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Consumer Mobility Awareness in Named Data Networks

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ABSTRACT Mobile data traffic has increased significantly due to the evolution of wireless communication technologies. The Information Centric Network paradigm is considered as an alternative to bypass the restrictions imposed by the traditional IP networks, especially those related with the mobility of its users. Despite the potential advantages of this paradigm regarding mobile wireless environments, several research challenges remain unaddressed, more specifically the ones related with the communication damage caused by handovers. This work presents a Named Data Network (NDN) based solution that supports Consumer mobility. The proposed scheme addresses a mobility manager entity that monitors and anticipates trajectories, while compelling the infrastructure to adjust to the new paths. This process results in an efficient way to manage the Consumers' mobility, and therefore, in a better quality of service to its users. The implementation and evaluation of the proposed solution uses the ndnSIM, through functional and non-functional scenarios, and with real traces of urban vehicular mobility and connectivity. The results show that the proposed solution is superior to the native NDN workflow with respect to content delivery ratio and number of timeouts.

INDEX TERMS Information centric networks, consumer mobility, single-data request, performance evaluation, mobility traces.

I. INTRODUCTION

Over the last years we have witnessed a significant increase in the number of portable communication devices, and consequently, its dominance over the Internet traffic. The mobile nature of such equipment raises several challenges for the underlying network to support the services with efficiency. Such challenges and demands are expected to increase with the advent of Internet of Things (IoT) and 5G/6G, where billions of IoT devices, many of them mobile, are expected to be connected in the near future, supporting many future applications, such as the ones that make up a Smart City [1].

From a network infrastructure point of view, mobility involves the physical and topological re-location of a device. Location-oriented networks are frequently dependent on connection-oriented protocols, for example, the Transmission Control Protocol (TCP). This means that, to settle the communication between two entities, a session between a client and a server needs to be established. When client mobility is introduced, the re-establishment of such session is required, so that both parties are aware of the up-to-date network addresses, causing severe disruption and degradation of the user's quality of service. A network supports Consumer mobility if it grants the users' re-configuration in the network location without disrupting connectivity.

The Internet has evolved rapidly and used primarily for content distribution. Research works in the literature have proposed the re-design of the current Internet's architecture to be Information-Centric, replacing host-to-host infrastructure with a content-based one [2]. The routing is based on the use of unique content identifiers, making content a first-class entity. In Information Centric Networks (ICNs) communications are explicitly made at the network level: when a Consumer generates a request for a specific content,

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it knows exactly what it should receive in return, without necessarily requiring the Content Provider cooperation. Thus, the establishment of persistent sessions is unnecessary, and the re-location of a given host does not demand for the re-establishment of a connection.

Amongst the different ICN architectures, Named Data Networking (NDN) is the most promising alternative to the current Internet architecture, capable of supporting communications independently from the content location and content dispersion, with the use of in-network caching [3]. Although being presented as a promising alternative to the current TCP/IP Internet architecture, the truth is that NDN still presents a large number of research challenges, including for example the lack of support regarding the mobility of its network elements, especially Consumers [4]. In NDN the content follows the reverse path of the Interest, which means that, in mobile scenarios the reverse path could be outdated if, for example, the mobile Consumer has moved from a point-of-attachment to another. In these situations Consumer mobility is provided by the re-transmission of the content requests at the new location, originating redundant content transmissions, and consequently, increasing the network overhead.

This work implements and tests a seamless content delivery approach to mobile Consumers through ICN-based communication architectures. The proposed scheme adapts and extends concepts from ICNs, through the dissemination and caching of the content at new recipients to serve a mobile Consumer. This requires the inquiry for the new location, which will be calculated by a remote mobility manager entity, resulting in a better quality of content delivery to Consumers.

The main contributions of this work are the following:

- The design and implementation of a network entity that is aware of its mobile Consumers and their mobility through time, with the aim to explore it for network assisted content delivery;
- The design and implementation of a mechanism that supports Consumer mobility in an NDN-based architecture by the means of a remote mobility management entity that establishes seamless handover;
- An NDN-based solution that is able to increase the quality of service of mobile Consumers in highly mobile environments, validated through extensive simulation results with non-real and real traces of vehicular mobility and connectivity patterns.

The remainder of this paper is organized as follows. Section II overviews the related work in ICN and NDN with mobility support. Section III details the proposed solution to deal with the Consumer mobility. Section IV assesses the performance of the proposed solution, and Section V draws some conclusions and directions for future work.

II. BACKGROUND AND RELATED WORK

In NDN, the Consumer mobility is easily provided by the retransmission of an *Interest*. Despite the simplicity of how the mobility concern is handled, there are some drawbacks [5]:

- A new request for the same content has to be established before handover, causing redundant *Data* transmissions;
- The retransmitted *Interest* has to follow a new communication path until it reaches the original or replica content. The cache functionality of NDN may not be used effectively if the route taken by the retransmitted *Interest* does not intersect the previous one. Hence, a new *Interest* turns useless the NDN states, such as in-network caching and Pending Interest Table (PIT) entries.

The aforementioned issues are well known by the NDN research community, leading to proposals to enable seamless ways to recover from the communication damaged due to the mobility of end-users [6]. In the *Mobility First* architecture [7], entities attached to the network are identified by globally unique names, which are separated from their network addresses. A Global Name Resolution System is in charge to manage all dynamic mapping between network addresses and object identifiers, as well as to make sure that these values are updated when a mobile node changes its network association. These names can be translated into one or more network addresses at various points in the network. A hybrid routing protocol is used, performing decisions based on both unique identifiers and network addresses, in a hop-by-hop basis. It supports on-path and off-path caching. Besides its characteristics, *Mobility First* is not an NDN-based architecture.

In [8], a proactive caching approach lets a candidate Network Access Router (NAR), that is expected to communicate with a Consumer after handover, to proactively retrieve and cache contents. NAR has additional functionalities when compared to a regular Access Poing (AP): it pre-fetches and caches content on behalf of the user. Once a mobile Consumer detects potential handover (detected by a stronger signal strength coming from another NAR), it communicates to its Previous-NAR (P-NAR) with a *Control Interest* packet. Once this happens, P-NAR stops transmitting the requested content by the user (although it still receives and caches the content). Moreover, it sends a *Control Interest* to the Consumer's Next-NAR (N-NAR) which updates FIB entries on the way. The N-NAR starts pre-fetching the Consumer's content from the ones cached at P-NAR, in the moment it receives the mentioned *Control Interest*. Later, the user fetches the unsatisfied content from the N-NAR due to handover interruptions, using normal *Interest* and *Data* packets. This proposal focuses on how to fetch the lost content again, *i.e.,* it does not solve the problem preemptively, but instead, it acts after the problem has occurred. It is also based on reissuing a new *Interest* through a new NAR, which means that the problems related with the Consumer mobility may happen again.

