An efficient information-centric mechanism for the next generation vehicular networks

Francisco Natário, francisco.natario96@gmail.com, Instituto Superior Técnico, Universidade de Lisboa

***Abstract*—As a crucial component of Intelligent Transportation Systems (ITS), the Internet of Vehicles (IoV) plays an essential role in intelligent cities. However, current Internet protocol solutions cannot guarantee efficient data delivery in highly dynamic mobile environments. Therefore, Named Data Networking (NDN), a leading architecture of Information-Centric Networking (ICN), is introduced into IoV to focus on transmitting and retrieving content, regardless of its physical location. The NDN architecture in-network caching and IP address decentralization characteristics are crucial to surpass IoV environment challenges. While the nature of the NDN architecture essentially supports consumer mobility, Producer mobility faces complex challenges. Producer mobility relies on up-to-date Consumer routing tables to minimize Interest packets delivery loss and Consumer delay in IoV scenarios.**

In this context, this work proposes an anchor-less signalling approach to the NDN data plane, aiming to mitigate the problems posed by the mobility of content Producers in dynamic networks such as IoV. The proposed mechanism ensures a reduced disruption in the data delivery process by using a unique Interest forwarding mechanism without relying on the existing routing protocol. We analyse the performance of the proposed approach against default NDN architecture regarding content consumer delay, consumer satisfaction, and network overhead.

***Index Terms*—Internet of Vehicles, Named Data Networking, Producer, Mobility.**

I. INTRODUCTION

MOBIlity has become a basic requirement for almost any communication network. The need for a mobility management paradigm to apply within IP networks resulted in a complex set of mechanisms implemented via a dedicated control infrastructure. The complexity and lack of flexibility of such approaches (e.g., Mobile IP [1]) promoted the development of promising Information-centric Network (ICN) [2] architectures as an paradigm shift to the traditional IP-based communication.

ICN approaches were developed to answer the ever-increasing urge from users to access information irrespective of its physical location, while helping to address a series of limitations in the current Internet architecture, e.g. mobility management in vehicular networks. ICN characteristics such as named content retrieval, innate multicast support, and in-network data caching are some of the advantages that surpass the challenging demands of vehicular networks and their evolution [3]. Such challenges encompass not only mobility management, but also new requirements such as seamless, secure, robust, scalable information exchange among cars, humans, and roadside infrastructures. Furthermore, the Internet of Vehicles (IoV) prioritizes information (e.g., traffic and congestion information) rather than a node identity and requires information to be propagated in environments with highly dynamic vehicle movement, while minimizing latency as a result of an increasing number of connected vehicles.

In ICN, the content-based approach means that the content is requested by its name as a mean to retrieve it from the network, decoupling content from its sources. The way for a user to get the content it desires is by its name, i.e. its identifier, without referring to the IP address of the node storing the content. We choose the Named Data Networking (NDN) [4] framework among other ICN architectures as large attention from the research community has been focused on its development and maturity.

The NDN communication is based on three elements: the Consumer nodes which aims to get data that may be provided by another element in the network; the Producer nodes which provide the requested content; the router nodes that may cache transit data aiming to support future requests.

To receive content, a Consumer sends out an Interest packet with a name to identify the desired data. The Consumer drives communication in NDN. A router remembers the interface from which the request comes in and then forwards the Interest packet by looking up the name in its Forwarding Information Base (FIB), which is populated by a name-based routing protocol. Once the Interest reaches a node with the requested data, a Data packet is sent back, carrying both the name and the Data content together with a signature by the key from the Producer. This Data packet follows in reverse the path taken by the Interest to get back to the Consumer: Data packets are forwarded based on the state set up by Interests in the Pending Interest Table (PIT) at each router.

While the NDN architecture provides a natural support for Consumer mobility (e.g., the Consumer can keep requesting information until it receives the desired content while changing domains), the Producer mobility faces many challenges, which are further emphasized in a highly dynamic environment [5] [6].

While the presence of in-network caches may help to smooth the effect of the Producer mobility, it can still cause unnecessary Interest packet loss for nodes without an updated forwarding information base, causing congestion that affects data integrity. Without a dynamic routing mechanism to ensure Interest broadcast control, consumers' continuous requests for content can lead to broadcast storm problems.

Furthermore, losing Interest and increasing network congestion due to the lack of forwarding information during producer movement can lead to profound implications for the quality of service of time-sensitive applications.

In order to tackle such problems, we use the existing NDN

Interest/Data packet structures to trace Producer movements and to build a reverse-forwarding path dynamically. We develop a proactive signalling mechanism to update the FIB tables at intermediate nodes aiming to keep the Producer content reachable after its movement, even in the absence of a routing protocol.

We propose PDCN (Producer Data Controlled Notification), which intends to solve the Producer mobility problem through the data plane.

We aim to solve the Producer mobility problem while assuring high packet delivery success, Interest broadcast minimization and low packet delivery delay in a highly dynamic network.

II. INTERNET OF VEHICLES

IoV is a vast network where vehicles exchange information with infrastructures, humans, and sensors, among others, to support different functions (such as dynamic information services, intelligent traffic management, intelligent vehicle control and more) [7].

IoV is expected to improve the intelligence level and autonomous driving ability and satisfy the requirements of many services and applications such as vehicular safety applications, road traffic efficiency and infotainment applications, and Video streaming [8].

However, Applications must function correctly under IoV environment-specific characteristics such as high scalability, dynamic topology, and non-uniform network density. Regarding high scalability, IoV environments have plentiful interacting entities and elements, creating a necessity for a large-scale functional network. Considering dynamic topology, IoV vehicles' dynamic movement and velocity create an ever-changing network topology. Finally, vehicle networks change with vehicle density and location conditions, e.g. city or highway environment.

The complex IoV environment and demanding application necessities make IoV prone to some complex communication challenges [9]. For instance, IoV applications require low service delay and reliable network communication, e.g., real-time communication, even when communication or network nodes malfunction.

In our proposed work, we intend to tackle delay constraints and fault tolerance requirements to ensure that IoV applications work correctly independently of the IoV environment characteristics.

III. NAMED DATA NETWORKING

The current IP-centric model cannot deal with highly dynamic vehicle movements. Vehicular environments have high mobility nodes, communication ephemerality and intermittency. The rash vehicular environments lead to IP address allocation/maintenance difficulties and stable end-to-end data delivery paths. Changing from an IP-centric network to an Information-centric network (ICN) will allow a paradigm change from end-to-end to content-based communication.

This communication paradigm is important since vehicles are Interested in retrieving contents regardless of the identity of the vehicle/roadside node producing it [10]. Furthermore, the network can use the NDN node caching properties to store content and content replicas throughout the network, which is beneficial to the intermittent connectivity on the road [4] [11] [3].

