecessary Interests and broadcast storms. It is the ratio of outgoing Interests against Incoming Interests. This metric needs to be evaluated with SIR because, although we genuinely want a low SOIR, it is only valid if

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[1] https://github.com/jfpereira88/ndnSIM-VAL

[2] https://marco.uminho.pt/data-archive/papers/

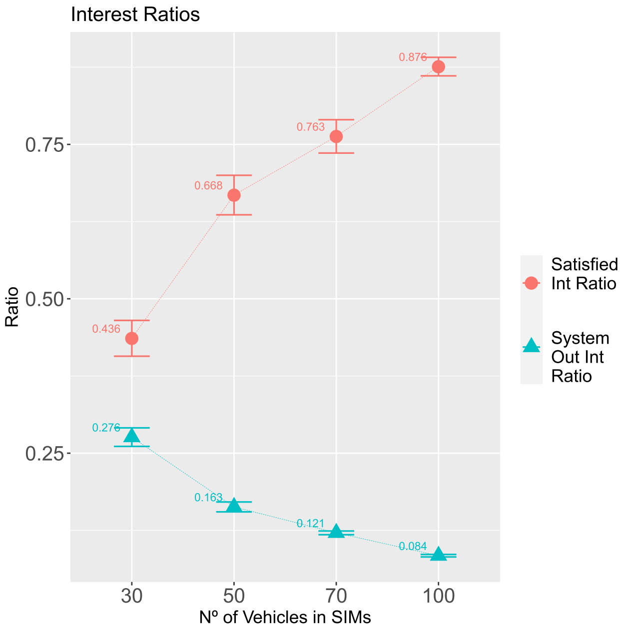

FIGURE 11. **Interest ratios.**

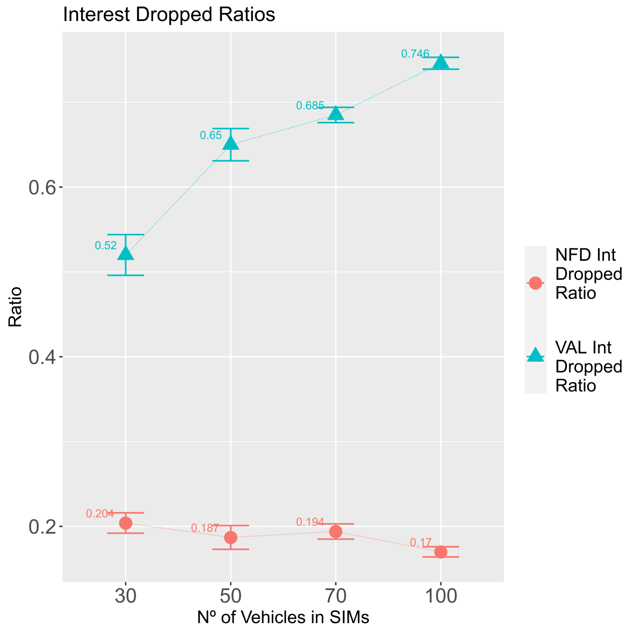

FIGURE 12. **Interest drop ratios.**

we have a high SIR. For example, we can look for the SOIR and SIR values in the 70 vehicles scenario. SOIR tells us that only 12.1% of the received Interests were sent back to the network, resulting in 76.3% of Interests being satisfied with Data packets.

Figure 12 shows the ratio of dropped Interest packets from the System's two components, VAL and NFD. This Figure shows which component is responsible for filtering out the incoming Interest packets. As we can see, in all the scenarios, VAL is the primary responsible for this effect. VAL's mechanism to mitigate broadcast storms, forwarding cancellation, and implicit acknowledgment are the main factors responsible for this outcome. For example, in Figure 11, we see that in a 50 vehicles scenario, only 16.3% of the received Interests were sent back to the network, resulting in 83.7% of Interest packet drops, and Figure 12 shows that VAL is responsible for 65% and NFD for 18.7% of those drops.

Figure 13 shows two metrics. First, the Data Delivery Ratio (DDR) is the ratio between the number of Data packets received by consumers and the number of Data packets transmitted from producers. As shown, this ratio can be higher than one, which is the effect of the cache. Second, we have System Out Data Ratio (SODR), which is equivalent to SOIR but concerning Data packets. These two metrics must be evaluated together to ascertain the System's proper behavior.