The work in [9] is a proxy-based mobility management scheme in NDN that reduces the packet loss during the handover. It uses a centralized manager node to keep track of the network conditions, and each mobile node is associated with a proxy from the infrastructure. The IP address is used to exchange the identity between the mobile node device and the proxy, securing association between both parties. When a node hands-off from one proxy node to another, the new one retrieves the content cached at the previous proxy node, and caches at its cache. This approach is similar to the one developed in [8]. With the use of *Hold request* messages, the previous proxy node is notified of the imminent migration to prevent unnecessary packet losses and resource consumption. Then, after handover, the Consumer notifies its proxy node about its new IP address, with a *Handover notification* message, containing the content sequence numbers received at the old location. This proxy then transmits the requested content that was stored for the Consumer towards the new location of the mobile device. This scheme reduces the packet loss during the handover. However, these solutions cannot optimally use on-path caching, and the packet transmission path is not optimized. Moreover, they require the exchange of control messages between proxy servers with the help of the current IP network. Apart from that, they suffer from the same drawbacks mentioned in [8].

In [5], Mobility Link Service (MLS) supports Consumer mobility by the means of content fragmentation and content retransmission. MLS uses a status report message to inform the previous NAR about the status of the transaction, such as the connection information that is changed after the handover of the mobile Consumer, used to request the retransmission of a fragment message. For every received *Interest*, a new transaction is made at the NAR. The *Interest* is passed to an upper NDN forwarding plane. When receiving a *Data* packet from the NDN layer as response of the *Interest*, MLS fragments these packets into several fragment messages, which are sent to the mobile Consumer. The mobile Consumer sends the status report message that includes the new transport endpoint information and the sequence number of the missed fragment message to the previous NAR. Upon the receipt of the status report message, the NAR updates the address information of the transaction structure and retransmits the lost fragment messages. The proposed solution does not keep track of the condition of a connection for a transaction, thus in the end, it cannot handle the movement of the mobile Consumer, but only the recovery of lost packets from the previous NAR.

The works in [10] and [11], although targeting a publish-subscribe scenario, present a Software-Defined Network-based solution to overcome the presence of stale paths originated by the mobility of NDN Consumers. The solution is divided into two phases: the detachment and the attachment. The former one settles on two inspection processes, one using the information on the Forward Information Base (FIB) tables, and the other using the information on the PITs. The attachment phase takes place with the mobility-related information collected by the previous phase and is managed by the SDN controller. The network overhead and the energy consumption are the only simulation results discussed by the authors. Therefore, one cannot evaluate the merit of such solution, for example, in the Consumer satisfaction ratio.

In [12] the authors research on Consumer mobility in NDN satellite networks. The idea relies on data recovery mechanisms operating in the so-called *shim* layer, between network and link layers, without the need for *Interest* packet retransmissions. The authors propose a framework that changes how NDN nodes manage faces, preventing a face from being removed after the associated link breaks. Instead, the framework allows such a face to send or receive data in order to finish pending data retrieval. Such framework is supported by a data recovery link service operating in the NDN link service. Simulation results show the effectiveness of the proposal against the native NDN implementations, without discussing the overhead introduced by the solution.

The work in [13] follows a similar approach to the one here presented: the authors propose a vehicle tracking-based Data packet forwarding scheme for complex urban road environments. The idea is to understand the vehicle's movement and, depending on the expected location, the *Data* packet is delivered to the next expected RSU. However, this work's main focus lies on the calculation of the vehicle's next location, and not so much on the NDN operation mode and the impact of the proposed changes. For example, there is no information about the NDN simulation platform used in the evaluation process and the overhead introduced by the proposed solution.

Some of these proposals focus on how to fetch the lost content, and some of them are based on reissuing a new *Interest*. Hence, the existing problems of the NDN Consumer mobility scheme can happen again. Moreover, some of the solutions resort to IP as an overlay to achieve seamless connectivity, unfulfilling ICN principles. Finally, most of the described related work focuses on the recovery of packets from the previous point-of-attachment through support packets, and not on the direct reception of the content from the Content Provider or replica node to the new AP where the Consumer is located. On a different perspective, our proposed work focuses on the deviation of the *Data* packet to the AP where the Consumer is about to handover.

III. NDN-BASED SCHEME FOR SEAMLESS CONNECTIVITY

In this section we present the mechanisms, packets and interactions to handle seamless connectivity for mobile Consumers. Before proceeding, one has to notice that the referenced topologies, apart from hosting Routers, Producers and mobile Consumers, also include Access Points (APs). Given the amount of handovers in a vehicular network, we will use the vehicular environment and its taxonomy to support the explanation of the proposed scheme. Therefore, APs are thereafter denoted as Road Side Units (RSUs), and they present the same caching and forwarding characteristics as regular Routers. Following the same rationale, mobile Consumers are sometimes denotes as On-Board Units (OBUs). Nevertheless, the rationale of our proposal can be applied to any mobile network.

The routes provided to mobile Consumers might originate handovers. Consider a mobile node, which is about to switch

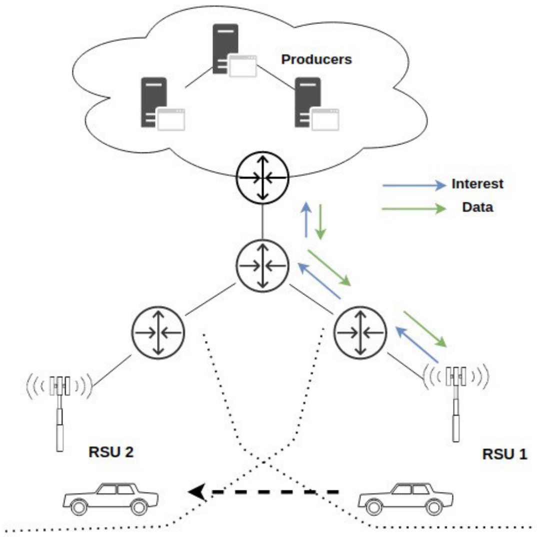

FIGURE 1. **Example of unsatisfied *Interest* caused by the mobility of the consumer.**

to a different RSU, sending an *Interest* packet, as depicted in Figure 1: because of topological factors, such as link delay, queue delay, computing and processing delays, the transmission of *Interest* and *Data* packets might not be fast enough, hence the Round Trip Time (RTT) is not short enough for the mobile Consumer to receive the content at the RSU where the *Interest* packet has been received. So, in the case of Figure 1, the OBU issues the *Interest* at RSU 1, but by the time the content reaches the RSU 1, the Consumer is no longer in the communication range of that RSU.

To address this problem, the content has to be deflected to the next RSU, *i.e.* the next RSU to be visited by the mobile node. Given the potential next RSU, and the instant where the mobile node enters its respective transmission area, it is possible to transmit the contents to the new location. To this extent, the network has to adapt itself, so the content gets deviated to the prospective RSUs. In the example represented in Figure 1, the *Data* packet should be delivered to RSU 2, so it can reach the Consumer at its new position. Such solution can prevent the loss of data packets while the movement occurs.

In our proposed solution, the RSUs take advantage of the Named Data Link State Routing (NLSR) protocol[1] to disseminate their configured *Name* prefix and topology, throughout the network. Through the advertisement of the infrastructured topology, each node is capable to know which *face* will lead, with a minimum number of next hops, to a specific RSU, by knowing its configured *Name* prefix, associated at the RIB table.

A. FORECASTING NEXT MOBILE POSITIONS

The base approach considers elements such as Producer, Consumer, RSUs and intermediate nodes (backend routers).