NDN focuses on the content name as the critical element in communication. Each content has a unique name that identifies them, i.e., for content copies, every single content has the same name. Furthermore, the content exchange between users no longer focuses on their connection but on the content. There are two types of packets in the NDN architecture, the Interest packet (i.e. the packet used to request a given content) and the Data packet (i.e. the packets with content information). The Data and Interest packets are the terminologies used throughout the work. Since communication is content-based, the security mechanisms are applied to the node's connection instead of being applied to the content. These features allow each network node to store content in the cache and serve as source nodes for future requests. This architecture thus allows an improved performance in content delivery. Furthermore, this straightforward design of NDN makes him an ideal choice for content-centric networks [4].

The NDN architecture has beneficial features in the context of vehicular networks and especially in the IoV paradigm. Characteristics such as name resolution allow names to be used to exchange content (such as weather conditions, road congestion information, and more) between nodes (eliminating the need for IP-based communication and node identifier) and thus facilitating the exchange of content to vehicles in motion.

On the other hand, in-network caching allows nodes (vehicles and roadside infrastructure) to save content throughout the vehicle network. Thus, allowing easy access to information under the intermittent vehicular connectivity of dynamic moving nodes. In conclusion, the main NDN principles, i.e., name-based communication, in-network caching and architecture, can meet the demand for time and space content retrieval in highly dynamic environments present in the IoV paradigm. Thus, NDN is an obvious solution for efficient information delivery in IoV.

IV. PRODUCER MOBILITY CHALLENGES

This section presents and discusses the most recent advances in tackling Producer mobility challenges in NDN. First, we define more precisely what are the challenges related to Producer mobility. Then we take a closer look into existing solutions: Mapping Based Mobility Approach (MBMA) [12], Indirection Based Mobility Approach (IBMA) [13], Location-Based Mobility Approach (LBMA) [14] and Control/Data Based Mobility Approach (CDBMA) [15].

Serhane et al. [16] introduces Producer mobility problems such as Interest Missing during Handover and Interest Succeed Delivering Before Handover. We describe the Interest missing during handover as the Producer mobility problem we intend to solve.

In NDN, the Interest packet is forwarded hop-by-hop using intermediate nodes' FIB rules to reach the Producer and trace the PIT table path.

However, considering Producer mobility, the Interest packets will follow the FIBs' old path to the Producer without reaching it since the Producer moved, leading to discarded Interests. Therefore, the provider's mobility provokes unnecessary Interest packet losses on the path towards the Producer. Furthermore, the Interest packet loss will continue until the FIBs, which leads them to be dropped, are updated. Thus, until all relevant routers completing the FIB entries are updated, the Producer mobility will result in long handover latency [17] [18].

The Producer movement will lead to invalid FIB entries, useless PIT entries, and request/content delivery failure.

The primary Producer mobility problem we intend to solve is the lack of Producer location information after handoff. After the handoff, the intermediate routers need to update their FIBs with the current Producer namespace [13].

When moving away, a Producer requires intermediate routers to update their routing tables to successfully receive future/ongoing content requests. However, updating the routing tables of all content routers takes much time. Furthermore, the reconstruction of the entire moving Producers routing table is costly, and inefficient [13].

These issues have profound implications for the quality of the handover experience and may affect and be unacceptable for time-sensitive applications [18].

Mapping Based Mobility Approach (MBMA) [12] It is a technique that provides mobility support to the Producer using a stable DNS server, rendezvous point or mapping server to track the content identifier and its current provider location, as illustrated in Figure 1. The DNS server, rendezvous point or mapping server processes all necessary mappings between the content provider and the content consumer. The Producer sends a namespace update to the DNS server. This forwarding mechanism occurs because the DNS server has permanently stored all the data sources and has its name in all mobile sources. Furthermore, The DNS server name will be the top hierarchical name in all mobile sources. For this reason, all the mobile sources will point and send their interest out to this server. The consumer sends an Interest to the mapping server, which answers with the information in the form of a forwarding namespace hint about the current location of the content provider [19].

Gao and Zhang et al. [12] introduce a Scalable Mobility Management (SMM) scheme with three different separation mechanisms to resolve the Producer mobility problem: (i) Content name/location separation, in which case a unique name identifies the content and its location. This separation helps the routing plane during the handover, as the full name of the access router does not need an update. The content name is only used for identifying requested data rather than routing Interest packets. The content source sets the location name of the contents stored locally as the name of the access router. The Producer needs to register the binding between the content name and its location name to the Locator/ID mapping system to support its mobility; (ii) locator/ID separation, in which the SMM scheme uses a Distributed Hash Table (DHT) to create a mapping relationship pair and store it at the mapping servers. The pair comprises a DHT key and a DHT value as the content name hash and the content locator hash, respectively. The objective of the DHT is to support a scalable and robust mapping system and improve the handover process; (iii) management/routing separation, in which case the moving Producer, once it attaches to a new access router, can either send a binding update to the mapping server, updating its new location, or send a binding update to the mapping server and the previous access router, updating both with its new location. This separation allows the Interest packets to be forwarded to the new access router without waiting for a binding update from the mapping system.

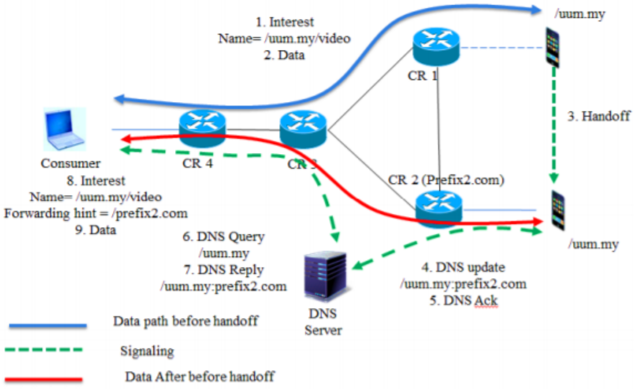


Fig. 1. Operational Model of MBMA [19]

Indirection Based Mobility Approach (IBMA) [13] is a technique based upon the Mobile IP mobility solution that uses a home agent to maintain the binding information between the content prefix and the content Producer location, presented in Figure 2. The content provider registers its content prefixes with the home router/agent. After the handoff from the current location, the content provider updates the binding information in the home agent, sending a binding update with its new location. The home agent then redirects the Interest packets encapsulating and tunnelling them to the current content provider location. Which conveys that IBMA only uses ICN/NDN between the consumers and the home agent. From the home agent to the Producer, it is used regular IP forwarding [19].