The metrics presented in Figure 14 indicate which component of the System is responsible for dropping more Data packets. At first glance, we can see that NFD drops more Data packets than VAL, which may seem that NFD is the major contributor to mitigating Data packet broadcast storms. However, NFD has no mechanism for mitigating this aspect. These high values of dropped Data packets occur because NFD is responsible for handling unsolicited Data. When an unsolicited Data packet is detected, the packet is dropped. Regarding VAL, the forwarding cancellation and implicit acknowledgment mechanisms also act when treating Data packets, and mitigate the number of unnecessary Data packets sent to the network.

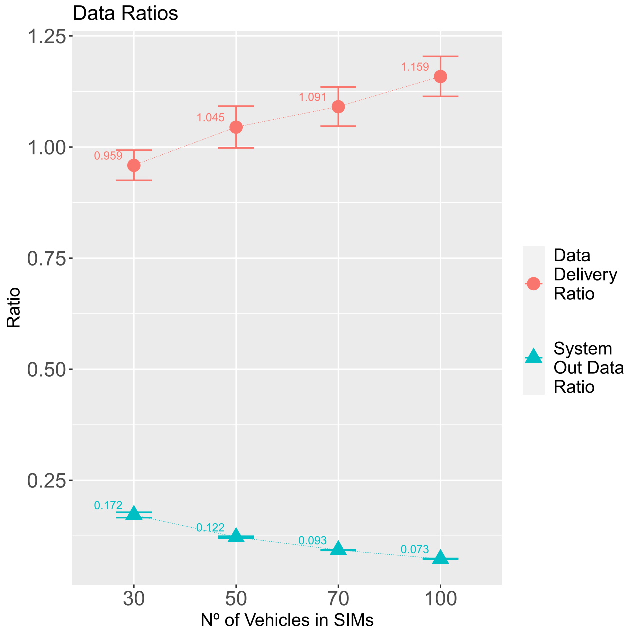

FIGURE 13. **Data ratios.**

The graph named Discovery Ratio, Figure 15, conveys the ratio of geoFaces usage. The ratio of geoFaces associated with a geoarea is shown in red. In blue, the graph shows the ratio of the floodFace, which is a geoFace without an

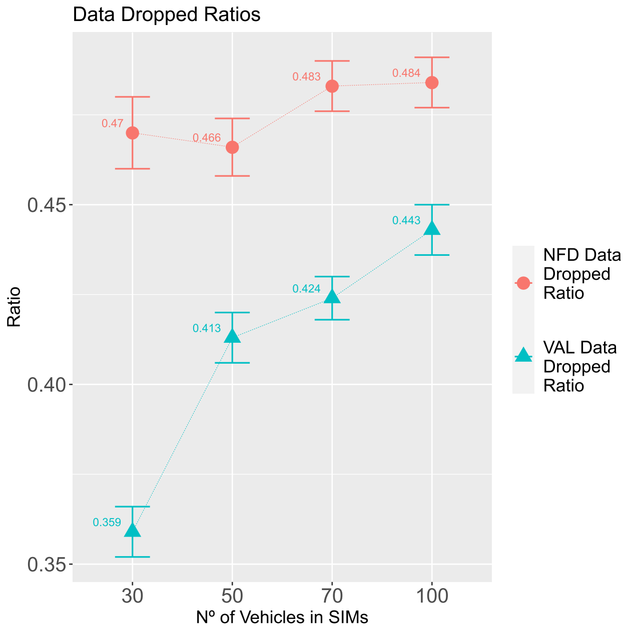

FIGURE 14. **Data drop ratios.**

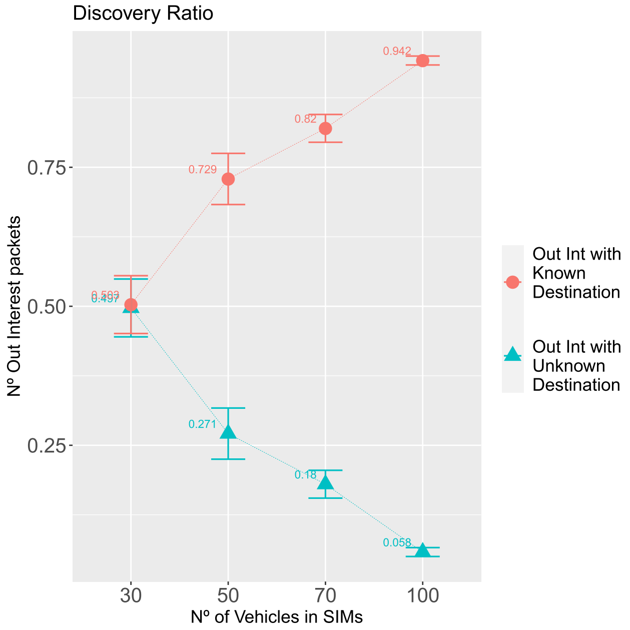

FIGURE 15. **Interests in discovery phase ratio.**

associated geoarea. The metric Out Interest with Known Destination (OIKD), is the ratio between outgoing Interest using geoFaces with an associated geoarea and the total number of outgoing Interests. The metric Out Interest with Unknown Destination (OIUD), is the ratio between outgoing Interest using floodFace and the total number of outgoing Interests. This Figure shows the VAL's capacity to discover and maintain the position of a producer.