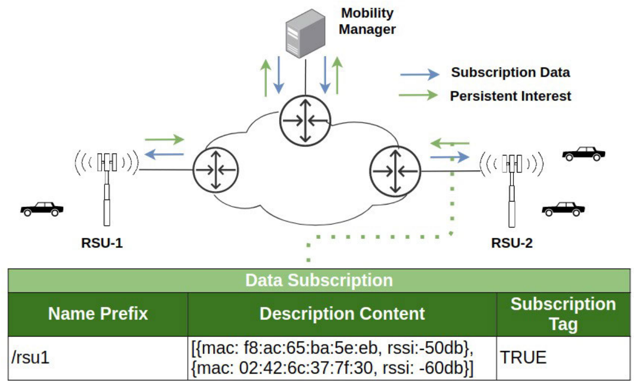

FIGURE 2. **Communication process of the RSU's neighbors status.**

The proposed solution considers the existence of an additional element: a Mobility Manager (MM). The MM is a node that hosts a forecasting module that is used to calculate and communicate potential migrations of the mobile devices. To forecast the next position, the MM periodically receives the knowledge about the recent state of the different mobile devices, and provides interchanging packets with the RSUs, using a publish-subscribe communication approach.

Each RSU has an unique content topic configured to the transmission of *Data* packets containing information about its mobile neighbours (such as MAC addresses and the Received Signal Strength Indicator (RSSI), obtained from the resulting beacons operating in the lower layer), which is subscribed by the MM. In Figure 2, the MM subscribes to two RSUs by transmitting two *Persistent Interests*, which name prefix of the topic corresponds to the configured Name of the RSUs. For example, the topic Name of RSU 1 is */rsu1*. Moreover, we can see that the *Data* packets sent by RSU 1 host information related to its neighbors (MAC address and RSSI). This data is transmitted to the topic already mentioned. The MM uses this information to forecast the next positions of mobile nodes, and helps our solution to provide seamless communication for mobile Consumers.[2]

B. PREDICTION REQUEST

Algorithm 1 presents the steps taken by an RSU when it receives an *Interest* packet through the wireless interface, sent by a mobile Consumer. By default, once an RSU receives an *Interest* wirelessly from a querier, it searches at the Content Store (CS) for the requested content (lines 2-3). In case it is cached at the RSU, it is wirelessly sent to the mobile Consumer in the format of a *Data* packet (lines 4-6). Otherwise, the RSU communicates with the MM module, as observed in Figure 3, through another *Interest* packet (packet number 1), representing a prediction query (lines 10-11).

[1] https://named-data.net/doc/NLSR/current/

[2] We present a complete solution with the supportive services to host a mobility predictor, following the NDN paradigm. The responsibility for detecting potential migrations of mobile nodes between RSUs is exclusive to the MM. We highlight that this work assumes the existence of a mobility predictor service, as the ones presented in [14] and [15], as this is not the contribution of this work.

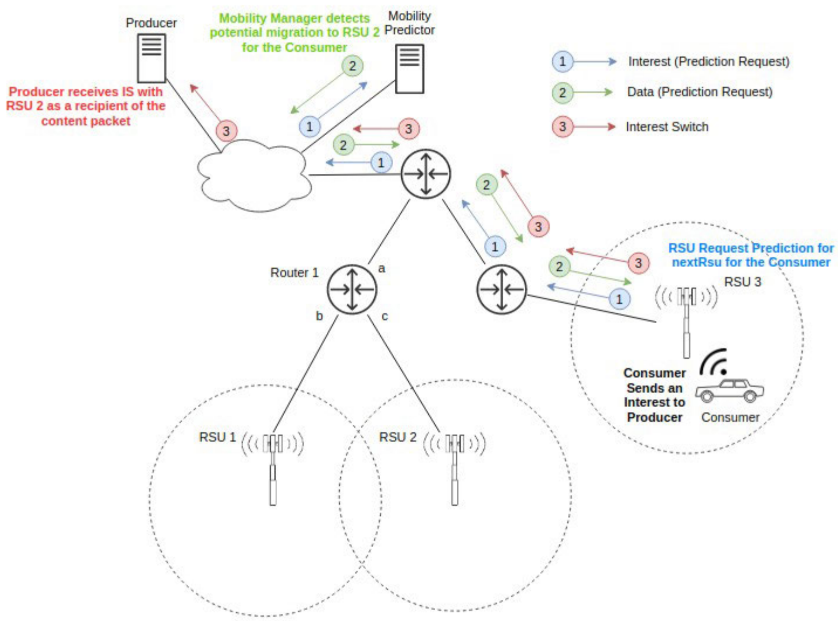

FIGURE 3. Example of a subsequent transmission of *Interest* with prediction request to the MM (1), the *Data* packet containing the predictions (2) and the following *Interest Switch* (IS) (3).

Algorithm 1: RSU Processing Method Triggered by the Reception of Consumer *Interests*

```
1
2  Algorithm processInInterest(Interest I, String
     ConsumerMAC, face inFace)
3  ContentName = getInterestName(I)
4  Content = checkContentStore(ContentName)
5  if Content != null then
6      DataPkt = Data(ContentName, Content)
7      sendPacket(DataPkt, inFace)
8  else
9      SequenceNumber = createSequenceNumber()
10     storeInterestPkt(I, SequenceNumber)
11     InterestPrediction =
         createPredictionQuery(ConsumerMAC,
         SequenceNumber)
12     sendPredictionQueryPacket(InterestPrediction);
13 end
```

This packet receives a sequence number, which is appended to the Name prefix of the message as a name component. The later is associated with the *Interest* received from the Consumer, additionally stored at the entity for a short period of time (lines 8-10). The name-prefix contains the following components:

- Identification of the MM: selects which MM from the topology should the forecasting results be calculated and transmitted from;
- Action: specifies the type of content desired by the requester;
- Identification of the RSU: the RSU hosting the mobile inquirer;
- Identification of the Mobile Consumer: the Consumer associated to the predicted *next RSUs*;
- Sequence Number: associated with the *Interest* packet requested by the Consumer.

Once the MM receives the aforementioned packet, it checks if the name prefix structure is according to what has been predetermined and if the first name component of the prefix equals its own identifier. If both conditions are correct, it retrieves the name of the component identifying the Consumer by its MAC address in order to determine its potential *next RSUs*, and creates and sends a *Data* packet (packet number 2 in Figure 3), containing the name prefixes of the *next RSUs*. Moreover, the name prefix of the packet is equal to the one designated to the received *Interest* packet. Otherwise, no reply is given by the MM.

The RSU needs fresh forecasting results. If predictions for a specific Consumer are outdated, then the actions taken by the hostess RSU might not be the appropriate ones. Notice that, the content provided by the aforementioned *Data* packet and its Name prefix are not to be stored at the CS at the intermediate nodes. This forces the *Interest* packets related with the mobility to be delivered to the MM, searching for updated information.