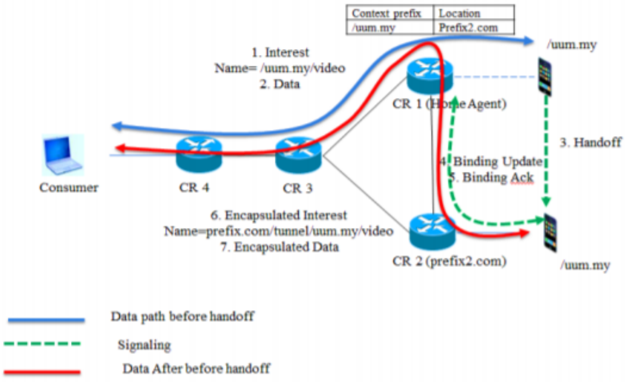


Fig. 2. Operational Model of IBMA [19]

Lee et al. [13] indirect-based scheme is based on tunnelling

Interest packets between a home router (i.e. a home domain content router) and the moving Producer. The Producer, throughout his movement, detects the NDN network attachment point and its name prefix information. The Producer compares the prefix information of the current attachment point with its prefix information. If the prefix information differs, the Producer sends an update to the home router. The home router is responsible for announcing the name prefix of the moving Producer to the other devices in the network. Thus, the network redirects the Interest packets to the home router, which will then encapsulate and send them to the content Producer.

However, Hussain et al. [19], and Lee et al. [13] identify the following problems in the indirect-based approach: (i) Process of encapsulation increases delay; (ii) Addition of extra functionality to the routers and data transmission may result in triangular routing increasing the latency period; (iii) Home router behaves as a single-point-of-failure.

Locator Based Mobility Approach is a technique based on the separation of content identifier and locator, as shown in Figure 3. As occurs with the IBMA approach, the LBMA approach relies on the separation between the content identifier and content locator. This separation is also managed by the home router, which is responsible for mapping the content identifier with the content location. The Producer, during the handoff, sends a packet to its home router with an update of its current location. The Interest packets originating from the Consumer are still sent to the home router after the handoff. The home router modifies the incoming Interest packet adding the new Producer location and forwarding the packet to the Producer's current location [19].

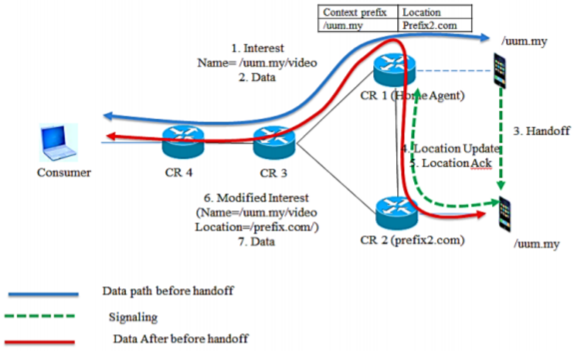


Fig. 3. Operational Model of LBMA [19]

Azgin et al. [14] propose a locator-based approach focused on intra-domain and inter-domain anchors. The anchors provide the overlay forwarding functionality as a service for a cluster of mobile flows. The scheme adopts three mechanisms: Anchor assignment, Name resolution and discovery, and Packet forwarding. In the Anchor assignment mechanism, different anchors are assigned to different namespaces using hash-based namespace groupings. Each ICN router within each domain is assigned unique hash-output identifiers. This assignment allows each ICN router to determine the name anchor responsible for a given namespace within its domain. With the name resolution and discovery, new Producers register into their local name anchor or anchors through a local name resolution (mapping the namespace hash to determine the local name anchor). The Producer is finally registered when the local name anchor registers the Producer's namespace at the corresponding global name anchor. The packet forwarding mechanism is responsible for label forwarding from both the Consumer and Producer side. The proposed architecture uses label-based forwarding to route packets to their corresponding namespaces anchors.

Together these mechanisms are responsible for handling the Producer mobility with reduced latency in both inter and intra-domains. However, the proposed mechanism integrates three new structures into the existing NDN architecture to manage name resolution, discovery and packet forwarding.

Control/Data-planed Based Mobility Approach is a technique based on the control plane and data plane separation to support mobile Producer, as illustrated in Figure 4. The control plane uses a server that controls the mobility signalling process during handoff. After the handoff, the data plane is responsible for forwarding packets between Consumer and the Producer. During Producer handoff, the Producer sends a location update to the controller [19].

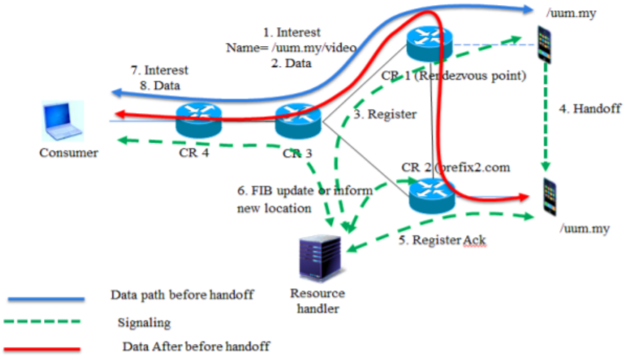


Fig. 4. Operational Model of CDBMA [19]

Torres et al. [15] propose a Controller-based Routing Scheme "CRoS" that follows the Software Defined Networks (SDN) technology. The CRoS is divided into two phases: A Bootstrap phase and a Name-Data routing phase. The former is responsible for the construction of the global view of the network. The controller receives information from all routers to create a global network view: i) registration information (routers send information about their presence and neighbours to the controller; ii) control discovery information (routers broadcast Interest packets to find the controller). In the Name-Data routing phase, a new Producer starts by registering itself by sending a specific Interest packet. The Producer sends the Interest packet directly to the controller, which registers the new Producer (stores the Producer content prefix in the Named-Data location table). This phase creates end-to-end routes between Consumers and Producers with a single route request. The two phases allow the controller to compute the best routes for content delivery.

The CRoS approach aims to reduce the routers-controller communication overhead by: (i) coding routing information on content names; (ii) reactively updating the controller upon router local information change; (iii) avoiding the replications of routing information from the controller to routers; (iv) restricting the Interest flooding. However, the CRoS protocol has decreased efficiency when the Producer mobility rate increases due to additional Interest packets required for the features mentioned above.

The analysis of the approaches described in this section should address the challenges posed by the presence of a mobility anchor, such as a DNS server (MBMA), the home router (IBMA and LBMA) or a resource handler (CDBMA). Moreover, while anchor-based approaches seem suitable for fixed networks, their management may face additional challenges in IoV networks characterized by their ad-hoc networking nature. Therefore, the best option is to use a proposal that does not rely on an anchor to manage Producer mobility. Such anchor-less-based mobility management proposal should rely only on the usage of a signalling protocol based on Interest packets to directly update the FIB in any needed node in the data plane, supporting Producers' mobility even in the presence of latency-sensitive applications.