In summary, the results demonstrate that VAL significantly mitigates unnecessary packet retransmissions, whether for Interest or Data packets. Furthermore, it is also observable the relation between content discovery, Figure 15, and SIR, Figure 11. Naturally, VAL works better in high-density scenarios. However, the results also demonstrate that in the low-density scenario of 30 vehicles, the main problem is delivering Interest packets to a producer. This aspect is demonstrated by the low SIR, the near 1 DDR, and the low usage of geoFaces.

VI. CONCLUSION

In this paper, we present a Link Adaptation Layer called Vehicular Adaptation Layer (VAL), that supports VANETs and geographic-based forwarding. VAL was implemented in ndnSIM. It supplies mechanisms to mitigate broadcast storms (forwarding cancellation), to overcome the lack of communication between nodes (implicit ack), to associate producers' and consumers' areas to data names (geoFaces) and a mechanism that learns where data resides (discovery phase). It also presents a forwarding strategy, based on geographical information, to guide Interests to producers' areas and Data packets back to the consumers. VAL also supports the implementation of alternative forwarding strategies that differ from the one described in this work. These mechanisms are implemented without disrupting NDN primitives or NDN data structures.

VAL serves the NDN forwarding plane, but does not replace it. It processes Interest and Data packets, and can use distinct forwarding strategies for their dissemination. This work is based [3] and [4], with substantial conceptual modifications to allow Data packets processing and modular forwarding strategies. The relationship between our Link Adaptation Layer, VAL, and the NDN forwarder is also more strictly defined, not allowing direct access in either way.

The novelty of this work can be summarized as follows.

- a strictly defined relation between the NDN Forwarding Plane and the Adaptation Layer (VAL) that does not change the NDN Forwarding behavior or its structures in any way;
- the capacity to treat Data packets and, if needed, use specific forwarding strategies to guide them.

In this work, a satisfactory proof-of-concept was achieved. All the implemented mechanisms work as outlined, and VAL can apply the designed forwarding strategy implemented in VAL Strategy. However, the development of a bulletproof geo-forwarding strategy was not the focus of this work. Instead, the forwarding strategy applied to VAL Strategy is intended to prove that geo-forwarding strategies can be implemented without interfering with any NDN structure.

In future work, we intend to develop an NDN protocol that creates a distributed pool of information that VAL forwarding strategies can use. This will allow for the implementation of more complex geo-forwarding strategies that do not depend exclusively on distance. This future work will also include a comparison of VAL with other solutions presented in the literature.

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JOÃO F. PEREIRA received the M.Sc. degree in telecommunication engineering and computer science from the University of Minho, Braga, Portugal, in 2020. He is currently pursuing the joint Ph.D. degree in telecommunication engineering from the University of Minho, University of Aveiro, and University of Porto, Portugal. He is also an invited Assistant with the University of Minho. His current research interests include next-generation networking and internet, named-data networking, and vehicular *ad-hoc* networks.

M. JOÃO NICOLAU received the Graduate degree in systems and informatics engineering and the M.Sc. and Ph.D. degrees in informatics (computer communications) from the University of Minho, Portugal, in 1992, 1995, and 2005, respectively. She is currently an Assistant Professor with the Department of Information Systems, School of Engineering, University of Minho, where she actually develops teaching and research activities in the field of communication networks and protocols. As a Researcher, she is also with the Urban Computing Laboratory, ALGORITMI Research Centre, University of Minho. Her current research interests include network technologies and protocols, routing in IP networks, networks simulation, and indoor positioning.

ANTÓNIO D. COSTA (Member, IEEE) received the Graduate degree in systems and informatics engineering, the M.Sc. degree in informatics, and the Ph.D. degree in computer science from the University of Minho, Portugal, in 1992, 1998, and 2006, respectively. He is currently an Assistant Professor with the Department of Informatics, University of Minho, where he has been developed teaching and research activities in computer networks and computer communications since 1992. As a Researcher, he is also integrates the Computer Communications and Networks (CCN) Research Group, Centro Algoritmi, School of Engineering, University of Minho.

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