C. RSU DECISION MECHANISM

Algorithm 2 describes the process triggered by the reception of the prediction information about one of the RSU's mobile neighbours. When an RSU receives a *Data* packet containing the forecasting results calculated by the MM, it retrieves the sequence number from the name prefix (line 3), and then it searches for the temporarily stored *Interest* associated with the sequence number in consideration (line 4). Then, the RSU selects the designated *next RSUs*.

Algorithm 2: RSU Decision Triggered by the Received Prediction Content

```
1
2  Algorithm processPredictionContent(Data D)
3  Name = getName(D)
4  SequenceNumber = getSequenceNumber(D)
5  interest = extractInterest(SequenceNumber)
6  Content = getContent(D)
7  NextRsus = getNextRsus(Content)
8  if length(NextRsus)>1 || (length(NextRsus)==1 &&
     !ContainsThisRsu(NextRsus)) then
9      SendBack = ContainsThisRsu(NextRsus)
10     interestSwitch = createInterestSwitch(interest,
         NextRsus)
11     sendInterest(interestSwitch)
12 else
13     sendInterest(interest)
14 end
```

By knowing the next position of a mobile node and proactively preparing the *next RSUs* for a seamless communication, it is now possible to prepare the new path between the Producer and the upcoming position of the mobile Consumer. To perform these actions, the traditional *Interest* and *Data* NDN packets have been slightly modified, which originate the *Interest Switch* (IS) and *Data Switch* (DS) packets.

D. SUPPORT PACKETS

As mentioned before, the proposed scheme requires the adaptation of the NDN regular packets, originating two new packets:

- *Interest Switch*: it is a derivative of the *Interest* packet with fields specifying the recipients. It follows the FIB entries of the intermediate nodes;
- *Data Switch*: it is a derivative of the *Data* packet, containing fields specifying the new recipients. It follows both PIT entries and RIB entries.

Both IS and DS contain new fields:

- *NumRecipients*: specifies the number of recipients of the consequent DS packet. This field helps decoding the packet, so it can interpret correctly the *Name* prefixes of the subsequent DS recipients;
- *RecipientPrefix*: represents the *Name* prefix of the recipient of the subsequent DS. The number of *RecipientPrefix* fields added to the packet equals the number specified in the field *NumRecipients*.

The IS has an additional field, called *SendBack*, a bit field that denotes if the content is to be additionally sent to the path it originally went through. In case the flag is disabled, no effective PIT entries are built. Hence, the content will not be transmitted to the nodes' incoming faces from which the respective *Interest* has traversed.

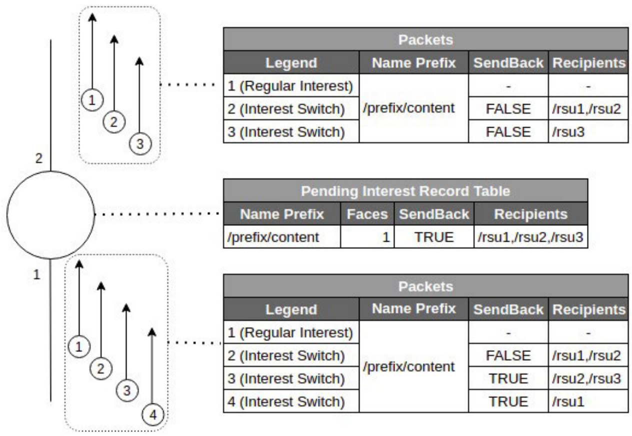

FIGURE 4. Example of the mechanism imposed to the subsequent *Interest* and *Interest Switch*, with equal *Name* prefix, when the associated PIT entry is not yet satisfied.

If the content is to be disseminated to another RSU, then an IS must be created (lines 7-11 in Algorithm 2), based on the prior *Interest*, adding the correspondent information in the fields: *SendBack*, *NumRecipients* and *RecipientPrefix*. If no handover is expected to that mobile node, the RSU will transmit the regular *Interest* packet that was cached before (line 12).

E. INTEREST SWITCH FORWARDING

The mechanism to process and transmit an IS is very similar to the regular *Interest* packet; however, it differs in the following:

- When the *SendBack* flag is not enabled, no entry is given to the PIT. Therefore, the content will not travel the reverse path taken by the IS;
- By default, when a regular *Interest* is received, the forwarding module will not route the packet in case there is already a PIT entry associated with the *Name* prefix denoted by the message. However, if the PIT entry is not yet satisfied and one or more ISs are introduced in the mean time, it cannot be ignored. Such mechanism is introduced because, besides representing a request of content, it also represents the delivery of the respective data to other recipients;
- The node is programmed to register PIT entries along with the *Name* prefixes of the recipients indicated by the IS. An IS is only thrown away if the *Name* prefix of the packet is associated with a PIT entry, and if the *Name* prefixes of the indicated recipients are registered on the same entry. Otherwise, either a PIT entry is created or updated with the *Name* prefixes of the new recipients. An example of the consequence of such mechanism is shown in Figure 4: the packet number 3 updates its *RecipientPrefix* fields, containing only the recipient with Name */rsu3*, since the other recipients have been already

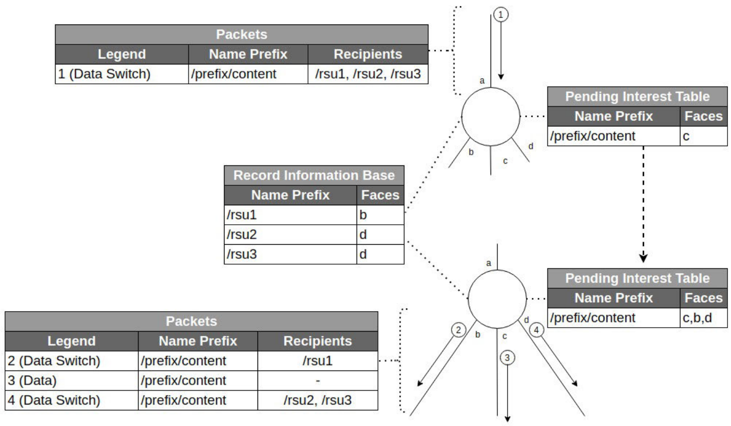

FIGURE 5. Example of content deviation caused by ***Data Switch*** bifurcation.

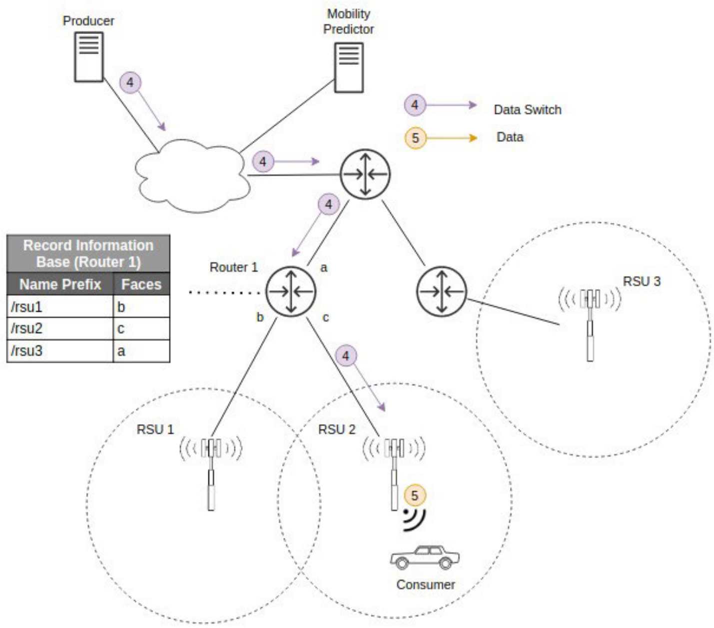

FIGURE 6. Example of the transmission of a DS packet, and proactive transmission of subsequent ***Data*** packet.

specified by the *Interest* 2, which has the same prefix as packet 1, 3 and 4. Packet 4 is dropped, since no new recipients have been specified.