V. ANCHOR-LESS MOBILITY MANAGEMENT

Anchor-less-based mobility-based management allows mobile nodes to advertise their mobility to the network without requiring any specific node to act as a Rendezvous point. In this section, we take a closer look into Map-me [20], an anchor-less approach. Map-me [20] is based on the following characteristics: (i) it addresses Producer mobility while focusing on providing fast handover and preserving progressing flows performance; (ii) it relies upon propagating forwarding updates of the Producer position to guarantee Producer mobility reliability.

The main contribution of Map-me as an anchor-less mobility-management mechanism is to leverage stateful forwarding and dynamic and distributed Interest load balancing to update the forwarding state at routers. Compared to the described anchor-based solutions, Map-me provides: (i) a simple data plane approach avoiding additional name resolution and discovery complexity; (ii) does not need a third party (a controller or rendezvous point) to process mobility handoff and location control; (iii) is lightweight in terms of required signalling messages; (iv) can better distribute traffic over the network and thus better cope with a more significant number of users. The Map-me solution is, for this reason, a potential anchor-less mechanism to solve the Producer mobility problem in IoV.

The Map-me solution comprises two components: an update protocol 5 and a notification/discovery protocol that complement each other.

The update protocol uses an Interest packet called Interest Update (IU), which the Producer forwards every T seconds to its previous FIB location. A special flag in its header identifies the IU. All routers that relay the IU packet from the current Producer location into the Producer's previous location update their FIBs, including the previous hop that forwarded the IU packet as the next hop towards the name prefixes offered by the Producer.

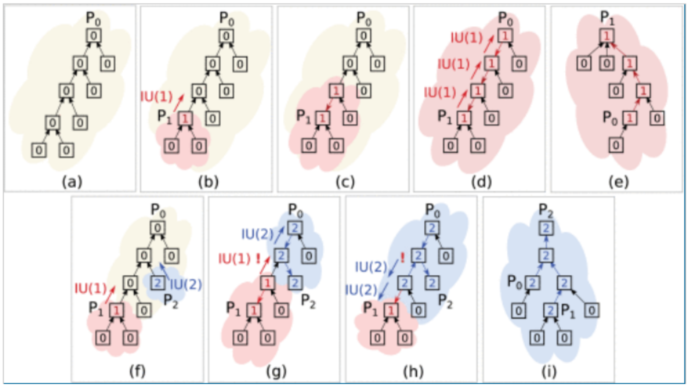


Fig. 5. Map me IU mechanism [20]

The discovery protocol is divided into the Interest Notification (IN) mechanism and the Producer Discovery (PD) mechanism.

The Producer uses the IN mechanism to ensure frequent yet lightweight Interest Notification packet broadcast to the network. The IN differs from the regular Interest packets by adding an identification flag and a sequence number to its header. The sequence number is used to modify FIB entries. The sequence number triggers FIB modification when it receives an IU that carries a higher sequence number than the one locally stored. The Producer uses the IU to follow FIB indication and update FIBs Tables through the network. However, contrary to the IU, the IN is broadcasted with one hop limit to all Producer neighbours. The Producer sends IN packet every time it attaches to the access point. The IN routes the Consumer requests to the Producer before the IU protocol finishes since the IN has only one hop distance.

The PD protocol is used when a Consumer Interest packet reaches a point of access with an invalid output face in the corresponding entry. After reaching this point, the Consumer Interest packet is broadcasted to a one-hop distance to all neighbours, aiming to find the breadcrumbs (IN) left by the Producer mobility. Therefore, the Consumer Interest packets can be forwarded directly to the Producer or be broadcasted if the point of access has no valid output face.

To implement such protocols, Map-me modified its FIB to incorporate additional information: sequence number and an associative array. The sequence number is used to prevent forwarding loops, control the propagation of Interest packets by the PD mechanism, and handle concurrent updates. The associative array maps a face on which IU has been sent with the associated retransmission timer.

Although Map-me seems a suitable solution to implement an anchor-less mobility management mechanism in a fixed network with the help of an existing routing protocol, it would face several challenges in a dynamic network scenario such as the one posed by IoV. These challenges include frequent connectivity disruptions, durability, and sudden network changes caused by node mobility and urban obstacles [21].

The MAP-me base operation relies on the Interest Update packets, which follow the FIB populated by the routing protocol. In IoV, the IU induces significant delays or fails due to constant network change.

The Map-me proposal was not created for a highly dynamic network without a routing mechanism. Although there are name-based routing protocols for fixed networks (e.g. Open Shortest Path First (OSPFN) and Named-Data Link State Routing (NLSR)), there are no name-based routing for dynamic networks [22]. The MAP-me base operation relies on the Interest Update packets, which, besides following the FIB populated by the routing protocol, induces significant delays. PDCN (Producer Data Controlled Notification) is a named-based routing protocol created to solve the challenges presented by IoV. PDCN uses its neighbour degree and Interest Notification method as routing and forwarding mechanisms to ensure data delivery while avoiding Interest broadcast problems without a routing protocol.

VI. THE PROPOSED SOLUTION

We propose PDCN (Producer Data Controlled Notification), which intends to solve the Producer mobility problem through the data plane. The PDCN is a forwarding and routing mechanism to solve the Producer mobility problem while assuring high packet delivery success, Interest broadcast minimization and low packet delivery delay in a highly dynamic network.

PDCN uses its neighbour degree and Interest Notification method called Notification Controlled Broadcast (NCB) as routing and forwarding mechanisms to ensure Data delivery while avoiding Interest broadcast problems.

The degree method is each node's decision to broadcast the Interest Notification considering the number of existing neighbours in its vicinity. Each node has a neighbour list, a list with the nodes that, during a given period, the node interacted with. The neighbour list length is the degree value. This value constitutes part of the IN packet.

During communication, each node updates the neighbour list with the nodes it enters into contact with. During the Interest Notification broadcast, every node receiving the IN will analyse its neighbour list and compare its length with the Interest degree number. Each IN has a degree number. After analysing the values, the node updates the degree value and broadcasts the Interest it received if it has more neighbour nodes than the node from which it received an Interest. Otherwise, the node does not broadcast the Interest.

The NDN architecture has a pre-routing mechanism that populates every Consumer node in the network with FIB-updated information by default, which is the necessary information to request content. Without pre-routing information, Consumer nodes discard the Interest packets. For this reason, NDN does not broadcast Interests without pre-routing information because it has no FIB next-hop information to request content.

However, PDCN is a Producer and a routing mobility solution. In scenarios where pre-routing information is not predefined, like in IoV environments, PDCN solves the routing problem by Updating FIBs with fresh next-hop relay nodes with a Data source and providing this information in a controlled manner through the network. The Producers use IN to inform the network of its movements by updating the FIBs. The IN updates the FIBs allowing the nodes receiving the IN to forward the Interests to the Producers using a specific channel, avoiding broadcast.

Our proposal uses a new version of the Interest notification mechanism of Map-me with a modified set of features. Furthermore, our mechanism does not use the Interest update mechanism nor the discovery mechanism applied by Map-me. While Map-me depends on the existence of a routing protocol that populates the FIB, our proposal only uses our new Interest notification mechanism to populate nodes' FIBs. The degree method provides a controlled broadcast of the Interest Notification packet, not one hop as in Map-me Interest Notification broadcast but multi-hop. Map-me implements its mechanism in a fixed network, while PDCN does not. The difference between fixed and mobile networks impacts how the packets, IN, are used. Map-me uses IN as a breadcrumb left by Producers at every encountered PoA. In PDCN, the IN is broadcasted periodically by Producers.

VII. PERFORMANCE EVALUATION

A. Base Scenario

PDCN implements its scenario in the ndnSIM environment. Our base scenario runs for 200 simulated seconds with 40 nodes (i.e. vehicles) moving according to a realistic vehicular mobility pattern using SUMO.

SUMO is a traffic simulator with the necessary simulation tools from real-world detectors to create advanced and precise traffic models. Sumo uses real-world elements like network data (e.g. roads), traffic infrastructures and demand, macroscopic and microscopic models to create complex vehicle models, and real-world traffic dynamics [23].

Sumo has the tools to recreate IoV scenarios and apply the NDN and PDCN architecture created in ndnSIM over the developed environment.

ndnSIM has a variety of NDN forwarding and in-network caching functionalities, which facilitate the development of different NDN applications. The ndnSIM also has different network environments to choose from, different routing protocols and different designs of congestion control [24].

The simulated vehicles ”run” within the road grid section of Manhattan, New York, and travel based on models derived from actual traffic data. PDCN uses IEEE 802.11p WiFi on 5.9GHz frequencies, ITU-R 1411 LOS propagation model, and a 10 MHz Control Channel (CH) for all traffic. All Consumer and Producers nodes transmit Interest and Interest notification packets with a uniform distribution frequency.

The application considered was a streaming audio/video application characterized by a CBR rate of 1Mbps with retransmission in the baseline scenario.

B. Performance Metrics

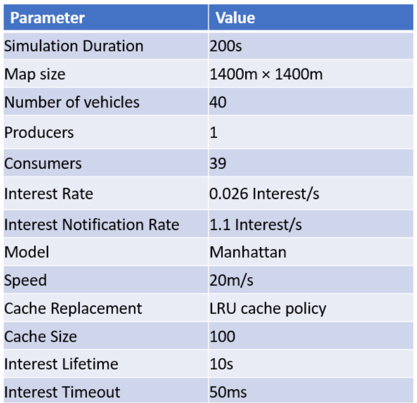
The following Performance Metrics were selected to provide a better understanding of the scheme performance.

- Success Rate: Proportion of successful Interest delivery, i.e. the proportion of successful delivered Interest by total Interest generated;

- Last Consumer Delay: Represents the delay between last Interest sent and Data packet received;
- Full Consumer Delay: Represents the delay between first Interest sent and Data packet received (i.e., includes time of Interest re-transmissions);
- Hop Count: Hop count is the number of network hops that the retrieved Data packet traveled on the way back from Producer application or cache;
- Retx Interests: Number of Interest retransmissions;
- Cache Hits: The Number of times an Interest is Satisfied by a Data cached;
- Cache Misses: The Number of times an Interest is Unsatisfied by a node;
- Overhead: Calculated as the percentage of total number of control packets generated by the scheme to the total number of Interests sent;

VIII. PDCN (PRODUCER DATA CONTROLLED NOTIFICATION)

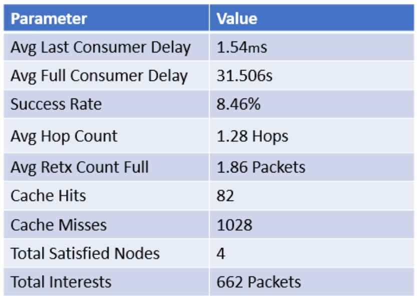
This section presents the aforementioned mobility management scheme implemented and results. The details of the experiments and select results are shown and discussed.



Parameter	Value
Simulation Duration	200s
Map size	1400m × 1400m
Number of vehicles	40
Producers	1
Consumers	39
Interest Rate	0.026 Interest/s
Interest Notification Rate	1.1 Interest/s
Model	Manhattan
Speed	20m/s
Cache Replacement	LRU cache policy
Cache Size	100
Interest Lifetime	10s
Interest Timeout	50ms

TABLE I
SIMULATION VALUES

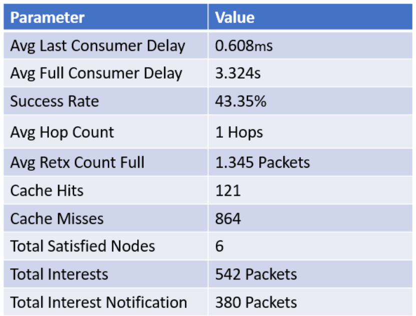
Table I summarizes the simulation parameters used for the first simulations in order to test the PDCN implementation performance against NDN.



Parameter	Value
Avg Last Consumer Delay	1.54ms
Avg Full Consumer Delay	31.506s
Success Rate	8.46%
Avg Hop Count	1.28 Hops
Avg Retx Count Full	1.86 Packets
Cache Hits	82
Cache Misses	1028
Total Satisfied Nodes	4
Total Interests	662 Packets

TABLE II
NDN METRICS

On the baseline scenario (40 nodes, low node density), PDCN, table III verifies an increase in Interest success rate by 412% compared to NDN, table II. This increase in success rate is expected since FIB maps information names to the output interface(s) that are used to forward Interest messages to the Producer. On the other hand, without FIB information, NDN broadcasts Interests hoping that a Producer receives the Interest packet, which to increase Interest Timeouts. The number of Interests timeouts is 66% higher in NDN, 7 compared to PDCN, figure 6. Furthermore, in PDCN, if a Consumer receives an IN with no stored and desired information, then the Consumer sends an Interest packet requesting the Data. This choice allows for a quicker Data reception which is essential for IoV dynamic topologies and non-uniform networks. The Consumer's quick response also diminishes delay constraints for demanding IoV applications. PDCN, III has a lower average packet re-transmission rate by 38% compared to NDN, table II.