F. DATA SWITCH DISSEMINATION

Once an *Interest Switch* is received and there is a content hit, either at an intermediate node or Producer, it proceeds by composing and transmitting a *Data Switch*. Besides incorporating the requested content, the packet contains the Name prefixes of the content receivers, in fields *RecipientPrefix*, specifying the total number of recipients in the field *NumRecipients*.

When a DS is about to bifurcate to a new path pointed exclusively by the RIB entries (Figure 5), the DS is transmitted to the faces pointing to RSU name prefixes in the RIB entries. The DS that still follows the PIT entries excludes the denoted recipients indicated by the mentioned DS, which causes a new bifurcation. If all necessary data switching is deployed throughout the transmission of the content, and no new recipients are indicated, then a *Data* packet is transmitted, behaving as native NDN.

In Figure 6, the bifurcation of the content is caused by the DS. Instead of transmitting the content using the reverse path of the *Interest* packet, in direction to the RSU 3, it follows the path to the recipient specified by the respective IS, resorting to the RIB of the intermediate nodes.

Once an RSU receives a DS, it checks if its prefix is one of the recipient prefixes in the packet. In that case, it proactively transmits the Data, as a regular *Data* Packet, to the wireless interfaces, to increase the probability of content delivery to newly arrived mobile Consumers. This behaviour is also shown in Figure 6: once the RSU 2 receives the DS, specifying its configured name as recipient (packet 4), the same entity transmits proactively the content as a *Data* packet (packet 5) to its wireless interface.

Moreover, the content provided by the DS is stored at the CS of the considered RSU. The reason for this action comes as a last resort to provide a more efficient content forwarding: the Consumer may have issued an *Interest* for the content, but it was not delivered due to the nonexistence coverage of its previous and next RSU when the *Data* packet was wirelessly broadcasted by the RSU. If the Consumer is programmed to reissue the same unsatisfied *Interest*, once it has coverage with its new associated RSU, the cached content is directly delivered.

To summarize, Figure 7 illustrates the sequence of events regarding the proposed mobility NDN-based scheme for seamless connectivity.

IV. EVALUATION

This section evaluates the efficiency of the proposed solution for seamless connectivity between mobile Consumers and content Producers. Two different network topologies are built and used for the analysis. The first one is used for functional scenarios, where mobility traces were generated following a non-realistic mobility pattern, allowing to freely evaluate scenarios using a different number of nodes, different trajectories and nodes' speed range. The other one is influenced by real mobility traces of vehicles.

The ndnSIM software, an Open-Source Simulator Platform extended from the widely known NS-3 research-oriented network simulator [16] capable of evaluating NDN-based solutions, was selected for the evaluation process. Three main metrics are considered to analyse the performance of the proposed solution:

- *Network overhead:* measures the amount of NDN packets transmitted by each NDN node, and is used to understand how the proposed solution impacts in the network's bandwidth utilization;
- *Timeouts per mobile Consumer:* measures the average number of Interests that were not satisfied by Data in the Interest lifetime period;
- *Satisfaction ratio:* measures the average ratio of satisfied requests, *i.e.* the number of Interests that were satisfied over the total number of transmitted Interests.

A. EVALUATION SCENARIOS

The topology used for the functional scenario consists of 36 RSUs, 13 intermediate nodes and several mobile nodes randomly walking. Three additional nodes are wired up to the network, behaving as Producers of content with different prefixes. Also, one MM is connected to the network, through a point to point link. A visual representation of the nodes and of their wired connections is illustrated in Figure 8.

On the other hand, to bring our evaluations one step closer to a real scenario, we use two real traces of urban mobility, both from the city of Porto, Portugal: mobility traces of

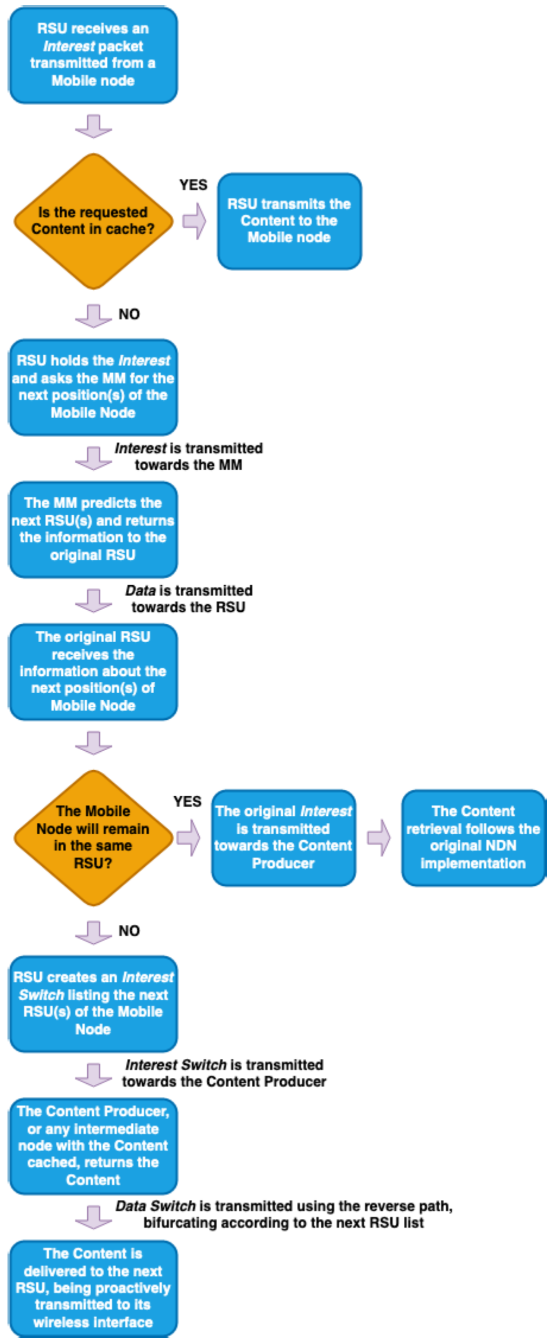

FIGURE 7. General overview of the proposed solution's behavior.

Sociedade de Transportes Colectivos do Porto buses, collected through the Porto Living lab IoT platform [17], and mobility traces of city taxis taken from the Taxi Service Trajectory Prediction Challenge 2015 .[3] In total, we consider 25 vehicles (a mix between taxis and buses), 50 RSUs and 19 intermediate nodes, spread throughout the city center, as illustrated in Figure 9, spanning over a period of four hours. The two datasets are from different time periods: the trace mobility of Taxis is from 2018-01-23 00:00:00, Tuesday, to 2018-01-29 23:59:56, Monday; the trace mobility of

[3] http://www.geolink.pt/ecmlpkdd2015-challenge/dataset.html

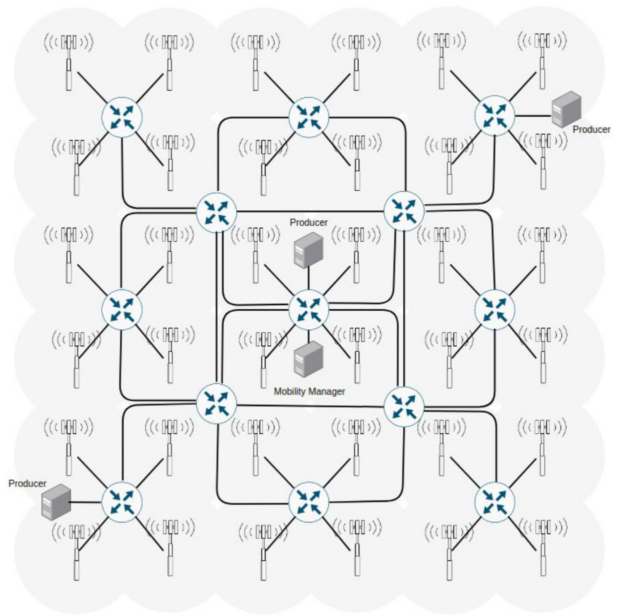

FIGURE 8. Wired topology used in the functional scenarios.

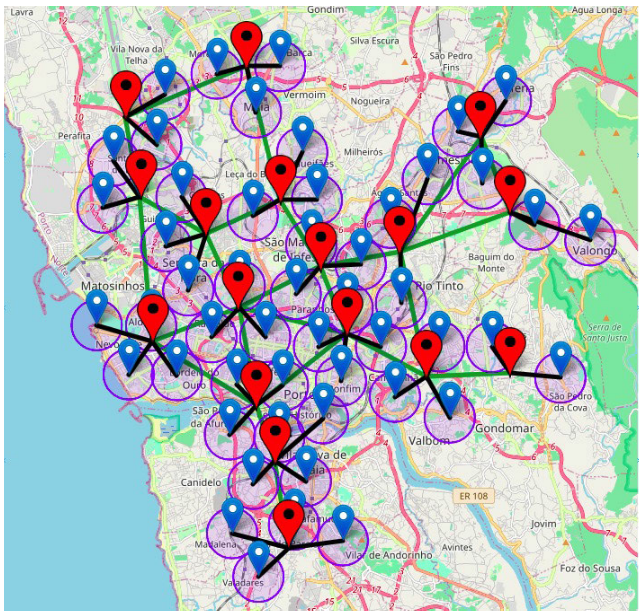

FIGURE 9. Network topology of the city of Oporto, Portugal. Backend Routers are represented by the red pins, and RSUs are represented by the blue pins.

Buses is from 2013-07-01 01:11:22, Monday, to 2013-07-09 22:05:38, Tuesday. The buses' and taxis' mobility traces were selected and formatted to be processed by the *ndnSim*. Moreover, a time adjustment was established, so the traces correspond to the same day of the week and hour. A 4-hour window is considered with the traffic peak times at a Friday.

B. MOBILITY MANAGER

An MM is built for each scenario. The application hosted by this node is aimed to have knowledge about every RSU transaction of the respective infrastructure's mobile Consumers beforehand. In other words, the MM is configured to know exactly the Consumers RSUs transitions and their respective epoch. Every time this node is asked for the prediction of the *next RSUs* for a specific Consumer, it replies by sending the different RSUs the Consumer will have coverage from, in a time ahead. All this information is calculated before the simulation starts. In the functional scenario, the MM follows a *God* behavior with 100% accuracy, configured with a 3 seconds window, *i.e*, when asked for prediction, it looks further in time (3 seconds ahead). In the realistic trace scenario, the MM follows an inference module based on a hidden Markov model as in [15], with each RSU reporting its neighboring information every 30 seconds. The accuracy associated with the prediction is around 95%.

TABLE 1. Baseline simulation configurations - functional scenario.

Average velocity	50 ± 10 units/s
Number of mobile Consumers	25 nodes
Number of existing contents per prefix	70
Frequency	5 packets/s
Content Store size	30
Consumer timeout	3 seconds
Interest lifetime	3 seconds

C. RESULTS

1) FUNCTIONAL SCENARIOS

This section analyses the proposed solution, from now on denoted as SDR-Mob (SDR from Single-Data-Request in opposition to pub-sub approaches), which is compared with the NDN native strategy. After a general analysis between the two solutions, we study how SDR-Mob is impacted with different number of mobile nodes, *Interest* frequency and mobile nodes' speed. The remaining configurations are illustrated in Table 1. The results presented are not cumulative, but per Consumer, and therefore, they contain the mean and 95% confidence intervals.

Figure 10 illustrates the average number of *Interest* packets sent and *Data* packets received, per Consumer. The results show that both native and SDR-Mob solutions are able to deliver approximately, in average, the same amount of *Data* packets by issuing the same number of *Interest* packets. To assure the efficiency of the solution, we will rely on the average number of Timeouts regarding the mobile Consumers point of view.

Table 2 shows the average number of Consumer Timeouts for both solutions. Through the observed results, it is fair to assume that SDR-Mob behaves better in a Consumer point of view, reducing 38.86% of the average Timeouts regarding the native approach. This means that, throughout the simulation, our solution had more satisfied *Interests* than the native approach. The difference is more visible when evaluating the number of Timeouts rather than the number of received *Data* packets from a Consumer's perspective. The explanation that supports this occurrence is the following: a node can send, in a short period of time, *Interests* with the same name, with

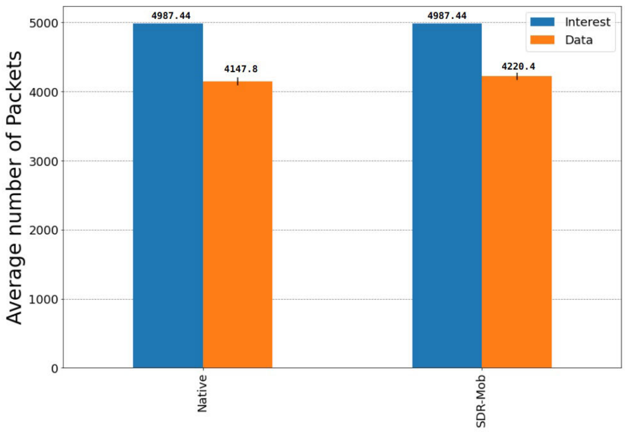

FIGURE 10. Average number of ***Interest*** packets transmitted and number of ***Data*** packets received, per mobile consumer - functional baseline scenario.

TABLE 2. Average number of timeouts per mobile consumer - functional baseline scenario.

Solution	Average number of Timeouts
SDR-Mob	318.12 ± 39.93
Native	520.36 ± 48.31

pending requests. That being said, those numerous requests with the same name can be satisfied by the reception of a single content packet with the aforementioned name. Otherwise, if no content with the correspondent name is received, the number of Timeouts are summed by the number of unsatisfied requests (independently of having the same name or not).