Parameter	Value
Avg Last Consumer Delay	0.608ms
Avg Full Consumer Delay	3.324s
Success Rate	43.35%
Avg Hop Count	1 Hops
Avg Retx Count Full	1.345 Packets
Cache Hits	121
Cache Misses	864
Total Satisfied Nodes	6
Total Interests	542 Packets
Total Interest Notification	380 Packets

TABLE III
PDCN METRICS

A metric in the tables II and III which corroborates the PDCN successful information sharing is the average hop count. PDCN has a greater average hop count than NDN since FIB update broadcast increased the number of nodes with a path to the Data nodes. During IN broadcast, a path is created from the nodes receiving the packet to the Producer of that packet.

Moreover, PDCN is more reliable than NDN as it also assures a more significant number of satisfied nodes in lower node densities. For a low density scenario (40 nodes), PDCN, table III, had 50% more nodes satisfied than NDN, table II. The maximum Consumer delay reduction compared to NDN was 848%, table III compared to NDN, table II.

The success of PDCN, III is at the expense of an increase of control packets by 39% compared to NDN, II, which is the price to pay to increase the success rate by 5.1 times and reduce the average full Consumer delay by 9.5 times.

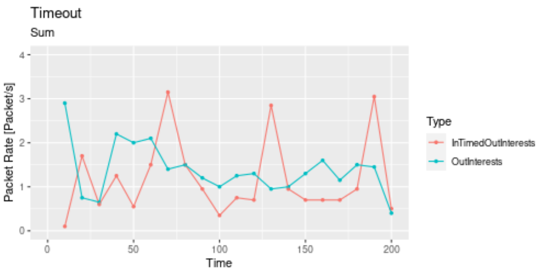


Fig. 6. PDCNwDM Average Timeout Packet/s

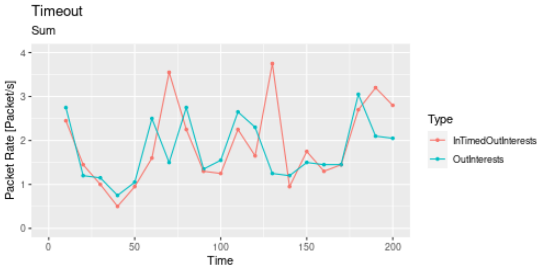
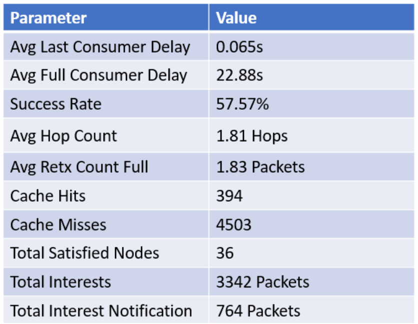


Fig. 7. NDN Average Timeout Packet/s

IX. IoV Density, Consumer and Producer Impact

In this section, we study the node density impact on PDCNwDM and NDN. We start by studying the Consumer node's density variation impact on both architectures. We intend to analyse the number of Consumers and Producers' impact on NDN and PDCNwDM before scaling to different and complex IoV simulations.

A. *IoV Consumer Impact*

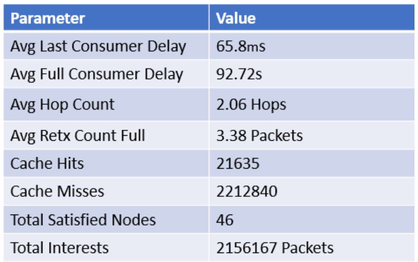


Parameter	Value
Avg Last Consumer Delay	0.065s
Avg Full Consumer Delay	22.88s
Success Rate	57.57%
Avg Hop Count	1.81 Hops
Avg Retx Count Full	1.83 Packets
Cache Hits	394
Cache Misses	4503
Total Satisfied Nodes	36
Total Interests	3342 Packets
Total Interest Notification	764 Packets

TABLE IV
PDCNwDM 120 nodes and 1 Producer

We start by comparing PDCNwDM with 120 nodes, as shown in Table IV against PDCNwDM with 40 nodes, table III. In the Consumer delay 120 nodes scenario, the average last delay is 107 times higher than for the 40 nodes scenario, and the average full delay is seven times higher.

Within a vehicle-dense environment, the interactions between nodes increase, increasing the number of broadcast INs. Adding to the increased number of Interests packets leads to an increased number of satisfied nodes and Interest success rate (increased by 33%) While in PDCNwDM with 40 nodes, table III, the Data could only reach 15% of the nodes, with 120 nodes, table IV, PDCNwDM reaches 29% of the total nodes. Although the increase in Consumer delay would be, at first sight, a signal of worst performance, it is adequate for the increased distance and hops that the packet needs to take to reach the Consumer. Finally, we conclude that for 120 nodes and 119 Consumers, table IV, PDCNwDM has a 34% increase in Interest success rate and a 500% increase in node satisfaction for a total packet increase of 345%, compared with PDCNwDM with 40 nodes, table III.



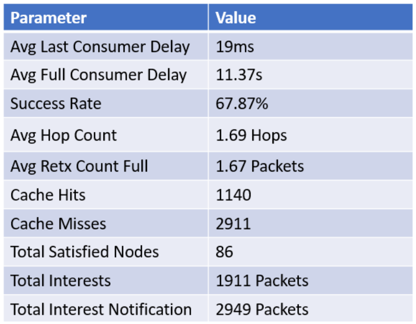
Parameter	Value
Avg Last Consumer Delay	65.8ms
Avg Full Consumer Delay	92.72s
Avg Hop Count	2.06 Hops
Avg Retx Count Full	3.38 Packets
Cache Hits	21635
Cache Misses	2212840
Total Satisfied Nodes	46
Total Interests	2156167 Packets

TABLE V
NDN 120 nodes and 1 Producers

A high vehicle-dense scenario like this and NDN's lack of broadcast control lead to broadcast storms. Unlike PDDCNwDM, NDN has to use Interest broadcast to reach for Data, table V exhibits an increase in Interest packets by 64417% compared to PDCNwDM. Broadcast storms lead to severe contention at the link layer, contention delay, packet collisions, inefficient bandwidth use, and more [25]. On Consumer delay, the average full delay increases by 305% compared to PDCNwDM. On total satisfied nodes, only 39% receive Data packets.

Finally, for PDCNwDM increasing the number of Consumers had an increase in success rate as well as total nodes satisfied through the four load levels, which implied that the increase in Consumer nodes tests had a positive impact on PDCNwDM. For NDN, the increase in Consumer nodes led to uncontrolled broadcast, which was expected, solidifying NDN as unreliable in dense Consumer node environments.