Table 3 shows the total and average number of packets transmitted by nodes of the wired infrastructure. If we consider *Interest Switch* packets simply as *Interest* packets, and *Data Switch* packets simply as *Data* packets, the total number of transmitted packets from the nodes of the wired infrastructure are 1 275 207 *Interests* and 1 941 833 *Data*, against 358 101 *Interest* packets and 493 937 *Data* packets transmitted in the native approach. The significant amount of transmitted packets by the SDR-Mob is not only due to the bifurcations of *Data Switch* packets into *Data Switch* packets and *Data* packets, but also because of the interchange communication between RSUs and the MM: (1) the periodic update of neighbor nodes information from each RSU to the MM; (2) and the request of mobility prediction by the RSU to the MM. Since the Consumer's *Interest* frequency is equal to 5 packets/s (which means, 5 mobility prediction requests per second only regarding a single Consumer), the higher values of *Interest* and *Data* packets interchanged in the SDR-Mob are not surprising, resulting in a better overall Consumer's satisfaction.

To evaluate the impact of the node's speed, new scenarios with four different speed ranges were simulated: [5 - 15] units/s, [20 - 30] units/s, [45 - 55] units/s, [95 - 105] units/s. The mobility traces represent sequential connected straight trajectories, representing the mobility of the node. Each straight trajectory has a speed uniformly distributed in the speed range.

TABLE 3. Network metrics in the wired infrastructure - functional baseline scenario.

Solution	Packets	Total number of transmitted packets	Average number of trasnmitted packets
SDR-Mob	*Interest*	938 586	17 709.16
	Interest Switch	336 621	6 351.34
	Data	1 485 682	28 031.73
	Data Switch	456 151	8 606.60
Native	*Interest*	358 101	6 756.60
	Data	493 937	9 319.56

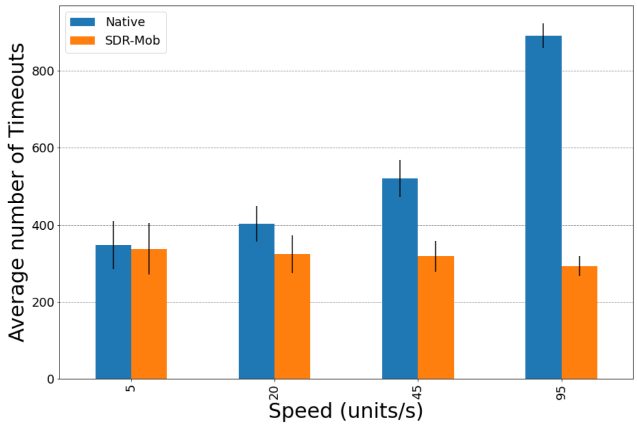

FIGURE 11. Average number of timeouts with the speed of the mobile nodes - functional scenarios.

Figure 11 illustrates the average number of Timeouts for both native and SDR-Mob solutions, regarding the different speed ranges. Regarding the native approach, the greater the speed of the node, the greater is the number of Timeouts in a Consumer point of view. This is expected since significant speed allows for more sudden handovers. Hence, the content might not be given soon enough before the Consumer's hand-off. On the other hand, the mobility-aware approach is prepared to handle communication regarding any of the selected speed ranges, deviating the contents appropriately to the nodes' *next RSUs*. In fact, by increasing the nodes' speed, the number of Timeouts slightly decreases in our solution. This happens because, since the scenario does not present full wireless coverage, and the areas without wireless connectivity are much less when compared to zones with wireless connectivity, when we increase the node's speed, each node stays less time in a no-coverage zone, increasing its time of contact with the infrastructure.

We can also confirm the consistency of our proposal regarding the different speed ranges by checking the values obtained in Consumer satisfaction ratio in Table 4, whose values are in between 84.46% and 84.73%.

To evaluate the impact of the number of nodes, new scenarios were simulated with three different numbers of mobile nodes: 15, 25 and 50. Figure 12 illustrates the average number of Timeouts per Consumers in both native and SDR-Mob solutions, regarding the different number of mobile nodes.

TABLE 4. Speed impact in consumer mobility - functional scenarios using mobility awareness.

Speed range (units/s)	Packets	Consumers	Producer	Consumer satisfaction ratio
[5 - 15]	*Interest* *Data*	124 686 105 305	45 476 45 457	84.46%
[20 - 30]	*Interest* *Data*	124 686 105 649	42 157 42 130	84.73%
[45 - 55]	*Interest* *Data*	124 686 105 510	37 932 37 918	84.62%
[95 - 105]	*Interest* *Data*	124 686 105 590	43 657 43 634	84.68%

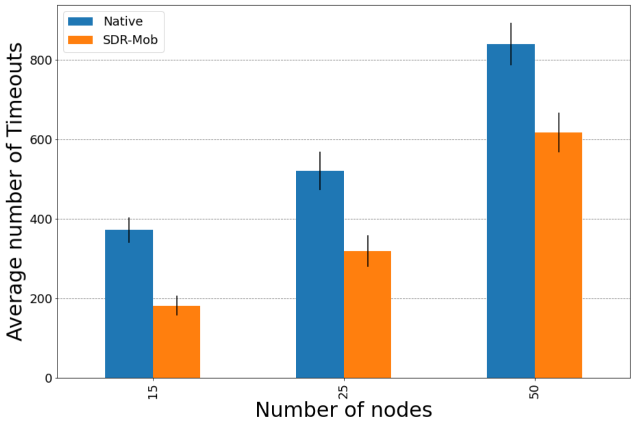

FIGURE 12. Average number of timeouts with the number of mobile nodes - functional scenarios.

The results show that the larger the number of mobile nodes, the more notable are the overall Timeouts, for both approaches. This is due to the following: the number of Timeouts can be proportional to the number of deployed *Interests*, since each one represents an *Interest* packet sent from a user. Furthermore, the more users the network has with the same *Interest* rate, the more are the inquiries made. Moreover, the mobile node can have situations of no RSU coverage, making the transmission of *Interests* useless and contributing to the rise of Timeouts throughout the simulation (since it is not satisfied). On top of that, wireless collisions are possible to happen due to the simultaneous transmission of packets in the wireless communication environment. With more packets being transmitted at the same transmission area, the greater are the chances for collisions to happen, and thus originating unsatisfied *Interests*. Despite this, the SDR-Mob solution presents less Timeouts than the native approach.

Table 5 depicts a degradation of Consumer satisfaction ratio when the number of mobile nodes increases, from a Consumer satisfaction ratio of 87.89% when simulated with 15 nodes, to 77.03% with 50 mobile Consumers. As referred previously in the case of proportional increase of average Timeouts by the number of mobile nodes, this degradation is at least partly due to the collision of packets in the wireless environment.

To evaluate the impact of the *Interest* frequency, three different frequencies are considered: 1 packet/second, 5 packets/second and 10 packets/second. Figure 13 illustrates the average number of Timeouts for Consumer in both native and SDR-Mob approaches, according to their respective *Interest* frequency value. It is observed an increase in the average number of Timeouts with the increase of *Interest* frequency; however, better results are observed in the mobility-aware approach (less average Timeouts than the native approach).