B. *IoV Producer Impact*



Parameter	Value
Avg Last Consumer Delay	19ms
Avg Full Consumer Delay	11.37s
Success Rate	67.87%
Avg Hop Count	1.69 Hops
Avg Retx Count Full	1.67 Packets
Cache Hits	1140
Cache Misses	2911
Total Satisfied Nodes	86
Total Interests	1911 Packets
Total Interest Notification	2949 Packets

TABLE VI
PDCNwDM 120 nodes and 6 Producers

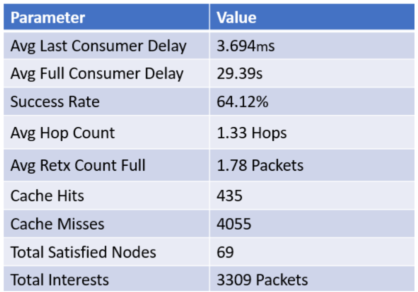
In this section, we compare PDCNwDM with six Producers to 1 Producer to study the Producers' impact on the simulation, table VI. Moreover, we compare PDCNwDM and NDN with 120 nodes and finally correlate the performance of both architectures with 40 and 120 nodes.

Adding Producers to the scheme increased the number of IN packets by 286% compared to PDCNwDM with one Producer and raised Data availability on the network.

An increase in Data availability and an increase in Total Satisfied Nodes diminishes the number of Hops that an Interest has to make to reach content, which explains the average Hop Count decreased by 6.6%. Although the number of Total packets increased by 18%, adding five Producers reduced Consumer delays, packet re-transmission, increased Total satisfied nodes by 139% and Interest Success rate by 18%.

These results suggest that PDCNwDM has a more positive impact in networks with less Producers. We can also expect that keeping adding Producers to the network would lead to more IN control packets than Interests and eventually lead to PDCNwDM decreased performance. Since PDCNwDM success is not based on IN directly but on Interest packets routing success.

The Table VII shows the impact that the number of Producers have in NDN.



Parameter	Value
Avg Last Consumer Delay	3.694ms
Avg Full Consumer Delay	29.39s
Success Rate	64.12%
Avg Hop Count	1.33 Hops
Avg Retx Count Full	1.78 Packets
Cache Hits	435
Cache Misses	4055
Total Satisfied Nodes	69
Total Interests	3309 Packets

TABLE VII
NDN 120 NODES AND 6 PRODUCERS

Compared to PDCNwDM, table VI, NDN, table VII, has 159% higher total Consumer delay; the success rate is 6% lower and 47% less total packets. These results suggest that NDN performs worse in delay constraint applications for this scenario than PDCNwDM. The price to pay for decreasing Consumer delay and increasing Satisfied Nodes is to increase the number of control packets by 47% compared to NDN, tableVII.

Although NDN performance is still worse than PDCNwDM, it is closer, which can be seen by the Interest success rate. Furthermore, adding five more Producers to NDN avoided the broadcast storm analysed in the previous section.

We can conclude that Producer variation significantly impacts NDN and PDCN. For NDN, table VII, it avoids broadcast storms and is responsible for a decrease in Consumer delay by 68% and total node content satisfaction by 50% compared to NDN with one Producer, table V. For PDCNwDM, table VI, it showed a decrease in full Consumer delay by 55% and an increase in total satisfied nodes by 138.8% compared to PDCNwDM with one Producer, table IV.

X. CONCLUSIONS AND FUTURE WORK

This work aims to solve the Producers' mobility problem framed in the IoV environment. We divide the discussion on the IoV and Producer mobility problem and tackle the challenges brought by both dimensions. IoV environment characteristics cause difficulties in operation to ITS and IoV applications such as vehicular safety applications, road traffic efficiency and infotainment applications, and Video streaming [26] [8].

IoV applications require low service delay and reliable network communication, i.e., real-time communication, even when communication or network nodes malfunction. The results from the different tests on Producer mobility, PDCN, table III, reduced Consumer delay by 848%, table II compared to NDN. Moreover, PDCN is more reliable than NDN as it assures a more significant number of satisfied nodes in lower node densities. For a low density scenario (40 nodes), PDCN, table III, had 50% more nodes satisfied than NDN, table II. Where for high density IoV scenarios, PDCN Consumer delay, table IV is 305% lower than NDN, table V.

The results depend on the percentage of Consumer and Producer nodes per Total nodes. The increase in Producers decreases the Consumer delay by 50% from 1 Producer table IV, to 6 Producers, table VI, in a 120 node scenario. For a high density scenario (120 nodes, 1 Producer and 119 Consumers) NDN, table V has a higher node satisfaction rate than PDCN, table IV by 28%.

However, in this scenario, Consumer density greatly impacts the node satisfaction rate since NDN creates a broadcast storm. The broadcast storm, established by the number of Interests sent V, makes it unreliable to consider NDN to have a better node satisfaction rate in high node dense scenarios than PDCN. Broadcast storms hinder Interest success rate, efficient bandwidth usage, Consumer delay, and more [25]. PDCN avoids broadcast storms in the same scenario and the scenario with an increased number of Consumers, reinforcing the impact of IN on PDCN's success.

The challenge arising from the Producers mobility problem in NDN that we intend to solve is the loss and discard of Interest packets during the producer movement.

We solve the problem of Producer mobility by adding a new IN packet to the Producer that the Producer proactively sends to the network. The Producer with the IN packet establishes an updated path through the nodes that receive this packet. Nodes update FIB tables according to the received IN packet. Consumer Interest packets directed to the content provided by the Producer will travel through the intermediate nodes or directly to the Producer, guaranteeing request delivery success, as we can analyse by the various tests produced.

On the baseline scenario (40 nodes, low node density), PDCN, table III verifies an increase in Interest success rate by 412% compared to NDN, table II.

For Producers analyses in a high node dense scenario, PDCN, table VI has 6% higher Interest success rate than NDN, table VII. With high density environments, higher Data availability and node interaction, it becomes easier for NDN to reach Producers, decreasing the Interest success rate discrepancy.

In addition, since the path to the Producer is updated, and the Interest packets are successfully delivered to the Consumer, the Interest re-transmission and the load/volume on the network/bandwidth diminishes. This load reduction on the network increases the network response speed, verified in the PDCN results. The re-transmission is directly related to the Interest success rate. The higher the Interest success rate, the lower the Interest re-transmission. For example on the baseline scenario, PDCN, III has a lower average packet re-transmission rate by 38% compared to NDN, table II.

Finally, the PDCN results, in general, showed that the solution is promising, as it obtained good results compared to the literature works. On the other hand, some open points exist, such as the performance in different IoV scenarios. Despite the proposed solution, further investigation is needed in this area with varying scenarios and metrics.

In future work, more than one SUMO simulation is needed to represent all the different vehicle scenarios, environments and vehicle conditions. For this reason, PDCN should be analysed against different SUMO simulations.

For future work in PDCN, further analysis should be made of PDCN in different IoV environments to test PDCN results for the different metrics. Further statistical analytics methods should be used in PDCN to retrieve more accurate results.

Finally, further tests should be made to the namespace and handover capabilities of PDCN. Although the PDCN routing mechanism allows consumers that wish for the content to retrieve it in contact with the producer or with consumers with a FIB updated path to the Producer, Producer handover through a hierarchical namespace should also be tested and impact analysed.

XI. CONCLUSION

In this work, we analysed and presented a solution for Producer mobility in a realistic vehicular scenario for the ICN architecture.

We contributed to the current Producer mobility literature proposing PDCN, a routing protocol to trace Producer movements and to build a reverse-forwarding path dynamically. PDCN keeps the Producer content reachable after its movement, even without a routing protocol, achieving an increasing Interest success rate. The experimental results of node density and Consumer and Producer density variation showed that PDCN could effectively minimize Consumer delay and maximize node satisfaction rate.

These results' success showed PDCN's promising capabilities in solving the Producer mobility problems introduced by NDN and the issues created by different IoV environments and conditions.

Mobility management is crucial for proper network functioning, and the Producer mobility problem needs to be resolved.

In future work, different statistical analytics methods and increased PDCN communication complexity should be implemented to test their impact in different IoV scenarios.

REFERENCES

[1] C. Perkins, "Mobile ip," *IEEE Communications Magazine*, vol. 35, no. 5, pp. 84–99, 1997.

[2] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Communications Magazine*, vol. 50, no. 7, pp. 26–36, 2012.

[3] M. Amadeo, C. Campolo, and A. Molinaro, "Information-centric networking for connected vehicles: a survey and future perspectives," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 98–104, 2016.

[4] H. Khelifi, S. Luo, B. Nour, H. Moungla, Y. Faheem, R. Hussain, and A. Ksentini, "Named data networking in vehicular ad hoc networks: State-of-the-art and challenges," *IEEE Communications Surveys Tutorials*, vol. 22, no. 1, pp. 320–351, 2020.

[5] M. Wang, J. Wu, G. Li, J. Li, Q. Li, and S. Wang, "Toward mobility support for information-centric IoV in smart city using fog computing," in *2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE)*, 2017, pp. 357–361.

[6] M. Wang, J. Wu, G. Li, J. Li, and Q. Li, "Fog computing based content-aware taxonomy for caching optimization in information-centric networks," in *2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2017, pp. 474–475.

[7] J. Contreras-Castillo, S. Zeadally, and J. A. G. Ibáñez, "A seven-layered model architecture for internet of vehicles," *Journal of Information and Telecommunication*, vol. 1, no. 1, p. 4–22, Feb 2017.

[8] W. Duan, J. Gu, M. Wen, G. Zhang, Y. Ji, and S. Mumtaz, "Emerging technologies for 5g-iov networks: Applications, trends and opportunities," *IEEE Network*, vol. 34, no. 5, pp. 283–289, 2020.

[9] W. Wu, Z. Yang, and K. Li, "Chapter 16 - internet of vehicles and applications," in *Internet of Things*, R. Buyya and A. Vahid Dastjerdi, Eds. Morgan Kaufmann, 2016, pp. 299–317. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128053959000162

[10] M. Amadeo, C. Campolo, and A. Molinaro, "Priority-based content delivery in the internet of vehicles through named data networking," *Journal of Sensor and Actuator Networks*, vol. 5, no. 4, p. 17, 2016.

[11] M. Amadeo, C. Campolo, and A. Molinaro, "Named data networking for priority-based content dissemination in vanets," in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2016, pp. 1–6.

[12] Shuai Gao and Hongke Zhang, "Scalable mobility management for content sources in named data networking," in *2016 13th IEEE Annual Consumer Communications Networking Conference (CCNC)*, 2016, pp. 79–84.

[13] J. Lee, S. Cho, and D. Kim, "Device mobility management in content-centric networking," *IEEE Communications Magazine*, vol. 50, no. 12, pp. 28–34, 2012.

[14] A. Azgin, R. Ravindran, and G. Wang, "On-demand mobility support with anchor chains in information centric networks," in *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1–7.

[15] J. V. Torres, I. D. Alvarenga, R. Boutaba, and O. C. M. Duarte, "An autonomous and efficient controller-based routing scheme for networking named-data mobility," *Computer Communications*, vol. 103, p. 94–103, 2017.

[16] O. Serhane, K. Yahyaoui, B. Nour, and H. Moungla, "A label-based producer mobility support in 5g-enabled icn networks," in *2020 International Wireless Communications and Mobile Computing (IWCMC)*, 2020, pp. 2094–2099.

[17] M. Hussaini, S. A. Nor, H. Bello-Salau, H. J. Hadi, A. A. Gumel, and K. A. Jahun, "Mobility support challenges for the integration of 5g and iot in named data networking," in *2019 2nd International Conference of the IEEE Nigeria Computer Chapter (NigeriaComputConf)*, 2019, pp. 1–7.

[18] Y. Rao, D. Gao, and H. Luo, "Nlba: A novel provider mobility support approach in mobile ndn environment," in *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, 2014, pp. 188–193.

[19] M. Hussaini, S. Awang Nor, and A. Ahmad, "Producer mobility support schemes for named data networking: A survey," *International Journal of Electrical and Computer Engineering*, vol. 8, pp. 5432–5442, 12 2018.

[20] J. Augé, G. Carofiglio, G. Grassi, L. Muscariello, G. Pau, and X. Zeng, "Map-me: Managing anchor-less producer mobility in content-centric networks," *IEEE Transactions on Network and Service Management*, vol. 15, no. 2, pp. 596–610, 2018.

[21] G. Grassi, D. Pesavento, G. Pau, L. Zhang, and S. Fdida, "Navigo: Interest forwarding by geolocations in vehicular named data networking," in *2015 IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2015, pp. 1–10.

[22] G. Xylomenos, C. N. Ververidis, V. A. Siris, N. Fotiou, C. Tsilopoulos, X. Vasilakos, K. V. Katsaros, and G. C. Polyzos, "A survey of information-centric networking research," *IEEE Communications Surveys Tutorials*, vol. 16, no. 2, pp. 1024–1049, 2014.

[23] P. A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wiessner, "Microscopic traffic simulation using sumo," in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, 2018, pp. 2575–2582.

[24] S. Mastorakis, A. Afanasyev, and L. Zhang, "On the evolution of ndnsim: An open-source simulator for ndn experimentation," *SIGCOMM Comput. Commun. Rev.*, vol. 47, no. 3, p. 19–33, Sep. 2017.

[25] O. K. Tonguz, N. Wisitpongphan, J. S. Parikh, F. Bai, P. Mudalige, and V. K. Sadekar, "On the broadcast storm problem in ad hoc wireless networks," in *2006 3rd International Conference on Broadband Communications, Networks and Systems*, 2006, pp. 1–11.

[26] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet of Things Journal*, vol. 1, no. 4, pp. 289–299, 2014.