TABLE 5. Number of mobile nodes impact in consumer mobility - functional scenarios using mobility awareness.

Number of mobile nodes	Packets	Consumers	Producer	Consumer satisfaction ratio
15	*Interest* *Data*	74 831 65 771	24 997 24 990	87.89%
25	*Interest* *Data*	124 686 105 510	37 932 37 918	84.62%
50	*Interest* *Data*	249 215 191 981	67 164 67 123	77.03%

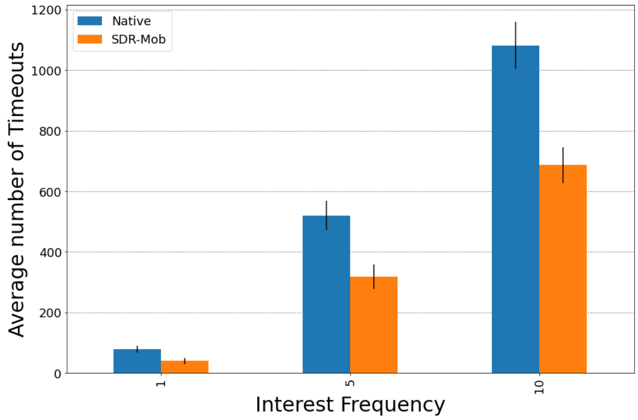

FIGURE 13. Average number of timeouts with the *Interest* frequency - functional scenarios.

TABLE 6. *Interest* frequency impact in consumer mobility - functional scenarios using mobility awareness.

Interest frequency [packets/s]	Packets	Consumers	Producer	Consumer satisfaction ratio
1	*Interest* *Data*	24 945 23 525	10 424 10 419	94.31%
5	*Interest* *Data*	124 686 105 510	37 932 37 918	84.62%
10	*Interest* *Data*	249 359 192 597	63 631 63 585	77.24%

Regarding the results of the SDR-Mob approach, represented in Table 6, it is also noticed a degradation of the Consumer satisfaction ratio when the *Interest* frequency increases, from 94.31% Consumer satisfaction ratio when the *Interest* frequency is set to 1 packet/s, to 77.24% when the frequency is 10 packet/s. This degradation is at least also partly due to: the more *Interests* are transmitted in the wireless environment, the greater the number of unsatisfied *Interests* due to collision.

2) REAL MOBILITY TRACES

From the real mobility data, we selected 25 mobile nodes to act as Consumers, and three static Producers. The simulation

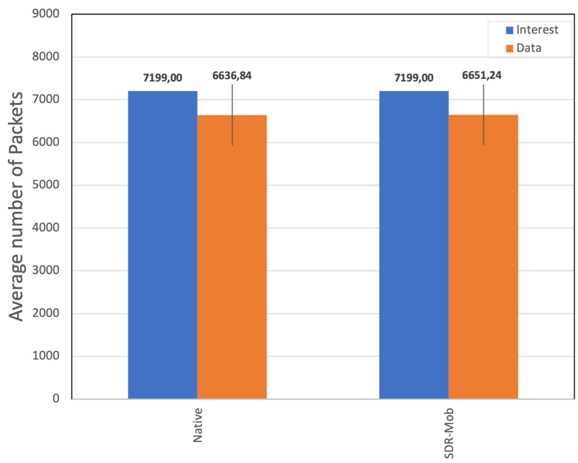

FIGURE 14. Average number of *Interest* packets transmitted and number of *Data* packets received, per mobile consumer - vehicular mobility traces.

TABLE 7. Timeout results per mobile consumer - vehicular mobility traces.

Solution	Total number of Timeouts	Average number of Timeouts
SDR-Mob	11 790	471.60 ± 647.43
Native	12 253	490.12 ± 646.03

TABLE 8. Network metrics - vehicular mobility traces.

Solution	Packets	Total number of received packets	Average number of received packets
SDR-Mob	*Interest*	1 112 187	15 235.44
	Interest Switch	103 632	1 419.62
	Data	1 294 680	17 735.34
	Data Switch	103 560	1 418.63
Native	*Interest*	504 392	6 909.48
	Data	772 123	10 577.03

parameters are the same as in Table 1, except for the Interest frequency, which is now set to 0.5 packets/s.

Figure 14 presents the average number of *Interest* and *Data* packets transmitted and received by the mobile Consumers, respectively, and Table 7 shows the average and total number of content Timeouts registered at the Consumer.

It is easily observed a resemblance between both approaches: the average and total number of Timeouts are similar between the two approaches, with a difference of 18.5 average Timeouts and a total number of 463 Timeouts from the mobile Consumers' perspective, showing better results when using the mobility awareness approach. Furthermore, the total number of *Data* packets received by the Consumers in both approaches is very close (the native approach registers 6 636.84 average number of packets, and the SDR-Mob registers 6 651.24).

The SDR-Mob scheme is able to achieve slightly better results for this particular scenario setup, but it might not be appropriate to use when the introduction of overhead in the infrastructure is crucial. In Table 8, it is easily observed that the average number of *Interests* transmitted by the elements of the wired infrastructure in the SDR-Mob approach almost doubles the number of regular *Interests* of the native approach. Moreover, the average number of *Data* packets increases from 10 577.03 to 17 735.34, from the native approach to the one proposed, resulting in a higher Consumer Satisfaction Ratio.

V. CONCLUSION

ICN comes as a blueprint for the revolution of the future Internet. A network architecture following this paradigm's principles, such as NDN, could completely change the current Internet in terms of scalability, security and mobility. Nevertheless, in the case where handovers occur frequently, like in vehicle communication environments, efficient mobility management has to be supported.

This work proposed an NDN-based approach to cover Consumer mobility. This approach is able to monitor and anticipate mobile nodes' position and trajectories, and adjust to the new paths, providing seamless mobility of Consumers and improving the reliability of the network. The solution relies on a network entity, the mobility manager, that is responsible to keep track of the latest information regarding the mobile Consumers, particularly their location, through publish-subscribe sessions between this entity and the RSUs scattered in the infrastructure; it is also responsible to deliver predictions about the *next RSUs* of Consumers to the RSU hosting them. Furthermore, the RSU acts as the entity responsible for the settlement of the communication path between the Content Provider and *next RSUs*, when potential migration of the mobile Consumers is acknowledged.

The results have shown that the proposed approach is able to handle Consumer mobility, outperforming the native solution, with a small number of Timeouts. Using the proposed solution, the content delivery time depends on the RTT of the prediction request and the one of the content delivery.

The future work may include: (1) a distributed mobility manager that enables decisions to be discharged closer to the edge, making the solution more suitable for ultra-dense environments; (2) the introduction of appropriate caching mechanisms, with mobility awareness, that could leverage the overall performance of our solution; or (3) mobility-awareness fragmentation strategies in the case of high link error rates, high mobility patterns and big size contents.

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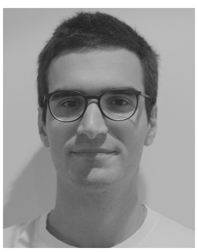

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